Artificial Power System Based on ACP Approach

Xisong Dong[1,2], Gang Xiong[2,1], Jiachen Hou[2], Dong Fan[1]

[1]State Key Laboratory of Management and Control for Complex Systems, Beijing Engineering Research Center of Intelligent Systems and Technology, Institute of Automation, Chinese Academy of Sciences, Beijing, China

[2]Dongguan Research Institute of CASIA, Cloud Computing Center, Chinese Academy of Sciences, Songshan Lake, Dongguan, China

xisong.dong@ia.ac.cn, gang.xiong@ia.ac.cn, hou.jiachen@gmail.com, dong.fan@ia.ac.cn

Abstract—**Modern power system is a typical multi-level complex giant system consisting of physical infrastructures, human operators, and social resources, etc. The conventional analytical methods and simulation systems can't provide sufficient guidance for its operation and management, because they are mainly based on physical models, natural phenomenon, or other existing control methods which are based on reductionism. ACP approach, mainly consisting of artificial systems (A), computational experiments (C) and parallel execution (P), which is based on holism and complex system theory, has its specific advantages in the research on power systems. In this article, ACP approach is applied to build up artificial power system (APS) by using multi-agent complex networks. With the help of APS, actual power system's control, scheduling, optimization and management can be improved further via providing theoretical guidance and technical support for the rolling optimizations in normal situations and emergency management in abnormal situations. As a case study, an APS constructed with actual data from North China power grid is constructed and its vulnerability is simulated and analyzed under random, dynamic and static attacks.**

Keywords-power system, ACP approach, artificial power system (APS), complex network, multi-agent, vulnerability

I. INTRODUCTION

Modern power system has already become a multi-level complex giant system involving natural, political, economic, social, environmental and human factors, and a man-made system with more and more complex structure [1]. On the one hand, it can improve the operation efficiency and promote the optimal resource distribution. On the other hand, the increasing operation uncertainty gives new challenges [2]. In recent years, many large-scale blackouts of power systems in different countries have happened and caused enormous social and economic losses [1].

With the development of power system, its regular operation and emergency management need to consider all factors at the same time, including engineering, social, natural and human factors. Unfortunately, there are no systematical and accurate models in most cases, which is a new challenge for theoretical analysis and simulation research of modern power system:

1) The existing control theories and methods of power system, only based on reductionism, can't provide good enough guidance for its operation and management, and they can't give scientific theoretical explanations and analytical methods for various complex phenomena, like evolution characteristics and consequent development mechanism, etc.
2) For power system itself, traditional simulation methods have many limitations. Along with the increase of complexity, its accuracy and reliability are difficult to assure. For example, its accuracy and reliability, its specific characteristics, like non-storage, intangible, uncertainty random demand and price diversity, and such effect factors as weather, holidays, society, economy, and politics, are hard to be handled.
3) The conventional power simulation systems are built with physical model or natural phenomenon, without deeply consideration on the influences of human behaviors, natural environment and social factors. So, it is difficult to carry out the operation assessments and adequate guidance for the operation and management of modern power system. Historic statistics in TABLE I show that the main reasons of blackouts are natural disasters, social and human factors which are all beyond power system [2].
4) Future smart grid is a major upgrade from traditional power system, which has a more complex configuration, and generates in-depth influences on various aspects such as power generation, transmission, distribution and users demand, lets the power grids of internal and external factors be coupled more closely in multiple dimensions, like time, space, object, objective and information, etc. [3, 4]. So, its complexity will be more obvious and serious, and traditional theoretical analysis methods can't be applied for its research.

TABLE I. THE ROOT REASONS STATISTICS OF 110 BLACKOUTS

Fault	Type	Number	Proportion	Total proportion
Natural disaster	Storm	13	23.03	53.64
	Wind	33	55.93	
	Lighting	6	10.17	
	Others	7	11.86	
Human factors	Protection	2	20.00	9.09
	Disoperation	5	50.00	
	Others	3	30.00	
Equipment failure	Lines	12	41.38	26.36
	Stations	15	51.72	
	Others	2	6.90	
Energy crises		4	100	3.64
Unkown		8	100	7.27

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In brief, the development of power system makes its operation and management become more complex, the interaction between power system and its social factors, natural elements and human factors become closer and closer, and the existing research theories and methods are difficult to study it. In most cases, it is impossible to establish systematic, sufficient and accurate models. So, to seek new solutions, introduce new concepts and methods, and set up new theoretical systems are needed.

