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Review of Smart Grid Comprehensive Assessment Systems

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Abstract

Smart Grid is an inevitable trend of power grid, and smart grid comprehensive assessment system can conduct a comprehensive assessment of the overall characteristics of smart grid, which can reflect the current level of the development, find the weakness and the constraints in the network development, identify the distance to the target, ensure the smart grid development achieve a unification of the quality, speed and efficiency. At present, many countries are studying on the smart grid comprehensive assessment systems. This paper analyzes the IBM Smart Grid Maturity Model, the DOE Smart Grid Development Evaluation System, the EPRI Smart Grid Construction Assessment Indicators, and the EU Smart Grid Benefits Assessment System, and compares the development levels, evaluation objects, target ranges, applications differences between these systems and the "two type" grid index system, the smart grid development assessment index system, and the smart grid pilot project evaluation indicator system suggested by China. The thoughts and the principles of building smart grid comprehensive assessment system, and the issues which should be noted are proposed here, which can provide necessary references and supports to construct the smart grid comprehensive assessment system.
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Keywords: Smart grid, integrative assessment, assessment indexes

1. Introduction

As an important infrastructure of the economic and social development, the power grid is a physical platform of realizing energy conversion and power transmission; meanwhile, it is an important carrier of achieving a wide range of optimal allocation of resources and promoting market competition [1]–[4]. When evaluating the power grid, for its unique physical properties and social attributes, the technical and

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economic factors should be considered, and the integrated social benefits should be reflected. Smart Grid is an inevitable trend of power grid, the agreements have been come to among most countries on which effects on tackling climate change, ensuring national energy security and promoting green economic development. Nowadays, countries at different stages of social development levels are discovering and exploring the effective ways of developing smart grid in close connection with their own national conditions.

Smart grid is a complex and huge system, and its practice is still in an initial stage [5]–[7], so assessing the comprehensive benefits of smart grid scientifically, detecting the deficiencies in its construction and operation and achieving the balanced development of technologies and economy have great practical significance on smart grid planning, construction, operation and management. On the one hand, smart grid is the upgrade and renovation of traditional power grid, which hold all features of traditional grid; On the other hand, smart grid shows many specialties, such as information, automation and interoperation, which have greatly enhanced and extended the various functions of the traditional power grid. Therefore, when assessing the smart grid scientifically, it is necessary to maintain the correct assessment of traditional power function and reflect the characteristics of smart grid technologies and their functional properties.

2. Smart Grid Assessment Techniques at Abroad

Europe and other developed countries have reached a high level on the development of the power grid construction and operation management, and accumulated rich experience in the evaluation process. Recently, many countries and well-known companies focus on how to establish the smart grid comprehensive assessment systems, which reflect the important position of smart grid assessment on the guidance to the smart grid development. Now there are the IBM Smart Grid Maturity Model, the DOE Smart Grid Development Evaluation System, the EPRI Smart Grid Construction Assessment Indicators, and the EU Smart Grid Assessment Benefits Systems.

2.1. IBM smart grid maturity model [1]–[10]

The Smart Grid Maturity Model is proposed by the IBM Corporation, American Productivity & Quality Center (APQC) and Global Smart Grid Federation. The Global Smart Grid Federation wants to encourage, guide and support the power companies around the world and related industries paying more effort and investment to the smart grid by using this Smart Grid Maturity Model.

The Smart Grid Maturity Model is defined as: improving system reliability and efficiency, accepting more new energy, and making more interaction between users with the grid. According to the understanding of the smart grid construction, the Smart Grid Maturity Model will be divided into five different stages. The five smart grid maturity levels are:

- The grid is beginning to explore the journey toward a smart grid, and may have a vision but not a clear strategy.
- The grid is investing in and implementing at least one of the essential functional areas of smart grid.
- The components of smart grid begin to be integrated with one another, providing operational linkages between two or more functional areas.
- The grid can achieve the integrative information and control across enterprises, and form a new economy or trade mode.
- When new business, operational, environmental and societal opportunities present themselves, the grid can take full advantage of them and develop itself.

According to the aspects of staff technologies and operational processes, IBM divides the smart grid assessment process into eight areas, as shown in Table 1.

