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PANEL SESSION: DEVELOPMENTS IN POWER GENERATION AND TRANSMISSION INFRASTRUCTURES IN CHINA[#]

(Tom Hammons, K. P. Wong, and Loi Lei Lai)

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Track 1: Understanding and Responding to System Wide Events

PAPERS

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1. DEVELOPMENTS IN POWER GENERATION AND TRANSMISSION INFRASTRUCTURES IN CHINA (PAPER 07GM 0433)

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On behalf of the Energy Development and Power Generation Committee, welcome to this Panel Session on Developments in Power Generation and Transmission Infrastructures in China.

The China electricity industry started in 1882. By 1949, the country had a small electricity system with 1.85 GW installed capacity and 6,500 km transmission lines. The electricity system expanded rapidly over last five decades or so. By the late 1990s, the expansion fundamentally changed the nationwide electricity shortage. The China electricity system now is the world's second largest with 338 GW installed capacity and generation was 1478 TWh in 2001. Official statistics show power consumption growth in China averaging 7.8% annually throughout the 1990s. Starting from the second half of 2002, China electricity supply was far short of demand because of dry spells that deceased hydroelectric supply, a generator shortage, and unexpected demand from energy-intensive industries. During this period, twenty-one provinces, municipalities, and autonomous regions in China suffered large-scale electricity shortages. Some had to implement load shedding to limit electricity consumption to avoid blackouts. By the end of 2005, China accumulated a total installed capacity of 508 GW. China's electricity output reached 2474.7 TWh. China Electricity Council (CEC) estimates that the electricity supply and demand will reach equilibrium in 2007. In 2005 and 2006, for each year there was 70 GW of new generating capacity added to the system. According to the International Energy Agency, to meet rapidly growing electricity demand, China will invest a total of nearly 2 trillion U.S. dollars in electricity generation, transmission, and distribution in the next 30 years. Half of the amount will be invested in power generation; the other half will go to transmission and distribution.

[#] Document prepared and edited by T J Hammons

Developing fuel sources for electricity generation has been difficult due to the fact that energy resources are predominantly located in the west and north of the country, while large economic and load centers are in the east and south of China. Transportation of energy adds tremendous costs to electricity supply. This has been especially so in the case of already expensive hydropower development.

China's energy policy is shifting towards diversification of energy resources because heavy coal use has had an adverse impact on the environment. Developing hydroelectricity serves the government strategy to develop the poorer western region. Moreover, the government is also ready to develop natural gas as fuel for power generation. Close to 10 GW natural gas-fired generation capacity was developed from 2001 to 2005, including 7.93 GW in eastern China using piped gas from Xinjiang and 2.0 GW in Guangdong Province using LNG shipped from Australia.

Integrated gas combined cycle (IGCC) technology is a type of electricity generating technology with high efficiency and low pollution that can meet the need for environmental protection. Efficiency of electricity generation can reach more than 60%. Research on this key technology has been started in China. It includes the technologies of the IGCC process, coal gasification, coal gas cleaning, gas fuelling engines and residual heat systems. In 2005, per kWh electricity on average in the coal fired plants consumed 374.00 gce. The larger the generation unit, the smaller the amount of coal consumption per unit of electricity generated. For unit generating capacity of 300MW, the coal consumption rate is at 341.88 g/kwh; for those units of 600MW capacity, the number is 326.34g/kwh. For supercritical units, the rate is at 320.58 g/kwh, comparable to the OECD levels. In terms of power transmission losses, the average figure is about 7% for the national power grids.

In China, much of the renewable resources are in regions with low energy demand, such as Inner Mongolia and Xinjiang. Because the need for electricity could be hundreds or thousands of km away, there are serious questions about the ability of China's already shaky transmission system to handle the movement of these large amounts of electricity. Where transmission capacity is not sufficient, it will be impossible to invest in transmission lines. In fact, some laws limit the amount of renewable electricity that can be supplied to the local grid because of concerns about the additional burden on the transmission system.

Though use of hydro and nuclear power is growing, coal will still provide the majority of China's energy needs in 2030. Whatever the fuel mix, if economic growth in China stays on course, China is likely to account for 25 per cent of the world's increase in energy generation in the next 30 years.

The China electricity policy is to achieve sustainable development of the power industry; to place equal emphasis on development and energy conservation; to attach great importance on environmental protection; and to deepen structural reform in the power sector. For the transmission grid, it plans to build West-to-East power transmission corridors with nationwide interconnection. The policy is to enhance regional and provincial grids interconnection and continue rural network construction and innovation. In addition, it strengthens construction of systems for protection, communication and automatic control. For power generation, China promotes energy conservation priority and the development of hydroelectric power. There are plans to optimize thermal power development and develop nuclear power and renewable energy steadily.

In October 2005, the "*Communist Party of China (CCP) Central Committee's Proposal on the Formulation of the 11th 5-Year Plan for National Economic and Social Development*" was released. According to this, the China power industry should continue resource saving and environment friendly development, and realize sustainable development. For the next five years, the China power industry will focus on optimization of efficient large-scale coal power plants, exploit hydro power while protecting the environment, actively develop nuclear power, strengthen power grid construction, increase power transmission from West to East, and speed up development of renewable energy such as wind, solar, and biomass. The Proposal demonstrates that up to 2010, the China electric power industry will increase its installed capacity from 570 to 870 GW. Investment of 125 billion US$ and 100 billion US$ will be needed in the power generation and power grid construction, respectively.

The state power industry, under the 11th Five Year Plan, will face new challenges and opportunities. This panel is therefore of special significance. It will discuss new technologies in power generation, transmission and distribution. It will present an in-depth analysis on key issues of development of the

China power industry, electricity in rural area, renewable energy, environmental protection, operational safety and security, information technology and automation.

The Panelists and Titles of their Presentations are:

1. Panel Session Introductory Paper: T J Hammons (University of Glasgow, UK), K P Wong (Hong Kong Polytechnic University, Hong Kong) and L L Lai (City University London, UK). Developments in Power Generation and Transmission Infrastructures in China (Paper 07GM 0433)

2. Yu-sheng Xue, NARI, Najing, China. Towards Space-Time Cooperative Defense Against Blackouts in China (Paper 07GM 0557)

3. Yin Yonghua, Chief Engineer, CEPRI, Beijing, China. Electric Power Systems in China—History of Development, Present Status and Future Perspectives (Paper 07GM0769)

4. Yanmin Song, NARI, China and Xiao-Ping Zhang, Director of the Institute for Energy Research and Policy, The University of Birmingham, UK. The Chinese Electricity Market Infrastructure and Operation Systems: Current Status and Future Developments (Paper 07G0852)

5. Qixun Yang, Board Chairman, Beijing Sifang Automation Co. Ltd., China and .Bi Tianshu, Professor, North China Electric Power University, China. WAMS Implementation in China and the Challenges for Bulk Power System Protection (Paper 07GM0839)

6. Shuyong Chen, Feili Huang, Baohui Zhang, Yixin Ni, Libao Shi and Zheng Xu, Various Institutions, China. Fast Development of Chinese Power Industry and its Impacts on Power System R&D Outputs (Paper 07GM 0807)

7. Xingwang Ma, Electricity Market Consulting Inc., Bellevue, WA, USA. Reliability Compliant Market: Incentives for Long-Term Transmission and Generation Capacity Adequacy (Paper 07GM0862)

8. Invited Discussers.

Each Panelist will speak for approximately 20 minutes. Each presentation will be discussed immediately following the respective presentation. There will be a further opportunity for discussion of the presentations following the final presentation.

The Panel Session has been organized by K. P. Wong (Hong Kong Polytechnic University, Hong Kong), T. J. Hammons (Chair of International Practices for Energy Development and Power Generation IEEE PES, University of Glasgow, UK)., and L. L. Lai (City University London, UK). Tom Hammons, K. P. Wong and Loi Lei Lai will moderate the Panel Session.

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8. Invited Discussers

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BIOGRAPHIES

Thomas James Hammons (F'96) received the degree of ACGI from City and Guilds College, London, U.K. and the B.Sc. degree in Engineering (1st Class Honors), and the DIC, and Ph.D. degrees from Imperial College, London University.

He is a member of the teaching faculty of the Faculty of Engineering, University of Glasgow, Scotland, U.K. Prior to this he was employed as an Engineer in the Systems Engineering Department of Associated Electrical Industries, Manchester, U. K. He was Professor of Electrical and Computer Engineering at McMaster University,Hamilton, Ontario, Canada in 1978-1979. He was a Visiting Professor at the Silesian Polytechnic University, Poland in 1978, a Visiting Professor at the Czechoslovakian Academy of Sciences, Prague in 1982, 1985 and 1988, and a Visiting Professor at the Polytechnic University of Grenoble, France in 1984. He is the author/co-author of over 350 scientific articles and papers on electrical power engineering. He has lectured extensively in North America, Africa, Asia, and both in Eastern and Western Europe.

Dr Hammons is Chair of International Practices for Energy Development and Power Generation of IEEE, and Past Chair of United Kingdom and Republic of Ireland (UKRI) Section IEEE. He received the IEEE Power Engineering Society 2003 Outstanding Large Chapter Award as Chair of the United Kingdom and Republic of Ireland Section Power Engineering Chapter (1994~2003) in 2004; and the IEEE Power Engineering Society Energy Development and Power Generation Award in Recognition of Distinguished Service to the Committee in 1996. He also received two higher honorary Doctorates in Engineering. He is a Founder Member of the International Universities Power Engineering Conference (UPEC) (Convener 1967). He is currently Permanent Secretary of UPEC. He is a registered European Engineer in the Federation of National Engineering Associations in Europe.

K.P. Wong (M'87-SM'90-F'02) obtained M.Sc and Ph.D. degrees from the University of Manchester, Institute of Science and Technology, UK in 1972 and 1974, respectively. Prof. Wong was awarded a higher doctorate DEng degree by UMIST in 2001. Prof. Wong is currently a Chair Professor and is the Head of Department of Electrical Engineering, Hong Kong Polytechnic University. Prof. Wong received three Sir John Madsen Medals (1981, 1982 and 1988) from the Institute of Engineers Australia, the 1999 Outstanding Engineer Award from the IEEE Power Chapter Western Australia and the 2000 IEEE Third Millennium Award. He has published numerous research papers in power systems and on the applications of artificial intelligence and evolutionary computation to power system planning and operations. His current research interests include evolutionary optimization in power, power market analysis, power system planning and operation in the deregulated environment, and power quality. He is a Fellow of IEEE, IEE, HKIE and IEAust.

L. L. Lai (SM'92, F'2007) received the B.Sc. (First Class Honors) and the Ph.D. degrees from the University of Aston in Birmingham, UK. He also gained his D.Sc. from City University London. Currently he is Head of Energy Systems Group at City University, London, UK. He is a Visiting Professor at Southeast University, Nanjing, China and also a Guest Professor at Fudan University, Shanghai, China. He has authored/co-authored over 200 technical papers. In 1998, he also wrote a book entitled Intelligent System Applications in Power Engineering Evolutionary Programming and Neural Networks. Recently, he edited a book entitled Power System Restructuring and Deregulation Trading, Performance and Information Technology. In 1995, he received a high-quality paper prize from the International Association of Desalination, USA. Among his professional activities are his contributions to the organization of several international conferences in power engineering and evolutionary computing, and he was the Conference Chairman of the IEEE/IEE International Conference on Power Utility Deregulation, Restructuring and Power Technologies 2000. Dr. Lai is a Corporate Member of the IEE. He was awarded the IEEE Third Millennium Medal, 2000 IEEE Power Engineering Society UKRI Chapter Outstanding Engineer Award, and 2003 IEEE Power Engineering Society Outstanding Large Chapter Award.

2. TOWARDS SPACE-TIME COOPERATIVE DEFENSE FRAMEWORK AGAINST BLACKOUTS IN CHINA

Yusheng Xue, *Member, IEEE*

***Abstract*—**With investigation on recent blackouts around the world, the three-defence-lines criterion, which has been the security standard for power systems in China, is reviewed. An adaptive space-time cooperative framework, named as Wide ARea Monitoring Analysis Protection-control (WARMAP) for defending power system against blackouts is introduced in this paper. It upgrades the individual defence lines to a global scheme. Its essentials are: (1) acquiring wide area measures by using RTUs, PMUs, fault recorders, protection management systems and system protection schemes; (2) integrating all information acquired via various equipments into a unified platform; (3) performing trajectory-based data mining and quantitative security analysis for time response curves obtained by PMUs or simulations; (4) adaptive optimization of preventive control, emergency control, corrective control and recovery control; (5) coordination among these controls; (6) coordinatin among WARMAPs in a multi-layer power system. It is well on the way to building WARMAPs in a two-layer power grid in China, which consists of East China Regional Grid and Jiangsu Province Grid.

Index Terms **—** Three-defense-lines, dynamic SCADA/EMS, quantitative stability analysis, early warning, risk-based optimal stability decisions, adaptive stability controls.

I. INTRODUCTION

Natual disturbances and human errors cannot be totally avoided, but should not lead to uncontrollable blackouts. A single event is unlikely to topple down a modern power network, nevertheless bad weather, information deficiency, faults in automation systems and man-made wrong decisions can bring about new contingencies one after the other. Under the strike of a series of cascading events, a system, however strong, can become fragile and may even evolve into power calamity. The August 14th Blackout in North America demonstrated the importance of the global concept of power system security and the integrative defense framework [1]. In fact, there were opportunities to hold out the disaster in different stages during the blackout evolvement, unfortunately they were not grasped promptly. Only with a good knowledge of the mechanism of a system wide blackout evolving from an occasional contingency, can defense scheme be optimized and coordinated based on the characteristics of different stages and can uncontrollable blackouts be effectively avoided.

Defense framework has drawn wide attention in power industry [2-4]. It was proposed in [5-8] to improve monitoring and control functions by using distributed autonomous real-time systems, enabling the power system to have self-healing capabilities. It was also pointed out that on-line dynamic analysis is needed to coordinate fast local control multi-agents and slow global control decision-making, with the objective being no load dropping after faults. However, the functional design of stability control infrastructure was not investigated, modeling and algorithms of control coordination were not dealt with, and the evolving mechanism of large blackouts was not taken into consideration.

Along with the rapid growth of loads in China, the increase of power transmission distances and the engineering operation of massive HVDC and FACTS equipments, the dynamic characteristics of modern power systems such as instability modes, coherency profiles and crucial interfaces are getting more complicated. Market-driven environment further increases the risk for evolving into an uncontrollable blackout from cascading outages. These factors highlight the requirements for

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optimizing and coordinating various defense actions.

Based on analyzing the regular pattern of the blackout evolvement, it is pointed out that the defense framework for modern power systems should advance the SCADA/EMS systems to dynamic ones, namely DSCADA/DEMS, realize on-line quantitative stability analysis and pre-decision, realize adaptive optimization of preventive control (PC), protection relays, emergency control (EC), corrective control (CC) and recovery control (RC) respectively, and coordinate them by minimizing the total risk. Wide Area Monitoring Analysis Protection-control (WARMAP) is such a space-time cooperative defense framework [9]. Its three essentials are: static and dynamic measurements from wide area; quantitative stability analysis based on both measured and simulated time response curves; optimal controls for various stabilities and coordination of all defense lines.