In order to overcome the limitations of traditional theories and methods, this paper presents a novel solution based on ACP approach and complex system theory. This solution can establish an artificial power system (APS) "equivalent" to actual power system, and then discover an effective way to realize the optimal operation in normal conditions and the emergency management in abnormal conditions.

The rest context is organized as follows: Section II introduces ACP approach; Section III presents the design, construction and validity of APS; Conclusions are drawn out in Section IV.

II. ACP Approach

ACP means artificial systems (A), computational experiments (C) and parallel execution (P) [5]. The first characteristics of ACP approach is to change non-dominant position of artificial system, to change its role from passive to active, from static to dynamic, from offline to online, and finally to have equal status with actual system. Thus, artificial system can play its role fully in actual system's control [6]. By considering all factors such as engineering, society, human and environment, ACP approach combines theoretic modeling, experience modeling and data driven modeling, to solve the difficulty of traditional modeling of complex systems. The interaction relationships among actual system' various factors and their evolution laws under normal and abnormal conditions can be studied by computational experiments based on the artificial system [6]. The reactions of actual and artificial systems can be compared and analyzed through their connection, and reference and estimation of their future status can be studied, then their control and management methods can be adjusted accordingly. Finally, parallel execution can be implemented by using those laws: in normal circumstance, artificial system is used to understand actual system's various evolution laws, then actual system's control objectives can be continuously optimized, and the occurrence possibility of abnormal situation can be reduced; in abnormal circumstance, emergency control methods of actual system can recovery to its normal circumstance quickly, so as to reduce its losses [7].

A. Artificial Systems

In ACP approach, "A" means to build up the artificial systems "equivalent to" actual systems, then the equivalent results of actual systems can be found by computational experiments results of artificial systems, the understanding from artificial systems are ensured to be equivalent to the understanding from actual systems [1, 6].

The accuracy approximating to the actual system is important for traditional simulation systems, but is no longer the only objective in artificial systems. Instead, the artificial system is considered "real", i.e. another possible reality of the actual system. Based on this assumption, the actual system is just one of all possible realities of the artificial system. So, the behaviors of actual and artificial system are different but considered to be equivalent for their evaluation and analysis.

There are no effective and widely accepted modeling methods for complex systems, especially those involving human behaviors and social organizations. Artificial systems might be the most promising among new modeling approaches.

B. Computational Experiments

Traditionally, the research on complex systems is very difficult, for example the researched object's test is impossible because of such factors as nature, economy, laws and ethics, etc. Their studies often use passive observations and statistical methods, because active tests, active evaluations and repeatable experiments are difficult to be conducted. Even allowed, too many subjective, uncontrollable, and unobservable factors will affect the validation and conclusions. So, it is critical to find a new effective way to conduct experiments for complex systems [7].

Using artificial systems, the behavior of complex systems can be predicted and analyzed. We can design and conduct the controllable experiments which are easy to manipulate and repeat; we can then evaluate and analyze quantitatively the impact of different factors. These computational experiments are a natural extension of computer simulation. Their calibration, analysis, and verification are considered. And such design principles as replication, randomization, and blocking, just as those experiments done in the actual systems. The comparison between power simulation system and APS are shown in TABLE II.

TABLE II. Comparison Between Power Simulation System And APS

	Power simulation system	**APS**
Object	Physical power system	Physical power system, its society and people
Modeling method	Mechanism modeling	Mechanism, data and experience modeling
Modeling scope	Engineering complexity, like equipment, process	Engineering complexity, social complexity
Simulation type	simulation and real-time simulation	Real-time simulation and super-real-time simulation (prediction)
Dynamics type	Transient	Transient, medium and long term dynamics
Object scale	Small-scale	Large-scale
Object scope	Specific local part (plant, transformer substation, etc)	Whole power system
Object involved	Physical power system only	Physical power system, politics, economy, society, human, weather, etc
Control means	Plan-response	Scenario-response
Control manner	Prior plans	Active defense and prevention
Control format	Offline plans	Online response
Control methods	Simulate actual situation	Computational experiments

C. *Parallel Execution*

Parallel execution can be implemented by using the results of computational experiments. On the one hand, the goals of the actual system can be achieved when it is guided by various computational results. On the other hand, the results of the actual system are fed back to the artificial system for its amendment. Then, the artificial and actual system can progress and improve at the same time [7].