Table 1.IBM Smart Grid Maturity Model

	Area	Specific contents
Staff technologies	policy management and supervision	Vision, strategic planning, decision making, strategy implementation and rules, regulatory, investment process, etc.
	organization	Communication, cultural, and organizational structure
	technology	Information, engineering, information integration and operation, standards, analysis tools, etc.
	society and environment	Environmental protection and green initiatives, sustainable development, integrated alternative energy and economy and feasibility of distributed energy
Operational processes	grid operation	The observability and control operation of advanced network, quality and reliability
	personnel and asset management	Optimization of assets and resources
	custom management and experience	Retail, customer care, prices choice and control, advanced services, power quality, visual display of performance
	value chain integration	Demand and supply management, distributed generation management, load management, market opportunities

Based on the decomposition of the five stages of smart grid and the eight areas, a total of about two hundred features are raised to represent various stages of smart grid characteristics and specific performance, to help the power companies determine their current stages, identify the gaps between the actuality and the target and find the orientation need to improve. As the assessment system has a large number of qualitative indexes, this system has a high demand on reviewers. When to use this assessment system, it needs to score according to the object's characteristics and determine their current level, referring on the expectations of each level, estimate their grade and level, then give the assessment results.

2.2. DOE's smart grid development evaluation system [11]–[12]

On July 2009, the U.S. Department of Energy (DOE) released a smart grid assessment framework system, which includes two aspects: one aspect is the understanding of U.S. about smart grid, the second aspect is the assessment metrics. The U.S. Department of Energy proposed that smart grid should have the following six performances:

- Enabling Informed Participation by Customers
- Accommodating All Generation and Storage Options
- Enabling New Products, Services, and Markets
- Providing the Power Quality for the Range of Needs
- Optimizing Asset Utilization and Operating Efficiently
- Operating Flexibly when Disturbances, Attacks, and Natural Disasters happened

The six properties are the United States Department of Energy's overall understanding of the smart grid, which can be explained as two major goals that the smart grid construction need to achieve: one is to provide customs with better services, and through custom's participation to increase the grid benefits, the other is to make the grid more flexible to respond to the various disturbances and natural disasters.

Based on the six characteristics of the smart grid, the U.S. Department of Energy proposes an assessment system, which consists of a total of four groups, twenty indicators, as shown in Table 2.

Table 2.DOE Smart Grid Development Evaluation System

Indicators class	Indicators
Area, regional and national coordination regimes	dynamic pricing, real-time operational data sharing, distributed power interconnection policy, policy and regulatory progress
Distributed-energy resource technology	demand-side resources for participation in electric-system operation, micro-network services, interconnection of distributed generation (including renewable and non-renewable), electric cars and hybrid vehicles, the response of non-grid power generation demand-side equipment
Transmission and distribution infrastructure	transmission and distribution system reliability, automation, advanced metering, advanced system measurement, capacity factors, generation and T&D efficiency, dynamic line capacity, power quality
Information networks and finance	computer security, open architecture / standards, venture investment

In this system, the indicators are divided into two categories: build indicators and value indicators. The build indicators describe the indicators which support the smart grid property, which can reflect the smart grid development degree and construction progress from a qualitative point of view. Value indicators can describe a certain degree which the smart grid to achieve, reflect the maturity of smart grid development and assess the effect of smart grid construction from a perspective of the amount. The transmission and distribution system reliability index, capacity factor index, efficiency of generation and T&D index, power quality index, venture investment index are value indicators, the remaining are build indicators.

This twenty indicators are proposed following by the description of the features and vision statement of the smart grid issued by the U.S., for example, dynamic pricing, advanced metering is the precondition for the customs' participating in the smart grid operation; the distributed-energy interconnection policy and the integration of distributed generation technologies respectively represent whether to encourage customs to develop distributed-energy and whether the grid has the ability to take full use of the distributed-energy; electric vehicles, electric appliances reflect the requirements which the smart grid meets the need of new products, new services, etc.

According to the performance of the smart grid objects, the assessment system describe the build indicators qualitatively by low, medium, and high levels, and obtain the indicator values through a quantitative way. The results of the indicators can be applied in different fields, such as the grid operation analysis or the taxonomy of features for smart grid.