In China, valuable experiences of phasor measurement unit (PMU), Wide Area Measurement System (WAMS), system protection schemes, on-line pre-decision making for PC and adaptive optimization for EC have already been accumulated with many engineering projects for years. With these experiences, the Phase-I of the WARMAP project for East China Regional Grid is already put into daily operation after near four years' development and detailed tests. The Phase-II passed FAT in Nov. 2006 and SAT in Dec. 2006. For WARMAP system of Jiangsu Province Grid, the Phase-I passed FAT in Oct. 2006 and the phase-II is expected to pass FAT in Jan. 2006.

II. THREE-DEFENSE-LINES FOR POWER SYSTEMS IN CHINA

The three-line-line criterion has been a well-established security standard for power system planning and operation in China [10]. The first defense line consists of grid strengthening, PC and protection relays to ensure system stability without load interruption under a non-severe contingency. The second defense line is armed with remote EC for severe contingencies. The third defense line is equipped with local CC such as out-of-step islanding and load shedding for extremely severe contingencies.

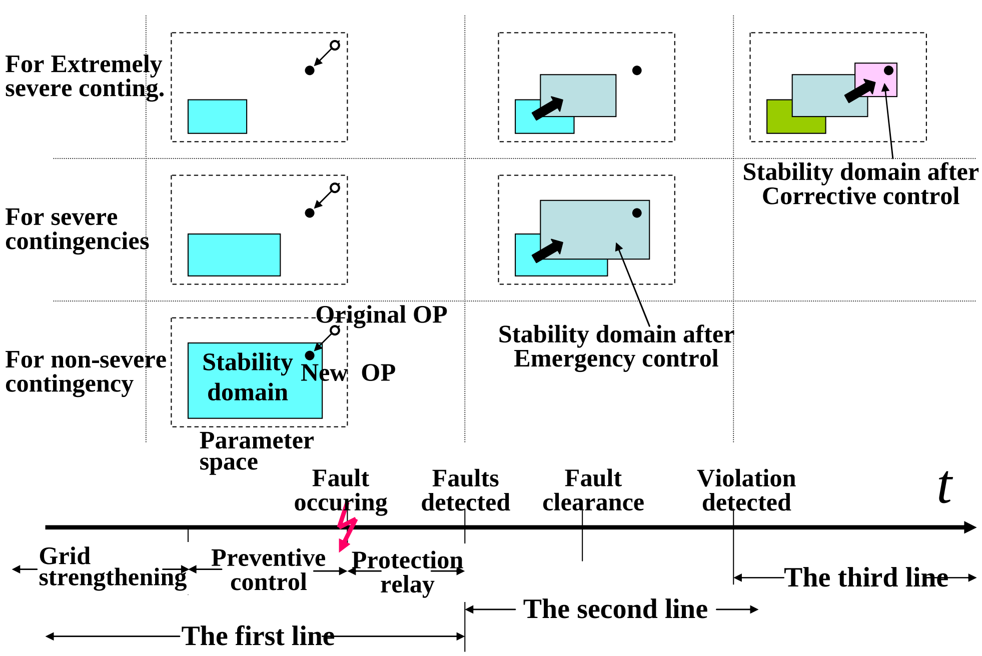

Fig. 1: Different defense lines with different mechanisms

In Fig.1, A broken-line rectangle denotes the parameter space and a solid-line rectangle denotes the stability domain corresponding to a set of contingencies and actions.

If the original operating point (OP) is outside the stability domain, the following actions could be considered according to severity of the fault: (1) before a non-severe contingency, PC actions shift the OP into the stability domain; (2) after the occurrence of a contingency, the faulted equipment should be removed selectively and quickly by protection relays; (3) after identifying a severe contingency, EC actions are selected to change the stability domain towards the OP; (4) Once out-of-step, low frequency or low voltage is detected, CC actions, such as out-of-step protection, under-frequency load-shedding and/or under-voltage load-shedding should be taken to prevent uncontrollable expansion of the blackout area; (5) RC actions are taken to restore the supply of the shed loads as soon as possible. Ref. [11] compares the characteristics of control laws of the three defense lines (see Fig.2)

PC affects the dynamics from the beginning of a fault, thus its control effect can be fully taken advantage of. However, PC is not applicable when generation reserve is not sufficient or dynamic congestion is very serious. Moreover, different contingencies may ask for contradictive actions. Preventive actions are open-loop control issued by operators with gaming before contingency occurrence.

EC assures power system stability by taking strong actions, such as switching on/off equipments, immediately after a certain unstable contingency occurring. Without increasing the system's daily operating cost, EC can raise the transmission capacity. Close-loop feed-forward control is implemented according to the pre-computed decision table indexed with both operating conditions and contingencies.

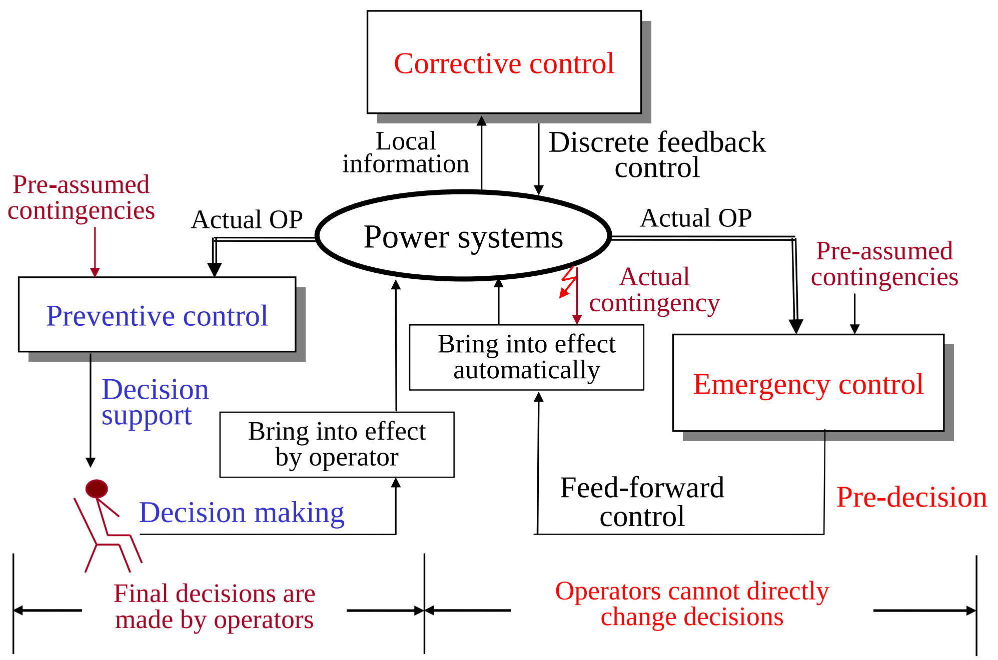

Fig. 2: Three types of stability controls

The features of time response curves initiate CC, where decentralized feedback control is adopted.

The Three Gorges power plant is the largest one in the world and a pivotal node in the center of the nation-wide interconnection grid. The Three Gorges Grid connects the plant to east, west, south and north.

Both EC system (FWK-300) and CC system (UFV-2F) of the grid are developed and manufactured by NARI, China [12]. Their functions include: monitoring operating conditions of the plants and the key cut-sets in the grid; detecting *N*-1 and certain *N*-2 faults and pole blocking; looking up off-line prepared control decision tables to implement control measures such as HVDC modulation, system islanding, generator tripping, load shedding in the 220 kV grids, implementing islanding actions if out of step occurs, implementing over-frequency generator tripping if necessary, and reliable exchange of data as well as commands. These control systems hold perfect operational records with neither disoperation nor mal-no-action since they were put into service in 2003.

These control devices are based on 32-bit CPU, DSP technology and a self-defined fashion for implementing decision tables**.** Various techniques for anti-interference and prevention of unintended operations and failed operations are applied.

There are more than 50 sets of such wide area stability control systems serving in China’s power systems now. They have played an indispensable role in ensuring the transient stability, thermal stability and frequency stability of power systems.

Although having successfully avoided system-wide blackouts in the relatively weak grids in China, the defense lines are facing great challenges in the new environment of rapid load growth, nation-wide interconnection, ultra-high voltage transmission and power market development. There is still a great deal of difficulties to break through in combining systematology, information theory and control theory, as well as in conduct data mining to obtain profound information, optimization within each defense line and coordination between different defense lines.

III. EVOLVEMENT OF CASCADING BLACKOUTS

System-wide blackouts usually result from a series of cascading outages. The evolvement process may be divided into five stages, namely a slow cascading outage stage, a fast one, a short stage of oscillation, a very short stage of breakdown and a long stage of restoration (see Fig.3, where the time intervals are taken from the 8.14 case).

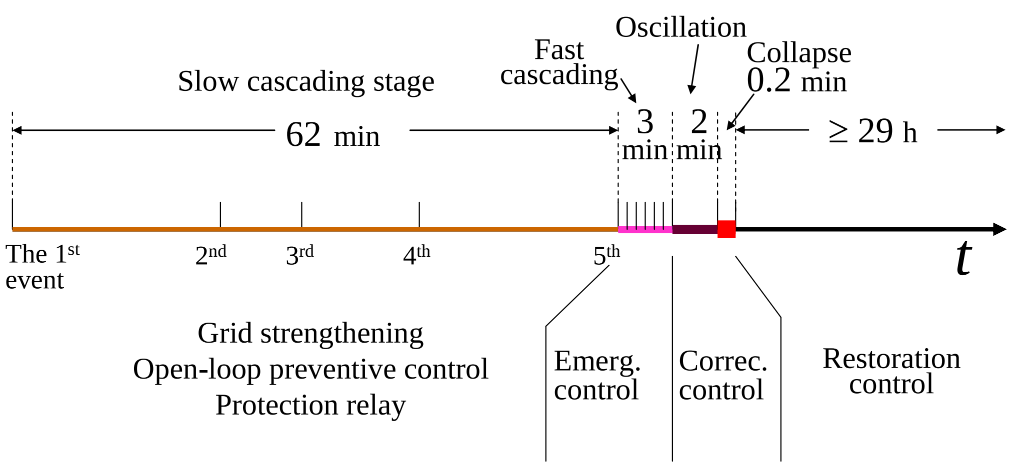

Fig. 3: Typical evolvement of cascading blackouts

The August 14th blackout is just such a case, where the first four time intervals between two successive events are 22, 9, 5, 29 minutes respectively. During such time intervals, operators can take PC measures to stop further outages, provided that advanced on-line decision support system is available.

Since the follow-on cascading outages occurred more and more frequently, PC is no more feasible and EC is the right choice.

Massive outages greatly reduced the stability limits; oscillation between the Canadian and American grids started at the 65th minute and lasted for 2 minutes. Then, a 10-second snow slide stage happened, resulting in the largest blackout in history. During this stage, only CC with feedback fashion can be counted on to contain the spread of blackouts and to ease the difficulties during the restoration stage.

In fact, there were opportunities to hold out the disaster at every stage during the whole evolvement, such as applying PC for the slow cascading outage stage, EC for the fast cascading outage stage, CC for the oscillation and collapse stages, and RC for the restoration stage.

Moreover, a space-time cooperative defense framework is preferred to integrate and optimize these different controls, which activate respectively before, during and after a contingency caused by either natural phenomena or wrong decisions.

For high-risk contingencies, it may be cost-efficient to pay for the daily additional operational cost of PC. If loss of load is not allowed after contingencies, generator tripping within the critical cluster can be used as an EC measure only when there are sufficient spinning reserves at the receiving end, otherwise PC must be employed. In other cases, PC can also improve system stability but may not be the best option.

To ensure system integrity without network splitting after contingencies, predictive control but not feedback control should be used. Moreover, EC must be used when PC is infeasible or requirements of different contingencies for PC are in conflict with each other.

If PC and EC are still not able to keep the system stable, CC must be used to avoid uncontrollable blackouts.

Obviously, each defense line plays a role that can hardly be replaced by others. The principle of "prevention first" should be understood as that there should be a response plan in each defense line, especially expected to be made on-line. It should not be simply asserted that PC is more important than other defense lines. Defense lines are closely related to each other while their economic characteristics of control cost are totally different. Therefore, coordination among them not only relates to the robustness of the defense system but also affects its economical performance.

The space-time coordinative defense of large blackouts is a very complicated dynamic programming problem that can be solved only by the method of decoupling and aggregation. When undertaking the optimization of one defense line, decisions of other defense lines are temperedly fixed in the external scenarios. Then coordination of various defense lines is conducted through iterations, in which the ratio of stability margin increment to total control cost increment is the basis for selecting the search direction.

IV. CURRENT TECHNIQUES FOR STABILITY ANALYSIS AND CONTROL

A. Current Status of Stability Analysis Techniques

Angle, amplitude and frequency are the three elements of AC voltage and current. They interact with each other through flow equations and rotor motion equations. At present, they are studied separately, and the transient stability issues of voltage and frequency are seldom considered.

Obviously, it is infeasible to search the optimal control actions for modern power grids by using exhaustive trial-and-error methods. Especially for the on-line pre-decision fashion, quantitative analysis techniques, including quantitative indices for various stabilities and their sensitivity analysis, are indispensable.

Operators want to know the distance to the stability limit in the process of cascading events, and compare the effects of different control actions. However, almost all existing tools for analyzing large disturbance stability cannot assess the stability degree. It was pointed out in Ref. [13] that the relative angle exceeding certain threshold (e.g. 180º) cannot be taken as the criterion of losing stability in power systems.

Another misunderstanding is that on-line pre-decision can be realized by using fast numerical integration alone. In fact, if unstable modes cannot be identified or quantitative indices are not given, it is impossible to optimize the control actions. Therefore, breakthroughs in stability theory, quantitative algorithms, adaptive optimization and coordination control framework are needed.

Moreover, present techniques of stability control lack the concept of risk, the capability of adaptation and the concept of coordination.

B. Current Status of Stability Control Techniques

PC and EC cannot adopt feedback control fashion, and cannot operate without prediction. The prior knowledge needed by the forward control has to be stored into the decision tables of the controllers.

Because of its explosive combinations of operating conditions and cascading events, the traditional off-line pre-decision for setting up the tables is becoming a bottleneck for applying forward control law. For modern power grids, on-line pre-decision should be adopted.

It is the common practice nowadays to select stability control actions by adopting an exhaustive trial-and-error method. Obviously, this is unacceptable to on-line pre-decision making. Moreover, present techniques for stability control lack the concepts of risk, adaptation and coordination.

C. Current Status of Data Collecting

Present stability control systems usually collect data by itself. In order to improve the observability of operating conditions, they should share data with other automation systems, such as RTU/SCADA systems and Wide Area Measurement System (WAMS) [14] in dispatching centers. PMU Measurements are also very helpful for multi-agents stability control.

D. Current Status of EMS

EMS can only analyze static security of the power system, but not the dynamic one. It can neither predict potential dynamic behaviors, nor support stability control. Therefore, EMS has almost nothing to do with the three-lines-lines.

V. PRACTICE IN ADAPTIVE OPTIMAL STABILITY CONTROLS IN CHINA

A. The Unique Method for Quantitative Stability Analysis

Extended Equal Area Criterion (EEAC) performs numerical integration to the full models in R^n, and then maps the resultant trajectory into a set of time-varying one-machine infinite-bus planes in a step-by-step fashion. Quantitative stability analysis can be performed for the image OMIB systems with time-varying parameters. The rigorous proofs can be found in Ref. [15].