Parallel execution means that the artificial system runs simultaneously with the actual system. It provides a control and management mechanism of complex systems through comparison, evaluation, and interaction with their artificial systems.

At present, ACP approach has successfully applied in the control and management of traffic system [8, 9], Emergency Management [10], ethylene production [11], and so on.

III. Designs And Construction Of APS

A. *Artificial Power System*

APS is an application of ACP approach in the research of the power system. Firstly, comprehensively considering various factors in the power system, including the equipment characteristics, human, environment, and social factors, APS can be constructed. Secondly, by computational experiments based on APS, comprehensive, accurate and timely assessments and amendments for the planning, design, operation and management schemes of the actual power system can be carried out without high cost and risk. Finally, parallel system is built to connect APS with the actual power system, therefore their control, operation and management can be carried out through parallel execution [1].

APS is the revolutionary improvement of power system simulations. Power system simulation is a reductionism method by using computers and numerical modeling technologies, simulating various states and development of its characteristics, resolving its various problems. It is a kind of up-down passive method. APS is a bottom-up active integrated research method. It is composed of all kinds of artificial components especially including human and social behaviors. It can model actual power system on boarder range and higher logic level, and carry out computing and analysis from qualitatively to quantitatively. It integrates mechanism modeling, data modeling and experience modeling, and considers engineering, social and human factors. It can simulate, assess and improve the operation evolution and emergency management of the actual power system. So, APS provides an innovative and practical way to realize the intelligent operation and management of the power system.

B. *Construction of APS Based On Multi-Agent Complex Network*

The power system is one of the biggest man-made projects, and a strong large-scale nonlinear dynamic system, which is a multi-dimensional, nonlinear, time-varying and large-scale system. Its nonlinearity, variety, hierarchy, integrity, statistics, self-similarity, self-organization and criticality all satisfy the general characteristics of complex systems. And, it can also be considered as complex network constructed by power plants, transformer substation and high-voltage transmission lines with different connection modes [13-16]. Recent research proves that it also has characteristics of complex network, such as small-world and scale-free characteristics. The complex network theory can provide a new thought and way for power system. It can scan the dynamic characteristics from a new angle, and provide new ideas for all kinds of complexity characteristics and evolution laws of complex power system [13-16].

However, the existing network statuses can only reflect its performance from the perspective of network connectivity, but can't reflect its many other characteristics well. For example, the difference of nodes is not considered, node might be stations, substations, transformers, or other high-voltage load. And, the influences of various factors, such as political, society, economy, environment, weather, equipment and human which are dynamic, complicated, variable, are not considered.

In order to solve the above problems, there are two aspects of work to be done. Firstly, the complex network model can be improved to become the weighted directed graph so that current transfer can be calculated better [16]. Secondly, agent theory is introduced to construct multi-agent complex network model.

Complex network theory and agent-based simulation can provide more satisfactory reality, more effective modeling methods to describe and study complex power system, which can greatly enhance its capacities of understanding, research and control. Compared with traditional modeling methods, agent-based modeling can not only provide more realistic modeling methods, but also get the emerging characteristics of complex system from micro to macro behaviors, to reveal the inner micro mechanism of complex system's macroscopic characteristics. Therefore, APS is established according to multi-agent complex network theory, which integrates the advantages of agent theory and complex network to reflect the essential characteristics of the actual power system.

So, the multi-agent complex power system can be constructed as follows:

a) Power plants, substations and transformers are taken as nodes regardless difference of themselves.

b) Only high-voltage transmission lines and transformer branches are taken as edges, not including distribution networks and low-voltage lines.

c) Merging the power transmission lines on the same tower, and branch parallel capacitor is excluded for removing self loop and multiple edges.

d) The network is directed according to the direction of power currents.

e) The nodes of network are taken agents, which have been simplified because of the large number.

f) Limit the communication of agents in the connection and direction of nodes agents. Determine the directions of lines by the communication of agents.