2.3. EPRI's assessment indicators for estimating the benefits and costs of smart grid demonstration projects [13]

The American Electric Power Research Institute (EPRI) established a smart grid construction and project assessment indicator system on the basis of the DOE's Smart Grid Development Evaluation System. The indicator system is used to assess the whole process of the smart grid and individual projects, which aims at assessing the smart grid construction levels and the benefits. The elements of the EPRI smart grid construction and project evaluation index system are shown in Table 3.

Compared with the smart grid characteristics proposed by the Department of Energy, EPRI emphasizes the importance of the grid's self-healing function, and makes it become one of the major characteristic of the smart grid. It means that the EPRI takes more attention on the grid construction, which can increase the proportion of the grid operation in the composition of smart grid.

The index system proposed by the EPRI is more specific and more detailed compared to the DOE system, which shows the purpose of estimate: assesses the smart grid construction process and analyses the benefits of smart grid projects.

Table 3.EPRI Smart Grid Construction Project Cost/Benefit Assessment Indicators

Smart grid characters	Smart grid construction assessment indicators
Enables informed participation by customers	the percent of the load managed, number of customers employing energy storage or generation systems, etc
Accommodates all generation and storage options	percent of distributed generation and storage that can be controlled directly proportion of DG that employs combined heat and power or a renewable source, etc
Enables new products, services, and markets	number of new residential products, amount of energy or capacity delivered as an Ancillary Service, number and proportion of annual vehicle sales in service area that involve plug-in electric and hybrid vehicles, etc
Provides power quality for the range of needs	reduction in system losses and equipment failures due to improved PQ, number of installation points and percentage and magnitude of the total load covered by microgrids, etc
Optimizes asset utilization and operating efficiency	level of asset utilization or load factor, reduction in O&M costs, reduction in grid equipment failures, etc
Addresses disturbances through automated prevention, containment and restoration	percent of network nodes and customer interfaces that are monitored in real time, improvement in reliability statistics, outages avoided through improved monitoring and deployment of DER/DR, etc
Operates resiliently against all hazards	DER penetration and geographic diversity, number of successful cyber attacks, improvement in outage restoration time, etc

2.4. EU smart grid benefits assessment system [14]–[15]

The drivers of smart grid development of Europe can be attributed to three aspects: market, security and power quality, environment [16]–[17]. The attention to the importance of environmental protection and the growing challenges of the renewable energy interconnection, makes the European smart grid pays more attention to the interconnection of the renewable and distributed generation, reliability, power quality and the value-added services of grid to all customers.

The goal of the European smart grid is developing a low-carbon energy system, by increasing the interconnection ratio of the renewable and distributed generation, and achieving the purpose of the energy saving by the demand side management. The smart grid proposed by Europe aims at ensuring power supply sustainable, economic, and security, by the use of the innovative products and services, intelligent monitoring, control, communications, self-healing technologies. The compatibility of the operation and action of the generation side, the customs and the members who have both the characteristics of power providers and consumers, would be reached.

Based on the above description of the smart grid, the European Network of Transmission System Operators (ENTSO) and the European Network Distribution System Operators (EDSO) published a smart grid benefits assessment system, which divides the benefits into nine parts, as shown in Table 4. The assessment system contains twenty one key indicators. By accessing the indicators we can estimate the benefits of the smart grid construction. The function of the system is evaluating and developing effective and efficient smart grid technologies, assessing the benefit of the smart grid projects and selecting more effective and more efficient projects.

3. Domestic Smart Grid Assessment Techniques

In recent years, the power grid of China has experienced a rapid development in the grid construction, which structure is more mature and more reasonable. The abilities of supplying electric services were raised and in some field, such as ultra-high voltage transmission, electric technologies have reached advanced level in world. The Chinese government attaches great importance to the smart gird development. Many enterprises represented by the Sate Grid Corporation of China are carrying out the research, construction and practical works of smart grid. Smart grid in China is at the same developing level with the word. The domestic electricity industries have carried out many practical projects in the areas of the smart grid, and proposed the "Two Type" grid index system and Grid Development Assessment Index System, etc [18]–[19]. Recently many studies have been carried out on the smart grid pilot projects evaluation, which provides reference for the next stage of promoting and extending smart grid technology.