The boundary of stability domain in parameter spaces can be identified with the sensitivity analyses of the stability margin provided by EEAC. Then, the stability control decision can be optimized.

B. Adaptive Optimization of PC

PC shifts some generation from the critical machines to the non-critical ones according to the unstable mode [16]. The smaller the excursion from the original OP, the lower the additional operating cost. Advanced on-line transient stability assessment and "on-line pre-decision, real time matching" techniques in Guangxi Grid's EMS have been put into normal operation service to support PC since Sept. 2003.

The Guangxi Grid model contains 1876 buses and 248 generators. 3 Dell 2650 servers are used to assess transient stability and another one to assesses voltage stability. It can complete the entire assessment cycle of 100 contingencies within 5 minutes. The fail-safe capability of the computing system ensures the continuous satisfactory operation of the PC functions when any server fails.

C. Adaptive Optimization of EC

An adaptive EC scheme was proposed to automatically refresh the decision table in a quasi-real-time fashion [17]. The decision-making is a non-convex nonlinear integer-programming and an effective algorithm was proposed [18]. The relevant software has been implemented in Shandong grid since Nov. 2002 and in Guangdong grid since Dec. 2002.

A scheme for both adaptive PC and adaptive EC has been implemented in Henan Grid for test operation since July 2004. The Grid model is of 2094-bus, 250-generator, 672-motor and 2048 possible control actions. The simulation period is 10s; time step is 10ms. It uses 8×IBM xSeries345 to update the decision tables every 5 min on-line.

D. Adaptive Optimization of CC

The optimization of low voltage (frequency) load shedding includes optimal device placement, set points and activation time. The set points optimization has been successfully applied to Liaoning Grid, Northwest Grid, Sichuan Grid, etc. Research projects on placement optimization and activation time optimization and intelligent out-of-step protection are under way [19].

VI. THE INTEGRATIVE DEFENSE FRAMEWORK

A. Three Essentials of the Integrative Lines Framework

With the development of nation-wide interconnection and power market, the risk of disasters evolving from local contingencies has increased evidently. In order to effectively prevent blackouts, the construction of wide-area information platform, on-line quantitative security analysis and adaptive optimization of control, must be paid attention to. The integrative defence framework should upgrade the analysis/control techniques from static to dynamic, from qualitative to quantitative, from offline to on-line, from customizing to adaptive, from conservative to optimized, from certainty based to risk oriented, from a temporary scheme to a global solution, and from isolated to cooperative.

B. Dynamic SCADA (DSCADA) and Dynamic EMS (DEMS)

In order to on-line assess transient security and stability, compute stability limits, support control decision-making, refresh decision tables and improve cost performance, it is required to integrate the above mentioned data sources, build a unified open platform of wide area information, and advance the SCADA/EMS to DSCADA/DEMS.

The data collected by PMUs can not provide any dynamic information regarding to a postulated scenario. In order to estimate system stability under a postulated contingency and assess the effects of assumed control actions, mathematical model based dynamic simulations are necessary.

C. Integrative Lines Framework with DSCADA / DEMS

A space-time cooperative defence framework consists of three sub-systems: information, analysis and control.

The information sub-system integrates the data collected from various data sources through the unified wide area information platform, including static data from SCADA systems, real-time dynamic data from PMU/WAMS, transient data from fault recorders, as well as pseudo-measurements offered by simulations on postulated scenarios. It is also necessary for DEMS to communicate with stability control devices effectively.

The analysis sub-system utilizes the integrated wide area information to realize the following functions: (1) direct analysis of static information from SCADA system and dynamic information from PMUs, including the monitoring of dynamic behaviors of power grids, the stability margin of disturbed trajectory, the analysis of the evolvement of contingencies, the monitoring of the auxiliary service quality, the on-line monitoring of low frequency oscillations and the validation of models and parameters; (2) improvement of state estimation and existing on-line static security and economic analysis with additional information from PMUs; (3) integrative analysis of both field information and numerical simulation results, such as the analysis, prevention and appeasing of low frequency oscillations, the assessment of the identity between dynamic response curves, the validation and correction of dynamic models and parameters, the quantitative analysis of angle, voltage and frequency stabilities, the analysis of mode behaviors and mechanisms, the estimation of stability domain, and the ranking of the postulated contingencies by the stability margin and risk.

The control sub-system supports the adaptive optimization of various stability controls, and realizes the space-time coordination between different defence lines.

D. Wide ARea Monitoring Analysis Protection-control (WARMAP) Scheme

Based on the above ideas, WARMAP system for defending blackouts is being developed by Nanjing Automation Research Institute (NARI), China. Like a "war map" for defending blackouts, WARMAP offers early warning, supports on-line decision making and integrates various defence lines, based on dynamic, adaptive, quantitative, optimal, risk-oriented and coordinative views (see Fig.4). This project has challenging research objectives and engineering application background. East China Power Grid and Jiangsu Power Grid are cooperating with NARI to build such integrative defence frameworks for their grids [20].

WARMAP conforms to the IEC61968 and IEC61970 standards, integrates wide area information from various data sources, such as PMUs, RTU/SCADA, fault recorders, protection management systems and utilizes the information from PMUs to improve measurement redundancy and performance of state estimation.

Combining with numeric simulations, WARMAP coordinates different defence lines with a global view, coordinates security with operating economy. With a friendly visualization interface, it provides information to support strategic and tactical decision-making. WARMAP integrates PC, protection relay, EC, CC, damping control and recovery control, in order to support their on-line decision-making, and coordinates their functions, data streams and activation.

E. Engineering Implementation of WARMAP Projects

Based on the above achievements, engineering projects for implementing WARMAP are well on the way in both East China Power Grid and Jiangsu Power Grid.

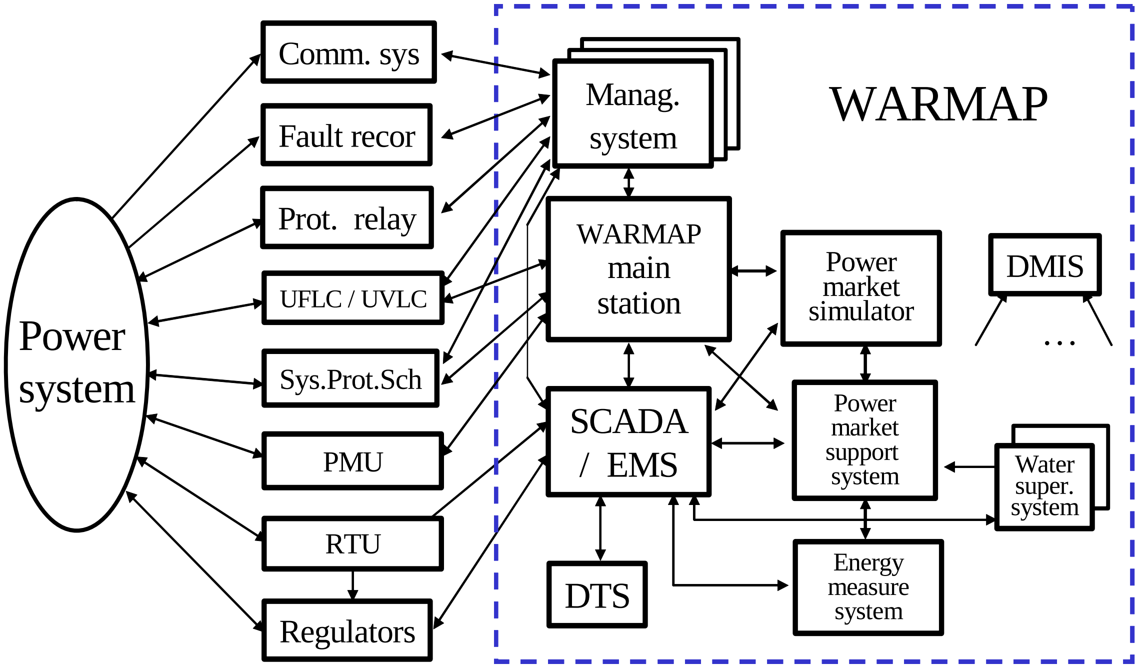

Fig. 4: The framework of WARMAP

The East China Power Grid is the largest regional grid in China, which consists of 5 provincial/metropolis grids, namely Jiangsu, Zhejiang, Fujian, Anhui and Shanghai. This regional grid is interconnected with the Central China Power Grid through 2 HVDC lines. In 2006 it has a total of 5000 buses and 460 generators with a peak load of 107 GW.

The Jiangsu Power Grid is one of the largest provincial grids in China and has a total of 1400 buses and 120 generators with a peak load of 40 GW in 2006. Its regional stability control system covers nine 500kV substations and 5 large power plants.

As an important information source for WARMAP, an open-platform-based SCADA/EMS developed by NARI has been put into operation in the two Grids since 2004 and 2005 respectively.

F. The East China Power Grid WARMAP Project

Phase-I of the East China Power Grid’s WARMAP, which passed the FAT in December 2005 and was put into daily service in May 2006, includes the following functions: integration and management of static, transient and dynamic fault data; real time monitoring of system dynamics; PMU data based fault analysis; monitoring of auxiliary service quality; on-line monitoring of low frequency oscillations, and verification of models and parameters.

Phase-II of the WARMAP passed its FAT in November 2006. It covers the following functions: state estimation adopting PMU data; PMU dynamic data based assessment of power quality; on-line quantitative analysis of transient angle stability and transient voltage security (margin, mode and power transfer limit); on-line assessment of static voltage stability; on-line decision support of PC of transient angle stability and transient voltage security; on-line analysis of low frequency causes; on-line decision support of PC of low frequency oscillations; verification of transient stability of system operations in power market environment; security and stability analysis of operational planning.

Besides angle stability, load stability, acceptability of transient voltage drop, acceptability of transient frequency deviation and low frequency oscillation, have aroused more concerns. Not only the PC, protection relays, EC and CC, but also the recovery control needs adaptive optimization [21].

The parallel processing system of the East China Power Grid WARMAP consists of 32 Intel Xeon Processor computers and the objective is to complete all the calculations for 100 contingency scenarios within 5 minutes.

G. Jiangsu Power Grid WARMAP Project

WARMAP of Jiangsu Power Grid is set up on a unified platform integrating EMS, WAMS, AVC, AGC and various stability control systems to implement global alarming and stability control.

The main functions include: integration of various automation systems at the control center; real-time PMU measurement based dynamics analysis; real-time predictive alarming; monitoring of auxiliary service quality; state estimation integrating data from EMS, WAMS and stability control systems; on-line auto-generation of contingency list; various security and stability assessments and control decision supporting; integration of EC devices at plants/substations with the control center station; optimization and coordination of various defence lines; coordination of 2 main control stations, 12 sub control stations, 8 generator tripping control stations and 6 load shedding control stations for power system stability.

The parallel processing system consists of 6 IBM eServer p5 550 computers and the objective is to complete all the calculations for 100 contingency scenarios within 5 minutes.

The Phase-III of this project, which deals with adaptive optimal EC and coordination among PC, EC and CC, is expected to be completed by the end of 2007.

VII. CONCLUSIONS

Although the three-defence-lines have successfully avoided system-wide blackouts in China, the risk of blackouts is increasing resulting from society, resource and economy pressures. If transitions of operating conditions can not be tracked, the timely warning of cascading events can not be given. If the space-time decision-making of various defence lines can not be adjusted in time, cascading trips may be incurred and eventually the disaster of blackout may occur.

This paper emphasizes the integration of information from various data acquisition systems, the support of quantitative stability analysis, as well as adaptive optimization of each defence line. It also emphasizes the coordination among various controls in different stages, including the preventive gaming before a contingency, the isolation of faults and predictive EC immediately after the occurrence of a contingency, the CC after the detection of insecure dynamics, and the recovery control after a collapse. It is very important to combine the measurement information with simulation information, and to extract system's dynamic characteristics from time response curves. Moreover, this paper points out that the practical applications of DSCADA and DEMS and their seamless incorporations with the defence lines are important characteristics of the new generation of dispatching automation systems.

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IX. BIOGRAPHY

Y. Xue obtained his PhD in Electrical Engineering from the University of Liege (Belgium) in 1987. He became a Member of Chinese Academy of Engineering in 1995 and has been the Chief Engineer at Nanjing Automation Research Institute (NARI), China since 1993. His research interests include nonlinear stability, control and power system automation.

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3. ELECTRIC POWER SYSTEM IN CHINA: HISTORY OF DEVELOPMENT, PRESENT STATUS & FUTURE PERSPECTIVE (PAPER 07GM0769)

Yin Yonghua, Chief Engineer, China Electric Power Research Institute (CEPRI), Beijing, China.

Abstract**:** This paper deals with the history of development present status and Future perspective of Electric power system in China. The development of nationwide interconnected grid, purpose of interconnection, key projects and R&D necessary for future are discussed. The nationwide interconnected grid will be basically established in 2020 and become one of largest power systems in the world.

Key Words: History of development Present status, Future perspective, Power System in China

1. HISTORY OF DEVELOPMENT

China power industry began in 1882 and installed capacity just reached 1.85GW with an annual generation of 4.3TWh when P. R. China established in 1949. By the end of 1999, installed capacity hit 294GW and the nation's total electricity generation amounted to 1230TWh.

During 1950s and 1960s, provincial power grids were gradually formed. In 1972, the first 330kV transmission line was built to establish a cross-provincial power grid – Northwest Power Network.

In 1981, 500kV appeared in China power grid. From 1980s and early 1990s, China power industry has stepped into the historical stage of large generator units, extra-high voltage and large power networks.

The first interconnection project of regional power grids was commissioned in 1989. It is a DC tie line of ±500kV, 1200MW from Gezhouba Hydroelectric Station to East China Power Network (ECPN). It was designed to transmit hydroelectric power of Gezhouba to ECPN.

From 1970 to 1980's, regional power networks, namely Northeast China, North China, East China, Central China, Northwest China and South China have been formed.

The annual installed capacity in China since 2000 is shown in Fig.1, and the utilization hours of thermal power since 2000 is shown in Fig.2.