Based on multi-agent complex network, combining Monte Carlo processing data with Fuzzy Neural Network analyzing expert experience, APS "equivalent" to the actual power system can be built (Figure 1 and 2). The evolution laws under various unexpected incidents can be tested by computational experiments executed on APS; then network topology, parameter variation, forecast, analysis, decision-making and recovery program and blackouts' prediction, occurrence, secondary occurrence, derivative occurrence, coupling, variation and crisis management can be studied; finally, emergency plans formulation, site management, decision support can be provided for the actual power system, and the interaction between various social factors and the power system can be studied, the effects and anti-effects of human and social behaviors and reaction can be analyzed, and the effects of different solutions can be evaluated and optimized, in order to provide reference, guidance and advice for normal and abnormal operation condition, and theoretical support to the crisis management of the actual power system's failure.

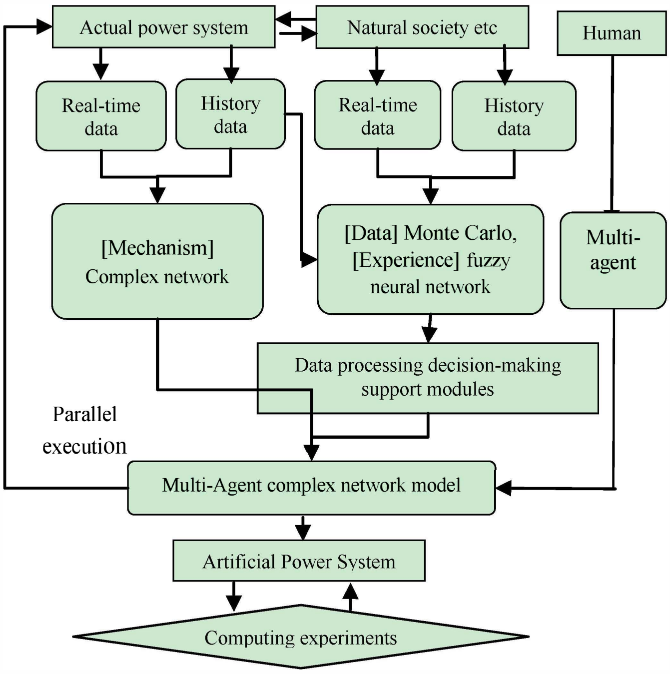

Figure 1. APS's diagram

C. *A Case Study of APS*

The APS model of North China power grid is built according to ACP approach discussed above. The model is built by the actual data, represents the power grid as a network of 2556 nodes and 2892 edges. The vulnerability indexes are attained, and then its vulnerability under different attack modes is simulated and analyzed.

In order to test the electric betweenness' status, three different attack modes were combined to launch a chain of attacks. The modes are shown below:

a) Random attacks;

Delete some nodes or lines agents randomly.

b) Static attacks

Delete the lines or nodes according to their degrees or betweenness from large to small.

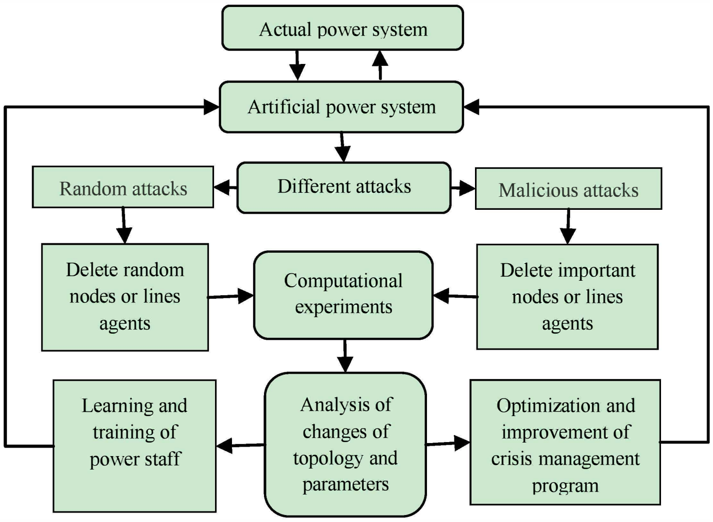

Figure 2. Computational experiments' diagram of APS

c) Dynamic attacks

Delete the lines or nodes with the largest degrees or betweenness, and re-calculate their degrees or betweenness after every attack; go round and round.

A total of ten such nodes or links are removed one after the other, the system's efficiency is calculated after every attack which can reflect the system's robustness to such attacks.