Table 4.EU Smart Grid Benefits Assessment System

Benefits	Indicators
increased sustainability	CO2 reduction
adequate transmission/ distribution grid capacity to bring the electricity generated from all sources to consumers	Distributed power capacity, maximum accommodate power injection, etc.
harmonization and standardization of grid connection procedures giving access to any type of grid users	Reduce the time of new users connecting to the grid, unified custom access standard
higher security and quality of supply	Peak load clipping rate, improve the prediction and control of emergency efficiency
enhanced efficiency and better service in electricity supply and grid operation	System losses reduction, the improving the system reliability
effective support of pan-European electricity markets by load-flow control to alleviate loop-flows and increased interconnection capacities	The improvement of cross-tie line capacity
coordinated grid planning and development involving joint European, regional and local grid	
cost efficiency of the deployed solutions	
enabling of new business models and the development of innovative products and services	

3.1. "Two Type" grid index system [20]

"Two type" grid, which was explained as "resource-saving and environment-friendly" power grid, is based on the theme of saving resources. The conservation and efficient utilization of resources are the cores of this grid, which aims to realize the goal of adapting to social economic development and coordinating with the environment. In essence, "two type" grid reflects the concept of sustainable development.

Based on the conventional evaluating on reliability, security and economy of power grid, "two type" grid index system further concerns the degree of saving resource and friendly environment, which provide quantitative index for the related "two type" works. "Two type" evaluation index system proposes the effective indexes which reflect the contributions of the power grid to the "two type society", also takes into account the measurable index which reflect the achievement of the "two type" grid. "Two type" evaluation index system contains the overall indicators which include general situation of power grid development, and sub-indicators which reflect specific situation.

- Analysis the measurable index from the point of view of planning, design, construction, scheduling and operation.
- Analysis the direct index and indirect index according to the subjects.
- Analysis the constraint index and reference index according to the binding of the measurable index.
- Study on the effective index from the aspects of resource conservation and environmental

protection.

On the way of from the process to result and from means to effect, “two type” evaluation index system first analyses the works that have been done in the fields of grid planning, design, construction, operation, and technical transformation, and then constructs the measurable index, then analyses effectiveness of various measures and constructs effective index. In the process of analyzing, designing the measurable and effective index, the principle should be followed of establishing the system from underlying index to high-level index, that is constructing the sub-tree index set first, and then the comprehensive index system. The proposed index system is shown in Table 5.

Table 5.“Two Type” grid index system

Measurable indexes	Planning stage	rid intensification, grid scale, advanced transmission technology applications
	Construction stage	optimization, environmental protection
	Operation stage	dispatching operation, technological innovation, demand side management
Effective indexes	Resource-saving	energy resource saving, land resource, facilities and material
	Environment-friendly	emission reduction, environmental governance

The bottom indexes of “two type” evaluation index system include a total of fifty three indexes: the proportion of renewable energy generation, scale network between regions or provinces, et al. By the application of the index system, it helps to judge the current situation of grid, provide guide for the planning of “two type” grid development, and achieve the goal of “two type” grid construction.

3.2. Grid development assessment index system [21]

The grid development assessment index system is under the environment of the rapid development of grid, which focuses on the assessment of power grid development level. The system carries out the evaluation on the economic development, power development speed, construction scale, proposes the quantitative assessment method and model. In the time of setting op this assessment system, the concept of smart grid has not been proposed clearly, and the assessment about the intelligence of grid is just discussed preliminarily.

Including the analysis of security and economy, the grid development assessment index system has introduced social and environmental factors. Taking comprehensiveness, simplicity and operability as principles, the grid development assessment index system was established from five aspects: security, economy, quality, coordination, intelligence. The proposed index system is shown in Table 6.