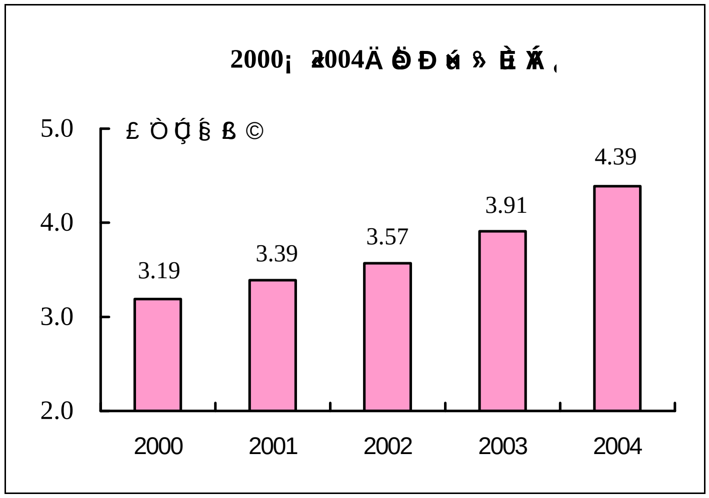

Fig.1. The annual installed capacity in China since 2000

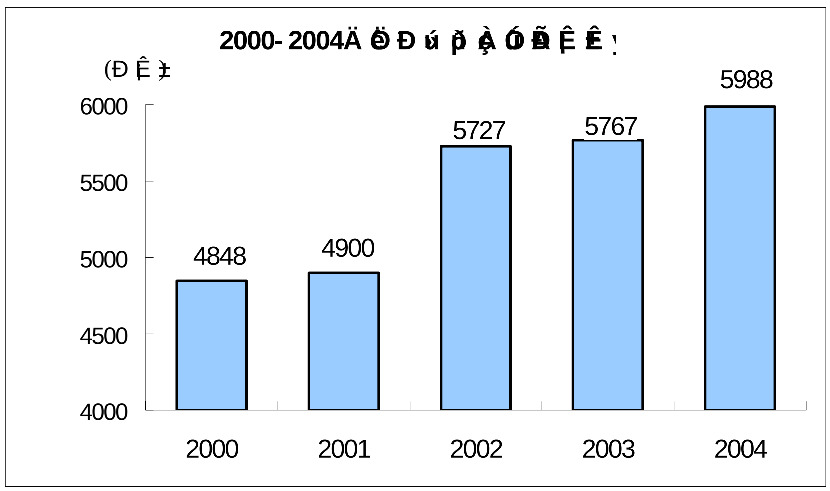

Fig.2. Utilization hours of thermal power since 2000

2. PRESENT STATUS

In China, the distribution of energy resources is quite uneven geographically. The 82% of coal deposits are scattered in the north and southwest. The 67% of hydropower are concentrated in the southwest. Therefore the north and west are called as the energy bases in China. But 70% of energy consumption concentrate in the central and coastal areas of the country.

So transmitting electric power from the energy bases is one of the ways making up the deficits of energy in the central and coastal areas, and it is imperative to develop regional power systems interconnection.

In addition, the comprehensive interconnection benefits, such as load leveling, emergency back-up, peak load savings, improving operation performance can also be obtained.

The construction of Three Gorges Hydropower Project has pushed the implementation of nationwide interconnection project. The nation's total installed capacity has reached around 510 GW and all the regional electric power systems have been interconnected by 500kV AC lines or HVDC lines in the year of 2005.

The main interconnection projects are shown in Table 1.

TABLE 1. MAIN INTERCONNECTION PROJECTS

05/2001	North- East China Power Grid (NECPG)	North China Power Grid (NCPG)	Transmitting power from NECPG to NCPG through 500 kV AC
10/2001	East China Power Grid (ECPG)	Fujian Provincial Power Grid	Exchange power through 500 kV AC
05/2002	Central China Power Grid (CCPG)	Sichuan & Chongqing Power Grid	Exchange power through 500 kV AC
06/2003	Central China (Three Gorges) Power Grid	East China Power Grid (ECPG)	Transmitting power from Three Gorges to ECPG (3000MW) through ±500 kV DC
09/2003	North China Power Grid	Central China Power Grid	Exchange power through 500 kV AC
06/2004	Central China (Three Gorges) Power Grid	South China Power Grid (SCPG)	Transmitting power from Three Gorges to SCPG(3000MW) through ±500 kV DC
07/2005	Central China Power Grid	West China Power Grid (WCPG)	Exchange power through Back-to-back DC (360MW)

3. FUTURE PERSPECTIVE

In order to achieve a continuable development in China, the policy, which is "Developing hydropower actively, thermal power optimally, nuclear power appropriately, renewable energy suited to local conditions", will be pursued.

From the year of 2005 to 2020, the new installed generation capacity will more than 30GW every year. So, it is a key period for constructing strong power grid in China. The main objectives are as follows:

3.1 POWER GRID DEVELOPMENT

With the principle of unified planning for power grid development, we make great efforts to implement the coordinated growth of powr grids at all levels including regional and provincial power grids, as well as those between power grids and power sources.

Now, we are planning to build the state bulk power grid with the voltage class of 1000kV UHVAC and ±800 kV UHVDC projects. From the year of 2008 to 2020, the UHVAC and UHVDC hybrid grids will achieve trans-regional, large capacity, long distance and low loss transmission, as well as optimizing the resources allocation in a larger scopes and to relief the stress of power shortage.

Large amount of power will be transmitted from coal power base and hydro power base in north and southwest area to central and coastal areas of the country through UHVAC and UHVDC hybrid grids .

3.2 TRANS-REGIONAL POWER TRANSMISSION

With the efforts to strengthen the ability of **T**rans-regional power resources allocation, we are keeping to enlarge the **T**rans-regional power transmission scale and realize a steady growing rate of **T**rans-regional power transmission capacity. One of the measures is to speed up the upgrading of existing 500kV grids by advanced transmission technology.

3.3 CONSTRUCTION AND OPERATION OF HVDC AND UHVDC POWER SYSTEM

Now, there are six long distance HVDC lines in operation in China. Through these HVDC lines, the power from southwest area and Three Gorges transmitted to South China and East China. The total transmission capacity of these HVDC lines is 15GW.

In July of 2005, the back to back DC project between North-west power grid and Central power grid is put into operation, The exchange power is 360MW.

The HVDC and UHVDC projects, which are in construction or in planning, are as follows:

(1) The second ±500 kV HVDC project from Guizhou province to Guangdong province in South China, with transmission capacity 3000MW, and it will be available in 2007.

(3) the back to back ±500 kV DC project between North-east power grid and North power grid, with transmission capacity 1500MW, and it be available around 2008.

(4) The project of ±500 kV HVDC from Ningxia in North-west China to Tianjing in North China, the transmission capacity is 3000MW, and it will be available around 2008.

(5) The project of two ±500 kV HVDC on one tower from Central China to East China, the transmission capacity is 6000MW, and it will be available around 2009.

(6) ±500 kV HVDC project from Hulunbeier Coal base in Hailongjiang province to Liaoning province in North-East China, the transmission capacity is 3000MW, and it will be available around 2009-2010.

(7) ±800 kV UHVDC project from Yunnan province to Guangdong province in South China, with transmission capacity 5000MW, and it will be available around 2009-2010.

(8) There will be three ±800 kV UHVDC project for Xiluodu and Xiangjiaba hydro power station in south-west China, in which two wii go to East China and one to Central-China, the transmission capacity of each project is 6400MW, and it will be available from 2011 to 2016.

(9) ±800 kV UHVDC project from Jingping hydro power station in south-west China to East China, the transmission capacity is 6400MW, and it will be available around 2013.

(10) There will be ±800 kV UHVDC project for Hulunbeier Coal base, in which one wii go to Liaoning province in North-East China, and another to North China, the transmission capacity of each project is 6400MW, and it will be available from 2015 to 2020.

3.4 750KV AND 1000 KV AC TRANSMISSION AND SUBSTATION PROJECT

In September of 2005, the first 750kV transmission project has been available in China. This project is regarded as a sample project, which extended for 146km transmission line from Guanting of Qinghai province to East Lanzhou of Gansu province in North-west China.

In the year of 2007-2008, a 750kV power grid located in North-west China will begin to take shape. The 750kV transmission and substation project is of significance to the acceleration of technology innovation on the power grid in China and the promotion of construction on the UHVAC power grid respectively.

In the year of 2008, the first 1000 kV AC transmission and substation project, as a testing and sample project, will be available, which is the tie line between Central China power grid and North China power grid. The length of this line is about 650 km.

3.5 CONSTRUCTION AND OPERATION OF URBAN AND RURAL POWER GRIDS

With urban and rural power grids construction and renovation, the grid structure is better reformed and the transmission line loss decreased in large amount. The reliability has improved greately, with the availability of urban and rural power kept above 99.89% and 99.0% respectively.

3.6 ENHANCING DEMAND SIDE MANAGEMENT

We pay more attention to enhance load forecasting, optimizing operation mode of power grid, and concentrating on the resources allocation optimization.

Backed by the government, we not only implements demand side management actively and give priority to supply electric power neede by people living and key consumers, but also arrange the enterprises to practice peak load shifting or peak avoiding properly, so as to relief the stress of power shortage at the most.

3.7 PROMOTING MECHANISM REFORM AND INNOVATION OF ELECTRIC POWER INDUSTRY

The mechanism reform and innovation of electric power industry have been positively promoted in China. We enhance construction of power market. Meanwhile, it accelerates the establishment of modern enterprise mechanism and perfecting corporate governance structure.

3.8 ENHANCING INTERNATIONAL COOPERATION

Due to insisting on the policy of “opening up”, we has built and remained strategic partnership with numbers of famous enterprises in many countries and regions in the world, leading to international cooperation widely in the field of power grid construction, mechanism reform, technical exchange, environmental protection, etc.

3.9 IMPROVING ENVIRONMENTAL PROTECTION

We pay close attention to seek the harmonious development between the power grid strengthening and environmental protection. High attention is paid to protect the environment and landscape, water source and reduce the waste emission. The government encourages to develop Renewable energies and clean power, such as wind power in some islands of coastal area, Xinjiang and Inner-Mongolia, etc.

4. CONCLUSION

(1) From 1970 to 1980's, regional power networks, namely Northeast China, North China, East China, Central China, Northwest China and South China have been formed.

(2) Transmitting electric power from the energy bases in west and north regions is one of the ways making up the deficits of energy in central and coastal regions, and it is imperative to develop regional power system interconnection. In addition, the comprehensive interconnection benefits, such as load leveling, emergency back-up, peak load savings, improving operation performance can also be obtained.

(3) The construction of Three Gorges Hydropower Project has pushed the implementation of nationwide interconnection project, and all the regional electric power systems have been interconnected by 500kV AC lines or HVDC lines in the year of 2005.

(4) By the year of 2020, The UHVAC and UHVDC bulk power grids will be formed. Total installed capacity will reach above 1000GW in the year of 2020.

(5) Large amount of power will be transmitted from coal power base and hydro power base in north and southwest areas to central and coastal areas of the country through UHVAC and UHVDC hybrid grids.

5. BIOGRAPHY

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1981-1994: Entered CEPRI in 1981, Engaged in research and development on power system analysis and control.

4. THE CHINESE ELECTRICITY MARKET INFRASTRUCTURE AND OPERATION SYSTEMS: CURRENT STATUS AND FUTURE DEVELOPMENTS (PAPER 07G0852)

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Abstract— At the end of 2005 the installed generation capacity of 500 GW made China the second highest in electricity production in the world. As China is being transformed into the manufacturing centre of the world, the increase of electricity demand is tremendous. New electric energy infrastructure – the super high voltage power grid is required to transfer bulk electricity energy over a very long distance in order to meet the need of social and economic development. This paper discusses the infrastructure of the electricity market in China in along with the development of the energy infrastructure. Then the Electricity Market Operation System (EMOS) and its application in China are presented. Finally the future development of the electricity market in China is outlined.

Index Terms—Electricity Market, Electricity Market Operation System (EMOS), Operation Model, A Notation in Three Dimensions

I. INTRODUCTION

Even though the electricity market models usually vary from country to country, however the purpose of the introduction of competition into a reformed power sector is the same, that is, to benefit from the electricity market. On the other hand, the electricity market is different from ordinary commodity market that is not produced and consumed instantly. Therefore, it is very important to design the electricity market while considering the special features of electricity commodity.

This paper discusses the structure, operation models and competition of the Chinese electricity markets. In line with the construction of a super high voltage transmission grid in China, the future structure of the electricity markets may be separated into three layers, which are national market, regional market and provincial market. This is followed by a proposed concept of the development of the electricity market in three dimensions.

In addition, the basic function and framework of the Electricity Market Operation System (EMOS) are described. Furthermore, its applications in the first phase and second phase of deregulation in China are discussed.

Finally, how the Chinese electricity market with three layers operates in different phases is also described. Then, a notation in three dimensions is used to describe the future prospects of the electricity market development in China.

II. THE INFRASTRUCTURE OF THE ELECTRICITY MARKET IN CHINA

A. THE STRUCTURE OF THE ELECTRICITY MARKET

At the end of 2005 the installed generation capacity of 500 GW made China the second highest in electricity production in the world. As China is being transformed into the manufacturing centre of the world, the increase of electricity demand is tremendous. New electric energy infrastructure is required to transfer bulk electricity energy over a very long distance. In order to meet the need of social and economic development, the National Grid Corporation and South Grid Corporation of China have designed and planned the construction of the super high voltage power grid [1, 3].

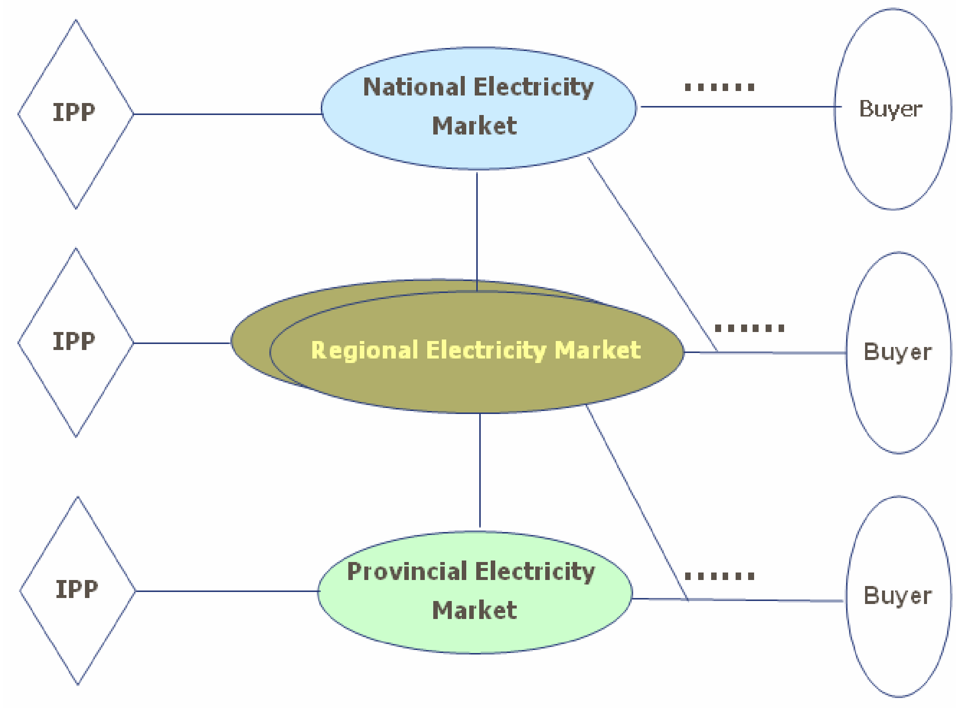

Fig. 1. The future structure of the Chinese electricity market.

The power grid is the base and carrier of the electric market. The super high voltage grid would make the united national electricity market possible and facilitate the nationwide electricity market competition. The development of the national electric market should keep the pace with that of the development of the national grid. The unified national grid is separated into different layers and regions, which can operate under the same regulations and rules. The electric markets should adapt to the structure of the national grid. According to the structure of the national power grid, the structure of the electricity markets may be separated into three layers, which are the national electricity market, the regional electricity markets and the provincial electricity markets as shown in Fig.1.