The efficiency of APS after the above three attack modes is shown in Figure 3, and following conclusions can be drawn:

i) The nodes or lines with the highest degrees or betweenness, which are usually the transmission lines or substations at 500kv according to actual power grid, play the roles of transmitting and distributing high power capacity, and they are much more important than others. It is also validated that the proposed vulnerability indexes meet with the operation condition of the actual power grid.

ii) Under random attacks, the curve changes slowly. But, under the dynamic or static attacks, when those nodes or lines with higher degrees or betweenness are removed, the network performance decreases drastically. This implies that the system is very robust against random attacks and is no protection ability against deliberate attacks. This shows that these nodes or lines with higher degrees or betweenness assure the super-importance in the system. Cascading failures scale will be enlarged rapidly if failures occur at these nodes or lines. Sometimes this kind of failures can result in large scale blackout eventually.

iii)For the nodes and lines of network with higher betweenness, both after under dynamic and static attacks, the network performance after the attack to lines decreases more drastically than nodes. In other words, the lines with higher betweenness are sensitive than the same nodes which implies that lines may be important in the security of power grid.

iv) For the nodes with higher degrees or betweenness, both after under dynamic and static attacks, the network performance after the attack to nodes with higher betweenness decreases more drastically than these with higher degrees. In other words, the parameter betweenness may be sensitive than degree, which implies that betweenness may be more important in the architecture of power grids.

v) At the same time, the performance after dynamic attacks is lower than static attacks, which shows the importance of nodes or lines with higher degrees or betweenness again.

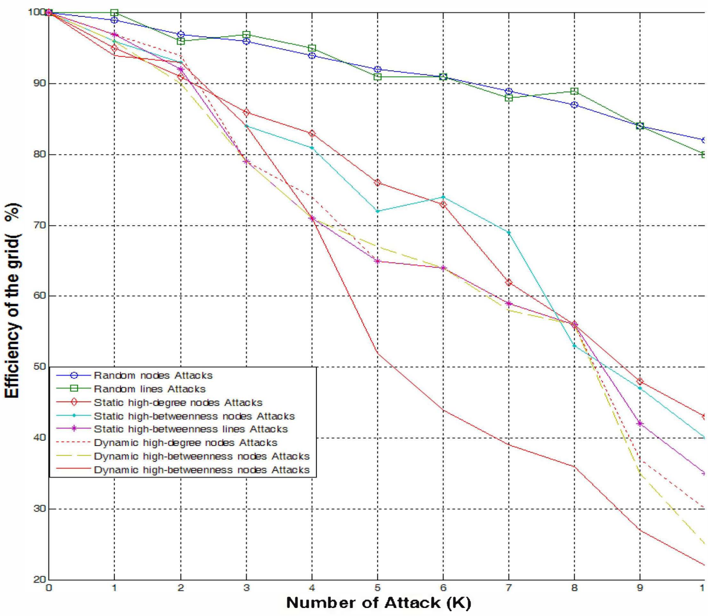

Figure 3. The efficiency of APS of North China power grid under different attacks

In brief, the system is very robust against random attacks. But, when the nodes or lines with higher betweenness or degrees are maliciously attacked, the system will suffer worse destruction than random attacks' damage. In order to update the whole grids' reliability, the protection and safeguard of these nodes or lines must be strengthened, which closely associates to network structure. The topology structures of power grids have important influence on their vulnerability.

IV. CONCLUSIONS

Modern power system is a typical multi-level complex giant system, so the conventional analytical theory and methods based on reductionism can't provide sufficient guidance for its operation and management.

This paper puts forward and studies the construction of APS based on ACP approach by using multi-agent complex network.

An APS constructed with actual data from North China power grid is analyzed under different attacks. Based on APS, the control, scheduling, optimization and management of modern power systems can be improved; especially its rolling optimizations under normal situations and emergency management under abnormal situations can be guided theoretically and supported technically. The proposed methods can provide scientific guidance for security and stability, quality and economical operation of power system. It can improve the operations and management level, and economic efficiency of power companies, reduce production costs, enhance their innovation ability, adaptability and comprehensive competitiveness.

This case study proves that the ACP approach is suitable for the research of regular power system. The same way, ACP approach can be applied for the research of smart grid, to provide its theoretical guidance and reference.

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