Table 6.Grid Development Assessment Index System

Security	structural safety, operational safety, stability, sufficiency and resilience
Economy	benefits of grid-scale and energy interconnection, new construction efficiency and economic of the power grid construction
Quality	quality of grid operation and construction, grid resource saving capability
Coordination	coordination of resources, social harmony, economic coordination, environmental coordination
Intelligence	smart grid scale basis, smart grid technology support ability, smart application effect

Taking account into the diversity and complexity of the indexes, the grid development assessment index system has carried out innovate study on the assessment method. Layered optimization mixed assessment method is used in this study. Based on the traditional weighted average algorithm and the expert scoring method, this system proposed an assessment model, which makes use of a combination of objective and subjective weights. The grid development assessment system has been decomposed into security, economy and other subsystems. The hierarchies of subsystems were determined, of which, the economic assessment of grid development uses the data envelopment analysis method, the quality assessment uses entropy method to calculate the superiority of index weight, and TOPSIS method is used to calculate the assessment results, correlation coefficient method is used to calculate the coordination of index values, a combination of quantitative and qualitative analysis method (AHP) is used to construct the intelligent assessment model. The final comprehensive assessment of the entire power grid could be gotten on an overall consideration of the subsystem evaluation weights and results.

3.3. Smart grid pilot project evaluation indicator system [22]

According to three typical pilot projects including smart substation, automation of distribution system and collection system of power utilization information, the corresponding evaluation indicator system is proposed. By analyzing and evaluating the effectiveness of the pilot projects from the aspects of technical level, economic benefits, social benefits and practicality,, the smart grid pilot projects would be adjusted, uniformed and generalized.

Smart grid pilot project evaluation takes the SMART (Specific, Measurable, Attainable, Relevant Trackable) criteria into consideration, and analyzes the pilot projects from the aspects of technique, economic, society, practicability, etc.

The smart grid pilot project evaluation indicator system uses the method of combining the AHP and fuzzy evaluation, and calculates the indexes values, then gets a comprehensive score. The indicator system focuses on studying and analyzing of the important pilot projects, such as smart substation, automation of distribution system and collection system of power utilization information.

1) Smart Substation Evaluation System

It is for smart substation whose voltage level is 110kV(including 66kV) and above. The technology, economy, sociality and practicality of smart substation projects could be analyzed and evaluated qualitatively and quantitatively. The proposed index system is shown in Table 7.

Table 7.Smart Substation Evaluation System

First level indicators	Second level indicators	Third level indicators
Technology	Interactive indicators	information standardization, configuration standardization, functional interaction
	Advanced indicators	smart equipment, measurement accuracy, easy to operate and maintain
	Quality indicators	auxiliary equipment, optimization measures
Economy	Cost indicators	construction costs, operation and maintenance costs
Sociality	Social impact indicators	land saving, materials saving

2) Automation of distribution evaluation system

Automation of distribution evaluation system focuses on improving the reliability of distribution network, the quality of power supply, capacity of security warning and emergency response. The proposed index system is shown in Table 8.

Table 8.Automation of distribution evaluation system

First level indicators	Second level indicators	Third level indicators
Technical	Security indicators	network structure, secondary equipment
	Self-healing indicators	Fault handling capacity
	Quality indicators	power quality
	Interactive indicators	information internet
	Advanced indicators	equipment coverage, advanced application of distribution network, intelligent function
Economy	Cost reduction indicators	operation and maintenance costs, equipment index
	Efficiency increase indicators	increase power supply
	Cost-effectiveness indicators	cost effectiveness ratio
Social	Environmental impacts indicators	energy saving, emission reduction
Practical	Promote the use of indicators	practical level, management system

3) Collection System of Power utilization information evaluation system

The purpose of constructing collection system of power utilization information is to transmit the information of power system and users interactively, which is one of the important characteristics of smart grid. The proposed index system is shown in Table 9.

Table 9.Collection System of Power utilization information evaluation system

First level indicators	Second level indicators	Third level indicators
Technical	Security indicators	system reliability, security indicators
	Interactive indicators	Information Internet
	Advanced indicators	Complete collection rate, prepaid expenses
	Quality indicators	channel availability, acquisition performance optimization, supporting management optimization
Economy	Cost reduction indicators	improve labor efficiency and the average investment
	Efficiency increase indicators	line losses reduction
	Cost-effectiveness indicators	cost effectiveness ratio
Social	Environmental impacts indicators	energy saving, emission reduction.
Practical	Promote using indicators	practical level, management system.

4. Comparison of the Smart Grid Evaluation System between China and other countries

4.1. Study on the smart grid evaluation system starts earlier at abroad, which is regarded as one important link during smart grid construction.