In principle, the major function of the national electricity market is to coordinate the electricity trading between different regions, and ensure the security and stability of the national power grid.

A regional electricity market should be open to the national electricity market and participate in the electricity market trading in the national electricity market wile optimizing the utilization of energy sources within the region.

A provincial electricity market should participate in both the regional and national electricity markets and accept the market scheduling from the national and regional electricity markets while optimizing the utilization of energy sources within the provincial area.

B. THE LEVEL OF THE COMPETITION IN THE ELECTRICITY MARKETS

The first level competition is the generation side competition with a centrally operated transmission system. The next level of the competition is called the wholesale competition that allows the large consumers to choose their own suppliers. The final level is the retail competition, in which not only the larger industrial consumers but also smaller consumers could choose their own suppliers.

However, the introduction of competition into a reformed power sector in China is a very complex process, which is related to our national energy strategies and policies, economic developments and national grid conditions.

The present Chinese electricity market is the one that is deregulated in the generating segment of the industry. The next level of the competition will be the wholesale competition, and then the retail competition, in which all energy will be traded through bidding.

C. THE OPERATION MODELS OF THE ELECTRICITY MARKET

Due to the special features of electricity commodity, a perfect electricity market should include a real time energy market, a day-ahead energy market and a long-term energy market. The long-term energy trading can be conducted by means of contract and futures. There are two types of contracts such as physical contract and financial contract, and three types of futures such as yearly futures, monthly futures, and weekly futures. How to design the electricity market model depends not only on economy rules of the market, but also on technology characteristics of power systems.

The four operation models of the electricity market have been used in China as shown in Fig.2. The main difference between these models is that the long-term energy trading type is different. In Model 1 and Model 2, only 15%-20% of the total energy is traded through market bidding, and 80%-85% is traded by means of long-term contracts. In Model 3 and Model 4, all energy is traded through bidding. Yet in spite of this fact, based on the analysis of different electricity markets, the models of the electricity markets may be divided into two types: Partly Energy Bidding and Total Energy Bidding. Model 1 and Model 2 are classified partly energy bidding models, which were used in the first phase of deregulation in China. Model 3 and Model 4 are called total energy bidding models, which have been used in the current Chinese electricity markets and suitable for the wholesale competition and the retail competition.

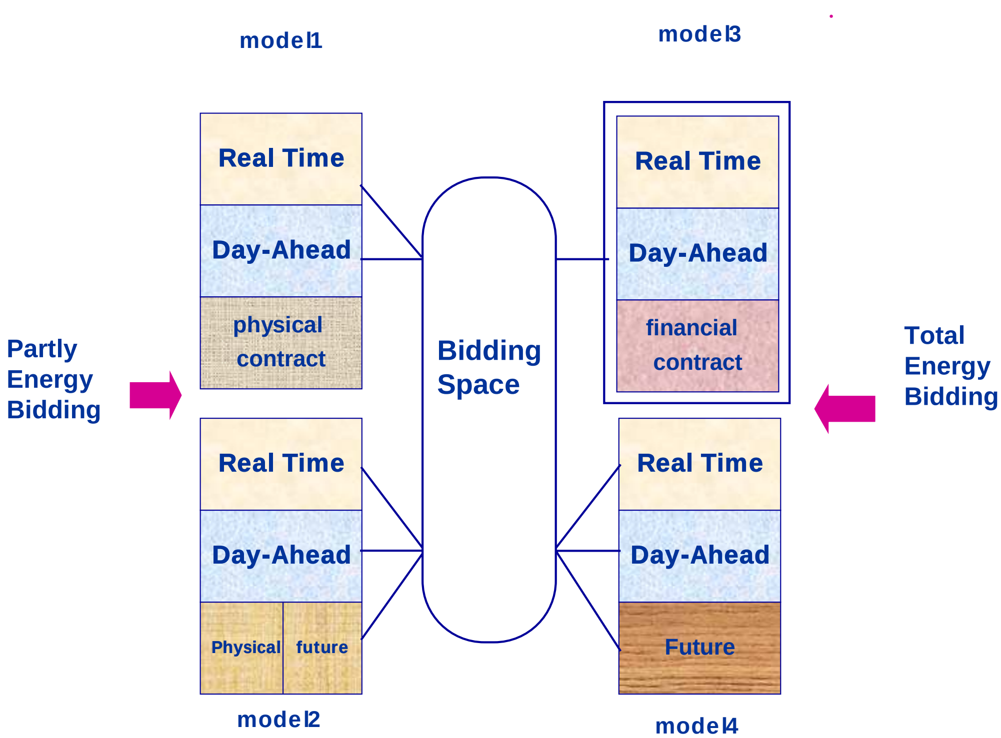

Fig. 2. The operation models of the electricity market.

D. NOTATION IN THREE DIMENSIONS

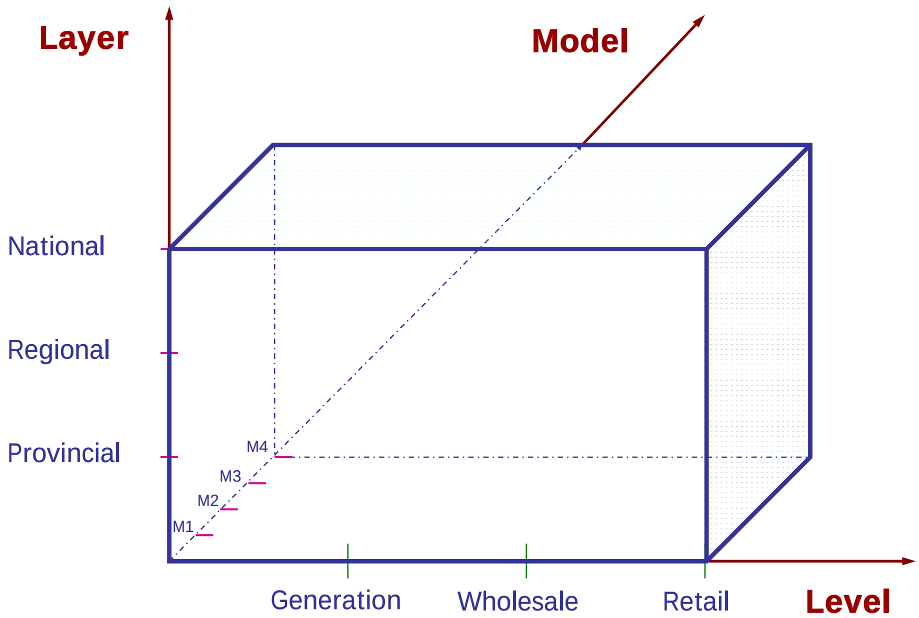

Fig. 3. A notation in three dimensions

Based on the above analysis, the development of the Chinese electricity market has three main attributes:

- The first is the electricity market separated into different layers and areas, which includes the provincial, regional and national market;
- The second is its operation models, which is from operation model 1 to 4;
- The last is the development level of the Chinese electricity market, which includes generation bids, wholesale bids and retail bids.
-

In order to describe the basic attributes of Chinese electricity market and trace its development, a notation in three-dimension is introduced as shown in Fig. 3 [2].

III. ELECTRICITY MARKET OPERATION SYSTEM AND ITS APPLICATION IN CHINA

A. THE ELECTRICITY MARKET OPERATION SYSTEM IN CHINA

The Electricity Market Operation System (EMOS) is a control and management system for the operation of electricity market. The requirements for the EMOS are almost the same in different development phases, with different market models and levels of the electricity market. The key issue for the design of the EMOS is that it should be suitable for the development of the three dimensional electricity markets. In the development of electricity markets, the key factor directly influencing the design of the electricity market operation system is the operation model.

The basic idea of the electricity market operation system design is to adopt different layered components, such as core algorithms, application functions and subsystems, to build the electricity market operation system using suitable market models. The system designed is composed of some subsystems that meet different requirements without over-lapping each other. The subsystems can be loaded or unloaded according to the requirements of the market model [2, 4].

Based on the ideas above, the EMOS only needs to install or uninstall the components of partial subsystems to adapt to the different market operation models or the change of the models, thus satisfying the requirements of the electricity market without rebuilding the whole system from scratch.

The main functions of the EMOS are as follows [5, 6]:

- The Bidding Process System (BPS) receives and processes the biding and re-biding data from generating units, based on the latest bidding;
- The Day-Ahead Trade System (DATS) calculates the pre-dispatch schedules of generating units on the trading day per trading interval;
- The Same-time Information System (SIS) issues the latest information in the market;
- The Real Time Dispatch System (RTDS) calculates and issues real time dispatch command according to the latest bidding data of generating units;
- And the Settlement and Billing System (SBS) settles all the income of the market participants by the market clearing price.

The other subsystems include the Operation Management System (OMS), the Contract Management System (CMS), Market Analysis & Forecast System (MAF), and the Futures Trade System (FTS). EMOS is interfaced with EMS, TMR and MIS through interface software. The participants of the market bid or offer through SPD-Net.

The general framework of the EMOS is shown in Fig. 4. It can be found that the EMOS consists of many "component" subsystems.

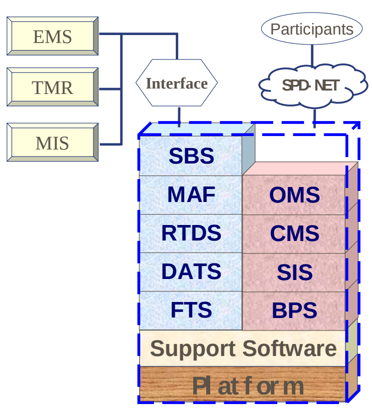

Fig. 4. The framework of EMOS

B. EMOS IN PROVINCIAL ELECTRICITY MARKET (2000-2003)

In 1998, Chinese Government set a target for China's power sector reform, that is, competition was introduced in generation with a centrally operated transmission system. Six electricity provincial electricity corporations such as Shanghai, Zhejiang, Shandong, Liaoning, Jilin, and Heilongjiang on a trial basis were selected to establish provincial electricity markets. Based on the regulations of the electricity market, the generating vendors would bid for sale to the electricity market. In January 2000, these electricity markets on a trial basis were put into business operations.

In the six pilot electricity markets, the competition was all introduced in generation with a centrally operated transmission system. Among the six pilot provincial electricity markets, the operation model of Zhejiang's energy market was using Model 3 consisting of a real time market, a day-ahead market and a long-term market while the rest of the other five electricity markets only consist of a day-ahead market and a long-term market and their operation model is Model 1 as shown in Fig. 2.

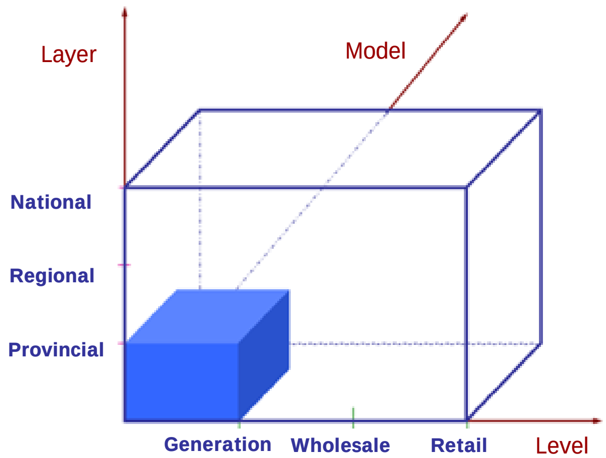

Fig. 5. The past electricity market in China.

Zhejiang Electricity Market was run by means of a spot market and financial contracts. The Market and System Operator (MSO) operated the spot market in which participants were governed by the rules and regulations for bidding, dispatching, market price and settlement. The model of "a Single Buyer and Contracts for Differences (CFD)" with all energy involved in bidding was applied in Zhejiang Electricity Market.

Among the six pilot provincial markets, the model of Zhejiang including real time, day-ahead and financial contract market is shown in on the right of Figure 6 where the long-term exchange subsystem was offloaded from the system shown in Fig. 4. The other five markets as shown on the left of Fig. 6 were using Model 1 where the RTDS was offloaded.

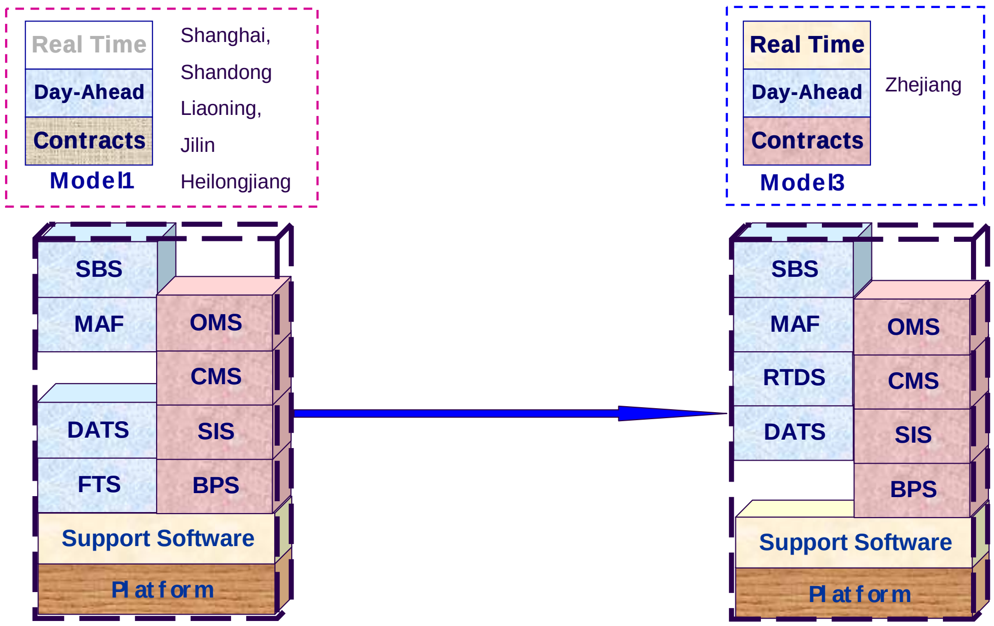

Fig. 6. The EMOS of Zhejiang electricity market.

After having been running for more than three years, the six pilot provincial electricity markets were all closed for further reform of China's power sector in 2003.

C. EMOS IN REGIONAL ELECTRICITY MARKET (2003-PRESENT)

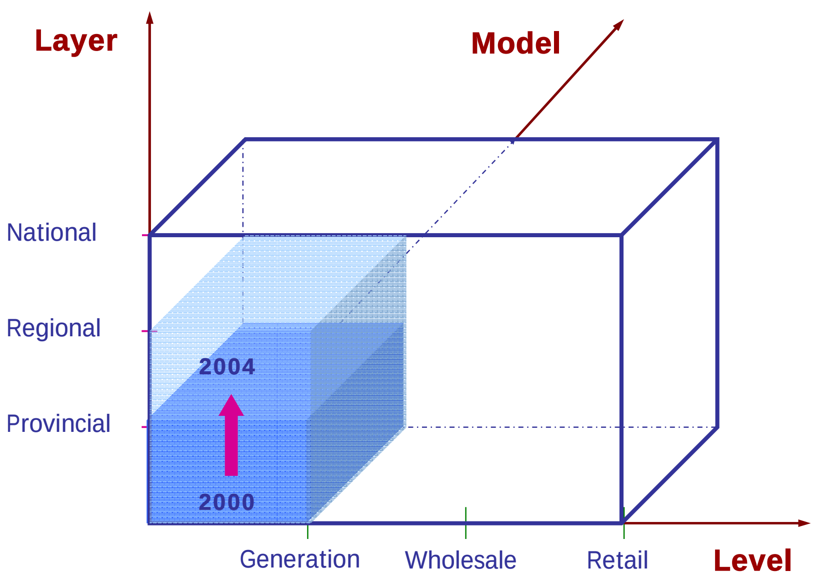

Fig. 7. The EMOS of the regional electricity markets.

In late 2002, in order to promote competition in the industry and help integrate the fragmented provincial power market, the Chinese government broke up the State Power Corporation, the former electricity monopoly, into 11 smaller generating, distribution and logistics companies, and the State Electricity Regulatory Commission (SERC) was established early that year, which laid a foundation for the implementation mechanism and helped create competitive regional electricity markets as shown in Fig. 7.

In 2003, the SERC set a target for building two pilot regional electricity markets in Northeast China and East China. In 2004, two regional electricity markets were put into pilot operation.

In the two regional electricity markets, the competition is introduced in generation with a centrally operated transmission system. The models of the two pilot regional markets are using Model 2 and Model 3. These markets have only long-term trade in the first stage of the market development, and will gradually develop day-ahead trade and real time trade.

The regional electricity market in East China is a common market. There were one regional market system operator and several provincial market system operators in the common market. 15%-20% of the total energy is traded through bidding in the regional electricity market, which consists of a day-ahead market and a monthly futures market, and 80%-85% is traded by means of long term contracts and real-time balancing mechanisms in the provincial electricity market [7].

The EMOS in East China includes the EMOS in regional MSO, assistant EMOS in provincial MSO and BIDDING terminal in IPPS, as shown in Fig. 8.

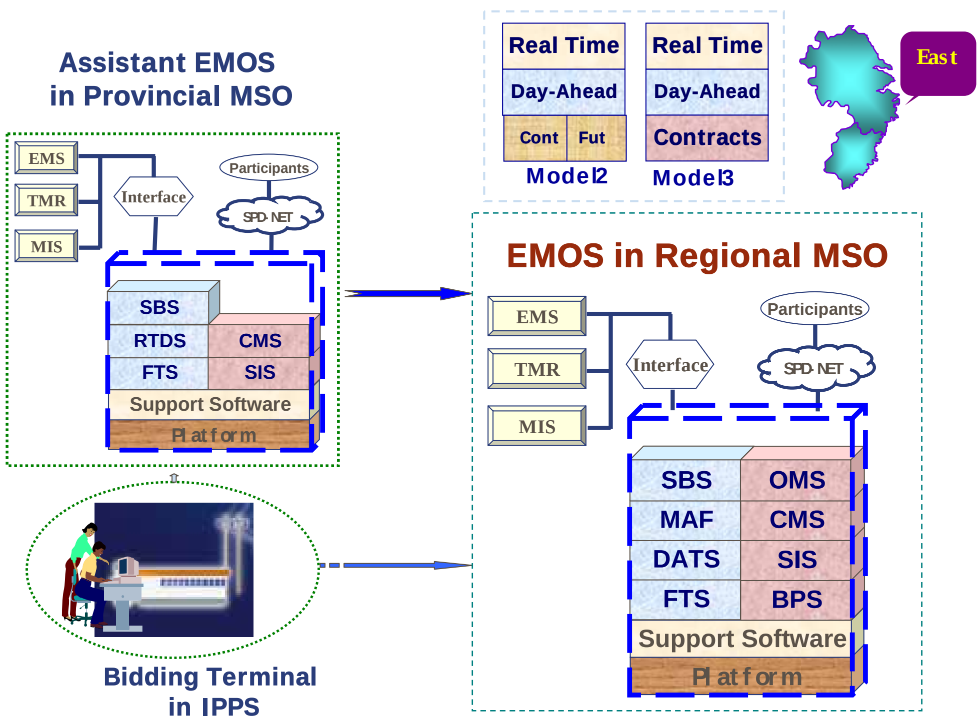

Fig. 8. The EMOS in the regional electricity market.

The regional electricity market in Northeast China is a unified market. Before July 2004, 20% of the total energy was traded through bidding in the regional electricity market, which consists of a real-time market, a day-ahead market and a monthly futures market, and 80% was traded by means of long-term contracts within provincial dispatch center. Under the supervision of the government, its operation model has been changed since 1st July 2004, 100% of the total energy is traded through bidding in the regional electricity market which consists of a real time market, a day-ahead market and a long-term market, 80% of the total energy is traded by means of yearly futures. The provincial dispatch centers receive the dispatch schedule of the generating units within its province and issue the dispatch commands to the generating units, ensuring the secure operation of the provincial power system [8].

The regional electricity market in South China has been building since 2005. The regional electricity market in south China is a common market. There were one regional market system operator and several provincial market system operators in the common market. At present, 15% of the total energy is traded trough bidding in the regional electricity market, which consists of a monthly market and a yearly futures market, and 85% is traded by means of long-term contracts. Real time balancing mechanism is used in the provincial electricity market. At the same time, regional electricity markets in North China, Central China and Northwest China would be prepared.

IV. FUTURE DEVELOPMENT OF ELECTRICITY MARKETS IN CHINA

A. THE COORDINATED OPERATION OF THE ELECTRICITY MARKET IN CHINA

The design objective of the national grid is to fulfill the requirements of power transmission from west to east and from north to south, removing the transmission bottle necks in economically developed areas, optimizing energy source distribution within larger areas, meeting the requirements of economic development, creating nationwide competitive energy markets.

The national electricity market will optimize the utilization of energy sources within nationwide areas. The national super high voltage transmission grid will promote electricity trade between different layers of the Chinese electricity markets, optimizing the utilization of energy sources within larger areas.

Fig. 9 shows how the national electricity market and the regional electricity market will operate in phase, optimizing the utilization of energy sources within larger areas [2].

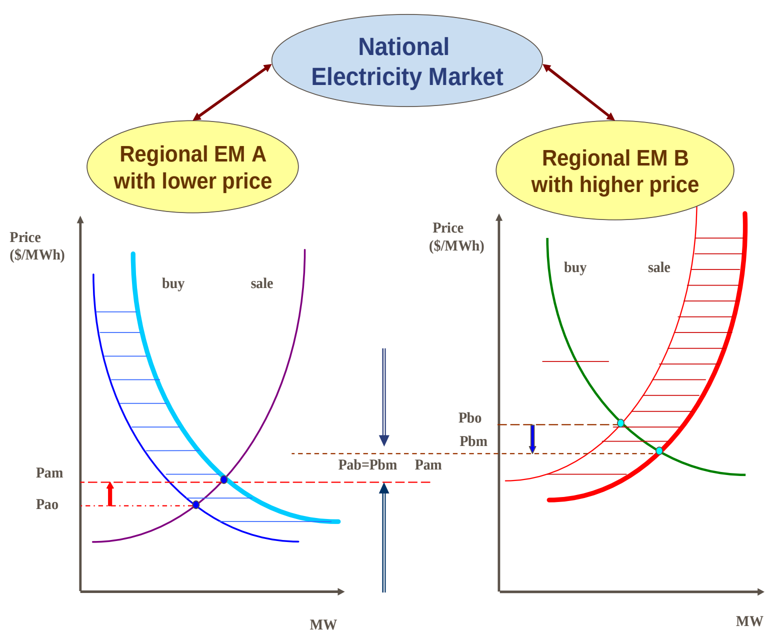

Fig. 9. The electricity trading between two areas.

As shown in Fig. 9, before the electricity in areas A and B is traded through the national electricity market, the Market Clearing (MCP) in area A and area B are set as Pao and Pbo, respectively, in which Pao is less than Pbo.

Area A and area B, as the national electricity participants, will bid, taking their regional marginal costs as references, their monotonously increasing supply curves, and offer their monotonously deceasing demand curves, respectively, in the national electricity market.

This means that the regional electricity market A will sell the electricity to the national electricity market in which the market price is higher. In contrast, the regional electricity market B will buy the electricity from the national electricity market, in which the market price is lower.

In this example, the electricity between area A and area B is traded through the national electricity market, in which the market price is determined based on the bid/offer data of market participants. The market price in the national electricity market is higher than that in area A and less than that in area B. Therefore, after having been traded through the national market, the MCP in area A will be up to Pam which is higher than Pao, and MCP in area B will be down to Pbm which is lower than Pbo. Through the national electricity market, the area B with higher MCP can buy the electricity from the area A with lower MCP. In the same way, the area A with lower MCP can sell the electricity from the area B with higher MCP through the national electricity market.

As a result, the customers in area A will pay more than before for the electricity they used. The power stations or power plants will earn more than before for the electricity they sold. However, the utilization of energy sources of the regional areas has been optimized and this will greatly benefit the society as a whole.

B. THE ELECTRICITY MARKET FOR TOMORROW

At present, the competition is only introduced into the generating segment of the industry. The purpose of the electricity market reform in China is to accumulate the experiences about the electricity markets and to prepare the introduction of competition of higher level in the future.

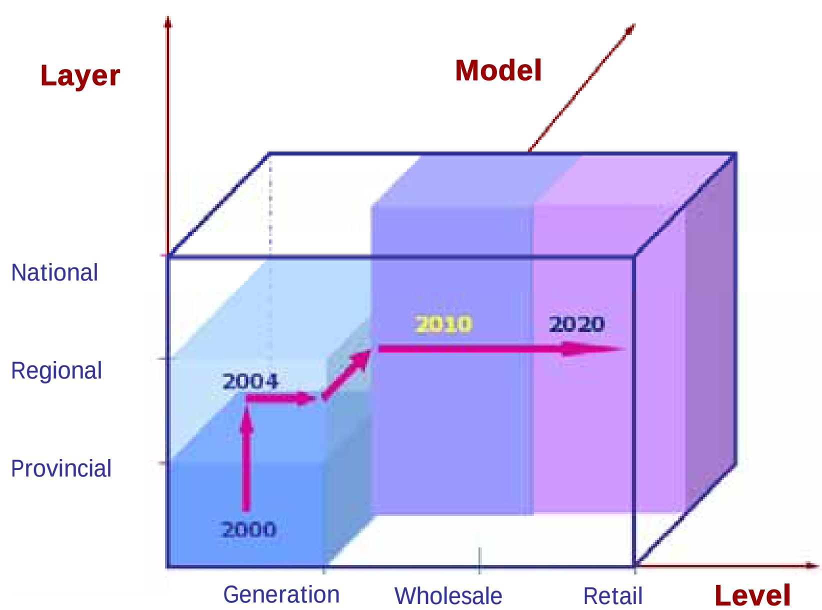

Fig 10. Chinese electricity market development trace.

By 2010, the national super high voltage grid will be formed. According to the structure of the national power grid, the structure of the electricity markets would be separated into three layers, which are the national market, regional market and provincial market. An even more competitive and orderly generating market will be fully established by 2010, when the competition level of the electricity market in China will be wholesale competition. The large consumers will be allowed to choose their own suppliers as shown in Fig. 10 [2].

The Chinese electricity market would have been developed for 10 years by 2010. Many experiences have been accumulated by then. The electricity market should have been ripeness. All energy should be traded through bidding. By 2020, the Electricity Market would have been developed for more than 20 years. The higher-level competition will be introduced into power sector. The large consumers will be allowed to choose their own suppliers.

V. CONCLUSIONS

The development of the Chinese electricity market derived from the requirement of the market economy, benefited from the government's promotion, and progressed thanks to the exploration and effort of the power sector.

The introduction of competition into a reformed power sector is a very complex process, which is usually based on national energy strategies and policies, economic developments and national grid conditions, etc. It has been recognized that electricity market models usually vary from country to country. Therefore, the operation models of the electricity market in China have been investigated.

This paper has discussed the structure, operation models and competition of the Chinese electricity markets. In line with the construction of a super high voltage transmission grid in China, the future structure of the electricity markets may be separated into three layers, which are national market, regional market and provincial market. This was followed by a proposed concept of the development of the electricity market in three dimensions.

In addition, the basic function and framework of the Electricity Market Operation System (EMOS) have been described. Furthermore, its applications in the first phase and second phase of deregulation in China have also been discussed.

Finally, how the Chinese electricity market with three layers operates in different phases has been described. Then, the paper has summarized the development of the Chinese electricity market.

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VII. BIOGRAPHIES

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5. WAMS IMPLEMENTATION IN CHINA AND THE CHALLENGES FOR BULK POWER SYSTEM PROTECTION (PAPER 07GM0839)

Qixun Yang, Board Chairman, Beijing Sifang Automation Co. Ltd., China and .Bi Tianshu, Professor, North China Electric Power University, China.

***Abstract*—**Synchronized phasor measurement technology has been gaining increasingly interests in China due to its wide area time synchronization capability and fast transmission speed. Over 10 years of implementation of wide area measurement system (WAMS) in Chinese power grid have shown its great value in power system dynamic monitoring and potential applications in system modeling and validation, feed-back control and system wide protection. This paper reviews the overall implementation of WAMS in China and analyzes the corresponding characteristics of WAMS. Moreover the challenges for bulk power system protection with synchronized phasor measurement technology are presented also.

Index Terms—Synchronized Phasor Measurement, wide area measurement system, wide area protection, power system

I. REVIEW OF IMPLEMENTATION OF WAMS IN CHINA

With the development of GPS, computer and communication technology, the prototype of phasor measurement unit (PMU) was first developed in United States in early 1990s. It attracts great attention in China since its birth.

The installation of PMU in Chinese power grid can be dated back to 1995. Chinese Electric Power Research Institute (CEPRI) introduced ADX3000 system from Ouhua Technology Co. Ltd, Taiwan, which had the function of phasor measurement and was commissioned as PMU in Chinese power grid. From 1995 to 2002, about 30-40 ADX3000 were installed and the main stations of WAMS were established in East China, South China, North-west and Sichuan Power grid and State Power Dispatching Center (SPDC) successively (the schematic diagram of Chinese power grid is in Fig. 1) [1]. ADX3000 adopted modem as communication media and internal communication protocol which made the data can be uploaded to the main station of WAMS every one second. The installed ADX3000 system successfully recorded dynamic process of low frequency oscillation occurred in Chinese power grid for several times which revealed the significant value of synchronized phasor measurement technology in the area of power system dynamic monitoring and also pushed the development of prototype of PMU of Chinese manufacturer.