As developed countries had accumulated considerable experience in the grid construction evaluation and given an important position to smart grid evaluation system, they endued great importance to evaluating the smart grid in parallel with the smart grid research and construction at the early phase of the smart grid construction. In addition to power companies and consulting organizations, many governments also support and preside the related work actively, which plays an important role in promoting the smart grid construction. In July 2009, the U.S. Department of Energy writed the smart grid assessment indicators system as an important part into its first smart grid report-“Smart Grid System Report”. As the famous international company who is one of the first advocators of smart grid, IBM proposed smart grid maturity model in 2009, which has been applied in more than fifty power companies.

In the smart grid planning, pilot, R & D and other fields, the difference between China and other countries are not obvious; however, the work of smart grid comprehensive evaluation in China is relatively passive, and government's guidance and incentive policy for smart grid are not clear enough. Although power industries, manufacturing companies, standards-setting agencies and other related enterprises have carried out many concrete construction works, they have not achieved a consensus in the smart grid evaluation criteria. There are risks of redundant construction and uneven development during smart grid construction.

4.2. Smart grid assessment system reflects different understanding of smart grid, and each assessment system tends to focusing on different emphasis.

At present, many areas of the world have reached consensus in smart grid strategic significance, structure composition and promoting measures. For example, smart grid is a complete power system which includes power generation, transmission, distribution, customer and other aspects; smart grid can promote economic development. However, due to different national conditions and stages of power industry development, different assessment indicators and criteria should be considered when setting smart grid development path and goal. For example, the facilities are aging and obsolete, and there are many prominent security and stability risks in the U.S. power grid, so the assessment indicator system developed by EPRI placed great emphasis on power system security and reliability. European countries are facing tremendous pressure of emission reduction and resources lacking, so they pay more attention to the new energy exploiting and low-carbon developing.

China should start from its own national conditions and propose a smart grid develop pattern which suits its economic and social development. China is in the stage of rapid urbanization and industrialization. As a public infrastructure, smart grid should apply its properties into severing the economic and social development, reflecting the strategy of energy adjustment and economic pattern transform, and severing the needs of all kinds of consumers. The smart grid assessment system in China should evaluate from the demands of whole society, and give a comprehensive evaluation to the smart grid technical feasibility, economic rationality and social benefits.

4.3. China needs to form a unified evaluation system, measuring the smart grid develop situation quantitatively and guiding the future direction of smart grid exactly.

Compared to smart grid assessment system abroad, Chinese remains in the stage of the traditional grid assessment system. For example, "two type" grid index system mainly focuses on the construction and implementation effects of the traditional grid; although the grid development assessment index system reflects the smart factor, the understanding of smart grid is confusing at that time and smart grid is just a supplement to the traditional grid, which can not form a scientific assessment to entire smart grid system. Although the smart grid pilot project evaluation indicator system focuses on the smart grid assessment, the main purpose of the assessment system is applied in independent specified project, which lacks the ability of mutual consideration and comprehensive evaluation, the smart grid system can not comprehensive assess the construction status and comprehensive benefits.

The proposed smart grid assessment system should treat smart grid as an organic whole, reflect the information, automation, interoperate features, give full consideration to the electric vehicles, energy storage, other value-added services model and social benefits of energy saving and environment protection, form a unity smart grid evaluation system on the basis of reflecting the time differences and regional differences during the smart grid development.

5. Conclusion

Smart grid has become a worldwide trend. Smart grid scientific assessment is directly related to the layout of construction, the direction of investment, technology route and the implementation effect and other key issues. Many countries have carried out research and practice work already and China is lagging behind, so accelerating the research and application of the smart grid assessment system is an important measure to promote smart grid construction.

China should pay attention to the following aspects when constructing the assessment system:

- Make full use of the role of the government, which should show the directions of smart grid and the assessment indicators study.
- Based on national situation and power development status, the assessment system should show the characteristics of Chinese economic and social development.
- The smart grid assessment system in China should evaluate from the perspective of the whole system, and realize a comprehensive evaluation to all aspects.
- The smart grid assessment system should reflect the time differences and regional differences of the smart grid development, which can play the role of reference and guidance to the smart grid planning and construction.

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