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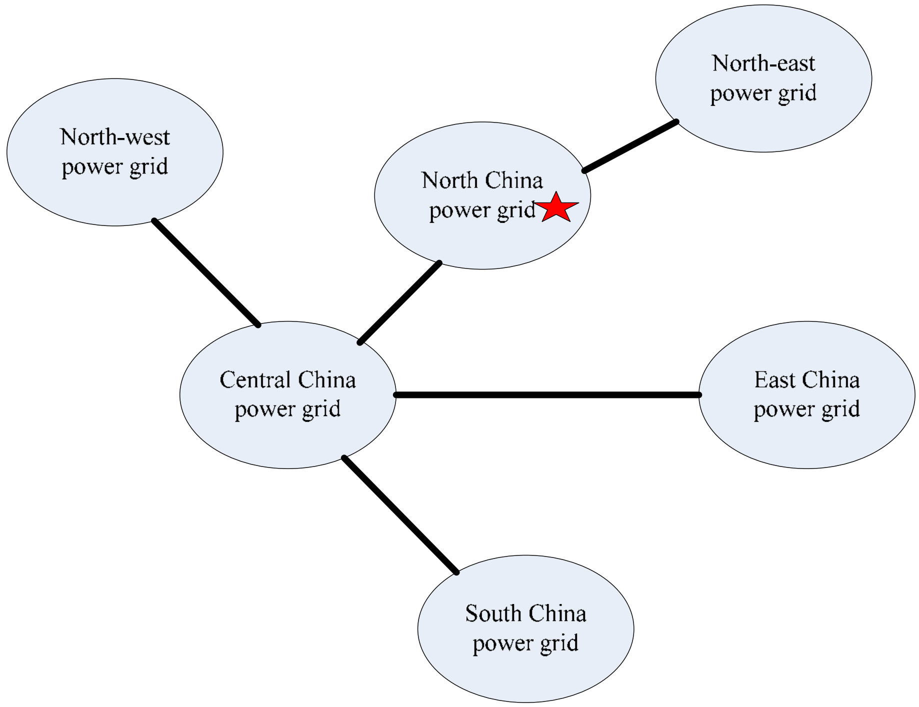

Fig. 1 schematic diagram of Chinese power grid

At the end of 2002, Chinese manufacturers have the commercial product of PMU which have been commissioned in Chinese power grid since 2003. By the end of 2006, over 300 PMUs are installed, which are mainly distributed at the substations and power plants of 500 kV and 330 kV voltage level. 7 regional WAMS are constructed in SPDC and North China, North-east, North-west, East China, Central China, South China power grids. 6 provincial WAMS are established in Jiangsu, Shandong, Guangdong, Guizhou, Yuannan and Shanxi power grids. Moreover, real time data exchange is realized among SPDC, North China and Northeast WAMS.

Since there are different approaches to achieve phasors and more than one manufacturer, a Chinese standard on PMU and WAMS is drafted by State Grid Company and manufacturers in 2003 and finally issued in 2005. The standard supplements transmission protocol of historical data on the basis of IEEE Std 1344-1995 (R2001). The synchrophasor standard provides a technical specification for manufacturers and allows interchange of data between a wide variety of users of both real time and off-line phasor measurements, which is of great importance for Chinese WAMS implementation.

With PMU, State Grid Company carried out man-made short circuit experiments on 500kV transmission line in North-east power grid in 2004 and 2005 respectively. Before the experiments, the simulation results show that the largest phasor angle difference would be around 20 degrees. However the true value recorded by PMU is only 6 degrees, which makes us "see" clearly the needs of power system modeling and simulation validation. Power system planning, operation and control all will benefit from this point. In addition, the blackouts occurred worldwide in recent years also confirm the urgent needs of WAMS. Therefore, for the next five years, all 500kV substations and 300MW & above power plants in Chinese power grid will install PMU according to *11th 5-Year Plan of Power Grid* [2].

II. CHARACTERISTICS OF WAMS TECHNOLOGY IN CHINA

COMPARISON BETWEEN CHINESE AND OVERSEA PMUS

Synchronized phasor measurement technology is the basis of WAMS. A comparison between Chinese and oversea PMUs is given in Table 1 [1, 3, 4].

Table 1 Comparison between Chinese and oversea PMU

Item	Chinese PMU	Oversea PMU
A/D sampling rate	96-200/cycle	20-96/cycle
A/D bit	14/16 bit	12/16 bit
Accuracy of signal magnitude	0.2%	0.1-0.6%
Accuracy of phase angle	0.2 degree	0.1 degree
Accuracy of frequency	0.001	0.005
Accuracy of synchronization	1μs	1μs
Communication channel	Ethernet	Dial and Ethernet

It can be seen technical specification of Chinese PMU is quit similar with that of oversea PMU. However, two characteristics of Chinese PMU should be noted.

1) There are two types of PMU in China. One type is the same with that of abroad manufacturers, which is installed in substation and takes voltages and currents of substation as inputs to calculate phasors. This kind of PMU appears in Table1. Another kind of PMU is installed in power plant and used to measure the rotor angle of generator directly. A sensor is put on the rotor of generator, which outputs a pulse each cycle to indicate the rotor position. The phase angle between the up-edge of this position pulse and the positive zero-crossing point of A phase voltage can equal to the rotor angle after phase compensation which is shown in Fig. 2. Besides, the latest PMU released in 2006 can measure excitation voltage, excitation current, valve position, output of PSS, etc.

2) Chinese PMU has high speed communication capability due to the private communication network built by State Grid Company. The private network assures that the bandwidth of channel from substation or power plant to dispatching center is n*2M (n>=1), which guarantees that the time delay of phasor in dispatching center is less than 40 ms on average. This do good for WAMS based power system control.

WAMS IN CHINA

The basic structure of WAMS in China is given in Fig. 3 [3].

In China the main station of WAMS is located at the regional or provincial dispatching center and composed of advanced application station, database sever and data concentrator. It can be seen the advanced application station retrieves data from data concentrator via LAN instead of Ethernet, which reduces time delay of the data. From this point of view, the data concentrator here is not the same with that in IEEE Std C37.118 although the names are same.

The data concentrator in main station is one of key points in WAMS. Currently some data concentrator already contains 5000 phasor measurements and the storage rate of the phasor is 100 H_z. With the fast development of WAMS, how to construct the data concentrator with 100 PMUs and 10000 phasor measurements and provide corresponding high-speed storage and enquiry technology is also a challenging work.

The functions of advanced application station include visualization of dynamic process and available transmission capacity, wide-area data recording and playback, and on-line low frequency oscillation analysis. Due to the long transmission distance and weak interconnection, low frequency oscillation is a quite severe problem in China. As an only tool catching the oscillation, WAMS plays an important role in low frequency oscillation identification and control in 2005 and 2006 in China. New identification and preventive control methods are undergoing development.

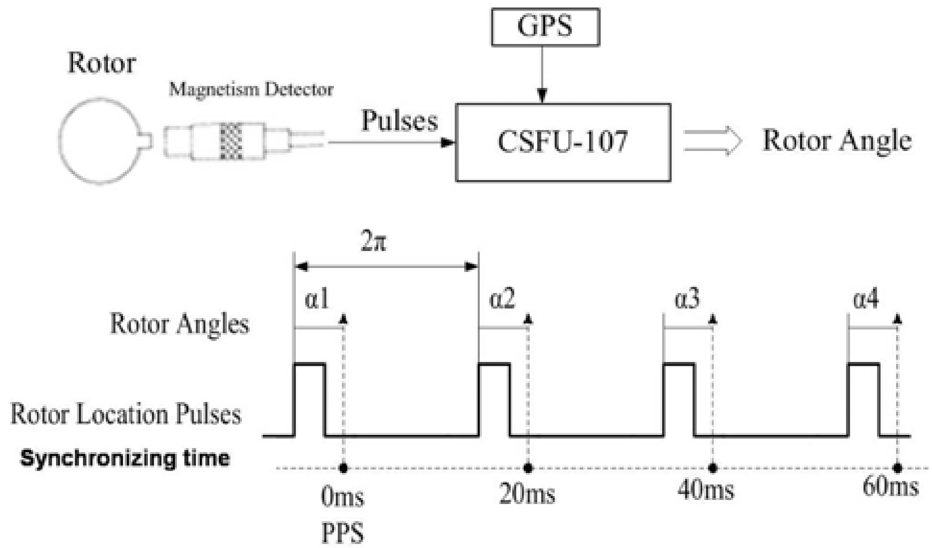

Fig.2 The illustrative diagram of rotor angle measurement

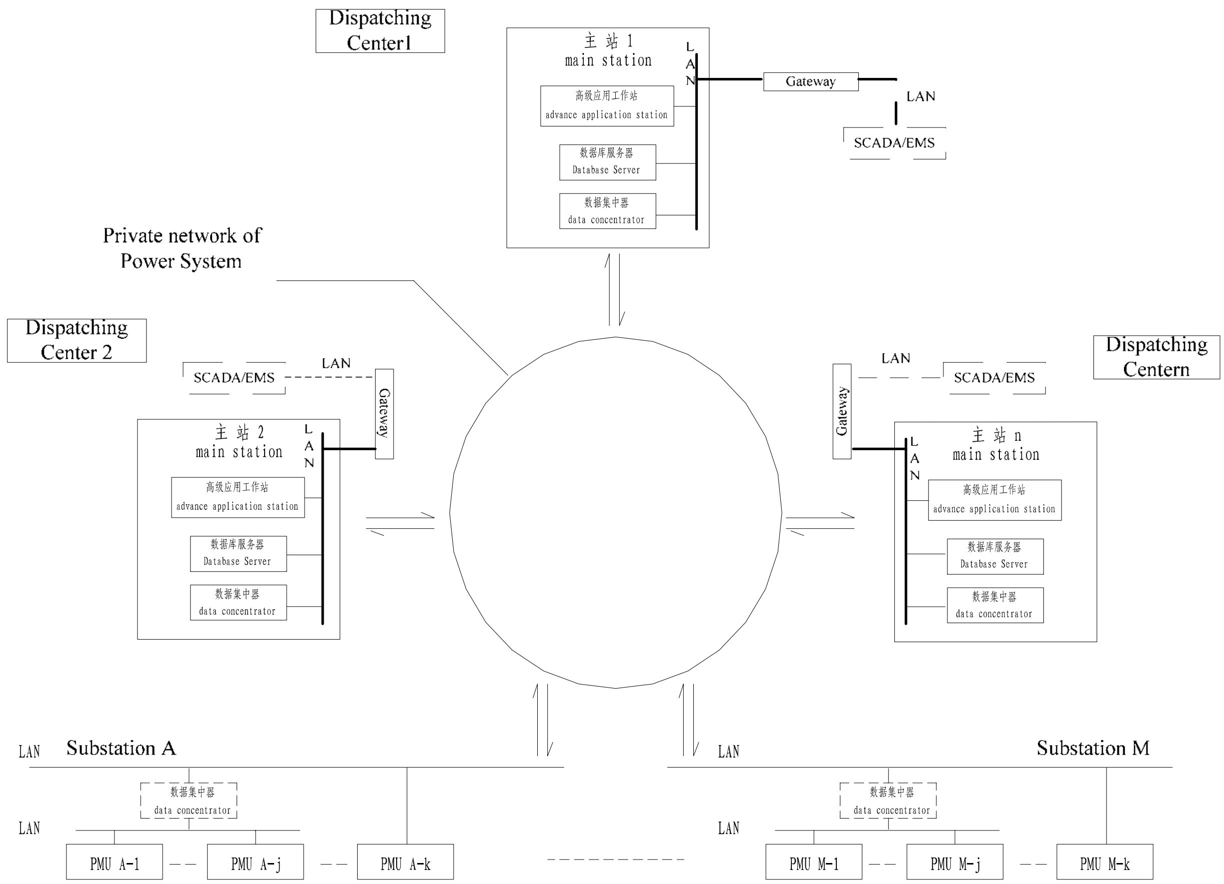

Fig.3 Basic structure of WAMS in China

III. CHALLENGES FOR BULK POWER PROTECTION WITH WAMS

WAMS is becoming one of most important data sources in power system due to its wide area time synchronization capability and fast transmission speed. How can we protect the bulk power system with phasors against blackout?

PMU TEST AND EVALUATION IN DYNAMIC CONDITION

A phasor representation for a power system in steady state is easy to understand and compute accurately. However, WAMS based bulk power system protection and control functions do act in dynamic process, and phasor measurements must take into account dynamic behavior of the system. The standards and testing methods we have mostly aim at PMU behavior in steady state. Then how to test and evaluate PMU behavior in dynamic condition is a question we have to answer.

In China, a working group has been initiated to study on the new standard of synchrophasor, which will define a more detailed technical specification about the functions and testing conditions of PMU and data concentrator.

DYNAMIC MODELING AND SIMULATION VALIDATION

Power system simulation is a basic tool for power system planning, operation and control, even after we have WAMS. Many cases, such as man-made short circuit experiments, WECC blackout playback and so on, demonstrate that the system model and parameters, especially load model and controller parameters of electric machine, might not be accurate in dynamic process. With the system trajectory provided by WAMS, it is possible to identify or validate system models and parameters.

Some research endeavor [5-9] have been done and obtained promising results. In man-made short circuit experiments in China, phasor measurements are used to validate the load model of North-east China power grid. Firstly, several load characteristic identification devices are installed at the typical load point in power grid. The general load models of typical loads are identified based on the measurements. Secondly, classify all load substations according to the typical load models and then generalize the identified load models to all load substations. The transient stability software with updated load model gets the better results. The detailed analysis is presented in [8-9].

WIDE AREA BACK-UP PROTECTION

According to statistic data, relays are involved in one way or another in 75 percent of major disturbances [10].

In July 1977, New York City experienced a blackout caused by two lightning stokes and the cascading trips by flow transferring. The economic and social impact of this event is disastrous.

On December 14, 1994, a fault occurred on a 345kV line in southern Idaho and was tripped correctly. However, an incorrect trip of the parallel line and the overload trip of third line made the system unstable. Finally the system was isolated into four islands, and the frequency dropped to 58.75Hz and 3,000MW of load was shed.

In August 2003, the blackout event was begun with the clearance of four key 345kV tie lines between Akron and Cleveland. Consequently, the flow was transferred onto the 138kV tie lines, which were loop circuits with those 345kV lines. As a result, those 138kV lines tripped in succession and the blackout occurred.

It can be seen that although the protective relays operated as the predefined logic, the system status was deteriorated and finally collapsed. One of most important reasons lies in that the existing protections only utilize the local data and try to eliminate the faulted element or mal-operating condition as soon as possible without consideration of the impact on the whole system [11]. When the network is in a heavy load condition, the clearance of a faulted line might cause flow transferring, which results in overload of other transmission lines and lead to cascading trips. In those cases, if the backup relays do not trip the overload lines before the thermal limits and leave enough time for operators to eliminate the overload, the cascading trips might be avoided. Therefore, the study of backup protections from the whole system viewpoint is a challenge for system security and reliability.

WAMS opens a new path for power system protections, especially for backup protections (The time delay of backup protections makes it possible to acquire and deal with the phasor data of power systems). Some research works [11-16] has been launched into this area. To handle the cascading trip problem, the fundamental solution is to monitor the load and try to identify whether the overload is caused by flow transferring or internal fault. If flow transferring does occur in the system, then block the backup relay when the thermal limit of the line is unreached.

It should be pointed out the philosophy of main protection should not be changed with the advent of WAMS. On one hand, acquisition of phasor measurements will inevitably increase the time delay of trip signal which has adverse impact to system component and stability. On the other hand, the introduction of WAMS information makes the main protection more complex which might be corresponding to lower reliability.

FEED BACK CONTROL

Feed back control includes low frequency oscillation damping control, voltage stability control, frequency stability control, transient stability control, etc. Among them low frequency oscillation damping control might be a good starting point for its relatively slow dynamic process.

South China Power Grid Company, Tsinghua University and Beijing Sifang Automation Co. Ltd have done pioneer work in this area. South China power grid including Guangdong, Guangxi, Guizhou and Yunnan is a long chain power network. The power is transmitting from the west (Guizhou and Yunan) to the east (Guangdong) via hybrid AC-DC lines. When the transmitting power is increased, low frequency oscillation might occur among Guizhou, Yunnan and Guangdong provincial grids. The basic idea of this project is to modulate DC powers on the DC links to damp the oscillation, which can be partitioned into the following steps.

1) Place PMUs in south China power grid optimally.
2) Realize on-line oscillation identification with phasor measurements.
3) Design adaptive control strategy to generate optimal modulating DC powers for DC links with the consideration of time delay of feed back signals.

Experiments on RTDS simulator have been finished at the end of this Nov., which show the proposed control strategy works well for damping low frequency oscillation and can be adaptive to the variation of operating point. It will hopefully be the first feed-back control in Chinese power grid.

IV. CONCLUSION

Synchronized phasor measurement technology is being mature and WAMS has been widely established in Chinese power grid, which is becoming one of the most important data sources of dispatching center. The large disturbances occurred in recent years demonstrate the powerfulness of WAMS in the areas of dynamic monitoring and system modeling and parameters validation. But how to integrate phasor data to develop advanced applications to prevent bulk power systems against blackout still opens.

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Jingtao Wu was born in 1970, in Beijing P.R.China. He got his BS, MS and PhD from Tsinghua University in 1995, 1998 and 2001 respectively. In 2002, he joined the Beijing SIFANG automation co., ltd. He is in charge of the development of wide area measurement system. By the end of 2005, more than six WAMS data centers has been realized by his working group, and more than hundred PMU installed in 220kV and 500kV power grid. His interest is WAMS technology and its applications.

6. FAST DEVELOPMENT OF CHINESE POWER INDUSTRY AND ITS IMPACTS ON POWER SYSTEM R&D OUTPUTS (PAPER 07GM 0807)

Shuyong Chen, Feili Huang, Baohui Zhang, Yixin Ni, Libao Shi and Zheng Xu, Various Institutions, China.

Abstract**—**The rapid growth of Chinese economy leads to fast development of electric power industry, which greatly promotes higher education on electrical engineering and the research and development (R&D) on power systems in China. In the meantime, the Ministry of Science & Technology of China (MSTC) and the National Natural Science Foundation of China (NSFC) play an important role in planning and supporting key and basic research projects on critical issues in power industry. In this paper the rapid growth of Chinese power industry is outlined. The NSFC sponsorship on power system relevant R&D is presented. And the higher education on electrical engineering is introduced. The Shenzhen RI of National Key Lab on Power Systems, jointly run by Tsinghua University and the University of Hong Kong located at Tsinghua University Graduate School at Shenzhen, is used as an example to show the impacts of fast development of Chinese power industry on power system R&D in China. The R&D output in China is then shown through paper publications. Finally the issues in power system R&D in China are discussed.

Index Terms**—**Power System

I. INTRODUCTION

In the last two decades, the economy of China has been developing very fast through the policy of "open to the world" and encouraging competition, which in turn significantly increases the demand on energy, especially on electric energy. The rapid growth of electric power industry greatly promotes higher education on electrical engineering and the research and development (R&D) on power systems in China. In the meantime, the Ministry of Science & Technology of China (MSTC) and the National Natural Science Foundation of China (NSFC) play an important role in planning and supporting key and basic research projects on critical issues in power industry. In this paper the rapid growth of Chinese power industry is outlined. The NSFC sponsorship on power system relevant R&D is presented. And the higher education on electrical engineering is introduced. The Shenzhen RI of National Key Lab on Power Systems, jointly run by Tsinghua University and the University of Hong Kong located at Tsinghua University Graduate School at Shenzhen, is used as an example to show the impacts of fast development of Chinese power industry on power system R&D in China. The R&D output in China is then shown through paper publications. Finally the issues in power system R&D in China are discussed.

II. OUTLINE ON THE FAST DEVELOPMENT OF CHINESE POWER INDUSTRY

In China, the electric energy supply reaches 42% of all the end user energy supply as observed in 2002, which will grow up to about 70% in 2020. In order to meet the requirements of rapid development of Chinese economy, the installed generator capacity has been increasing rapidly. In 1987, the national generation capacity was over 100GW, while within 8 years it had doubled to over 200GW in March 1995. In April 2000 and May 2004, the total generation capacity reached 300GW and 400GW respectively. And by the end of 2005, it has reached 500GW. Since 1996, the generation capacity of China has been No. 2 in the world. And the electric energy production of China has also reached No. 2 in the world thereafter. In the next decade, the electric load forecasted by the State Grid Co. (SGC) will be about 570 GW, 752 GW and 966GW in 2010, 2015 and 2020 respectively, and the corresponding generation capacity will reach 799 GW, 978GW and 1211GW (see Fig.1)

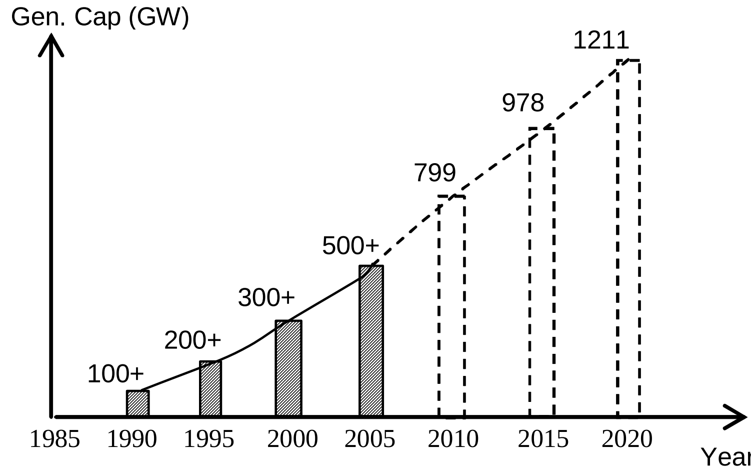


Figure 1 Generation capacity in China

However because of the large population in China, the electric energy used per capita is still at lower level. Fig. 2 shows the comparison of kWh per capital. In 2002 the kWh per capital of China is about 1280, which is about the average level of the world in 1970s, and 50% of the current average level of 2500 kWh per capita. Therefore the power industry in China will continue to grow rapidly in the future.

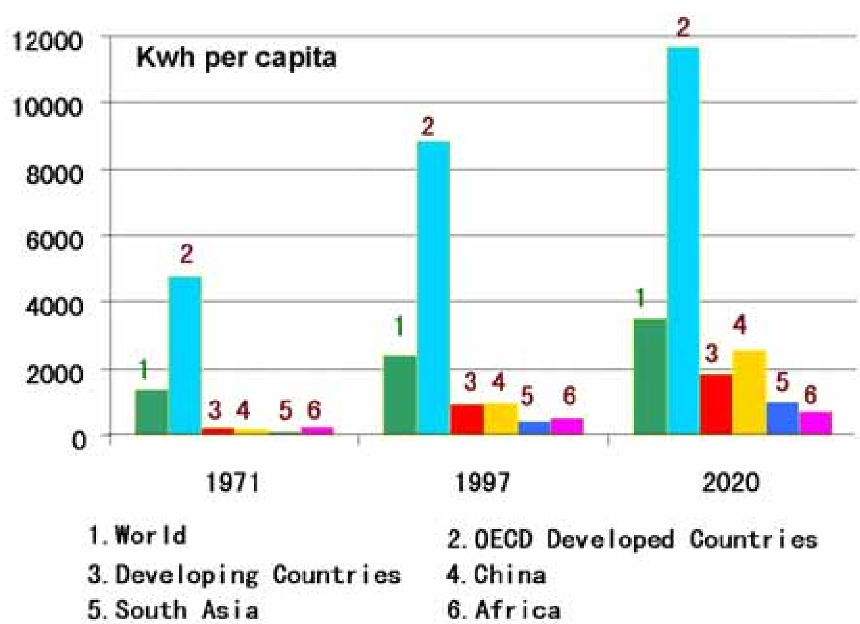


Figure 2 Comparison of kWh per capital

The Chinese power systems have following features.

- The load in China is mainly in the South & East of China, while coal and water resources are mainly located in North, Northwest and Southwest of China, which leads to the long-distant heavily-loading transmission system from west to east and north to south of China.
- Since the resources of petroleum and natural gas are not rich in China and the coal production can not meet the requirement of power generation, nuclear power plants constructed in the load centre are under planning, but the total nuclear power capacity will be no more than 5% till 2020. In the meantime, the hydraulic power utilization will be accelerated especially along the Yangtze & Yellow Rivers. In general coal-fired and hydraulic power will be over 90% of total capacity in the next 20 years with small amount

of nuclear and renewable energy.

- Based on above facts, China will construct ±800 kV HVDC and 1000 kV UHVAC transmission systems to interconnect 7 regional power grids of Northeast, North China, Northwest, Central China, East China, Chuan-Yu (i.e. the Grid composed of Si-Chuan Province and the City of Chong-qing) and South China together in the near future. Figure 3 shows the possible interconnection of regional power grids in China in 2020.

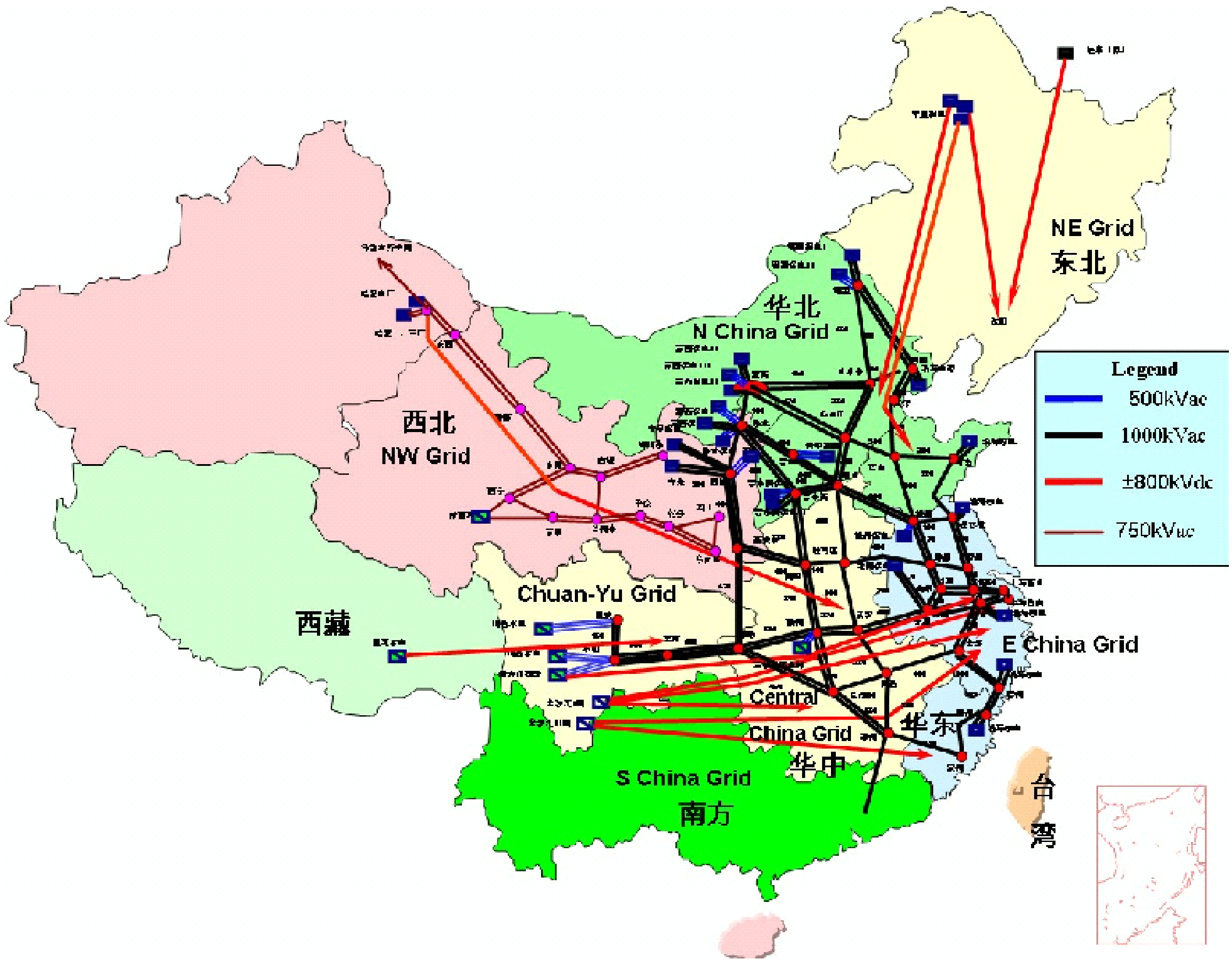


Figure 3 Interconnection of Chinese power grid in 2020 (planned)

- In the meantime, power industry deregulation is underway in China. In its first stage, the traditional vertical monopolistic operation has been converted the single-buyer mode of regional power markets with large gencos established and separated from the former State Power Co. (which is now renamed as the State Grid Co., SGC). Since the Ministry of Electric Power does not exist anymore, the SGC will have the power to plan and construct inter-regional transmission systems, arrange their bilateral power exchanges and supervise the operation of regional grid companies, etc. (except that the S. China Grid Com. is operating independently approved by the State Council for certain degree of competition in the transmission sector). In the 11^{th} 5-year plan (2006-2010), the wholesale mode will be realized in regional power markets. The power utilities will form the power supply companies and join the competition in power markets. The traditional transmission tasks will be implemented by the grid companies as transcos allowing open-access as most power markets in the world.
- In the next decades, the key challenges in Chinese power systems are:
  - Optimal planning of nation-wide power system interconnection with security consideration.
  - Key technology for ultra-high-voltage (UHV) transmission systems.
  - Optimal operation of the Chinese power system using advanced technologies (such as AI, IT, computer and communication engineering, applied mathematics and control theory applications, etc.).
  - Improvement of power system reliability and power transfer limit to avoid power system blackout and severe stability crises.
  - Strengthening power market operation at high-efficiency and encouraging energy saving of end-uses and environment protection to realize sustainable development of power industry in China.
- To cope with the secure and optimal operation of the complex transmission networks in China, advanced technology will be widely explored, investigated and developed. International collaborations and academic exchanges should be greatly strengthened. It can be foreseen that along with huge amount of investments entering power industry, the R&D funds for power systems will increase rapidly.

III. R&D ON POWER SYSTEM SPONSORED BY NSFC

In China R&D funds support power system projects through several ways. In the State Council, there are commissions which will support power system R&D projects relevant to their functions, including the State Development and Reform Commission, the State Economy and Trade Commission, and the State Electric Power Surveillance Commission.

In the ministry and provincial government level, the Ministry of Science & Technology and the Ministry of Education as well as provincial governments will sponsor key and basic research projects on power systems; support key lab operations in power systems and sponsor outstanding young investigators' research on power systems. The SGC and the S. China Grid Com. and their sub-companies as well as the manufacturers of power system facilities will also sponsor the R&D projects on power system technology with potential applications in real power systems. In addition to these approaches, the NSFC plays a significant role in supporting basic and key research in power systems in China.

The NSFC was founded in February 1986 with the approval of the State Council, which is aiming at promoting and supporting basic research and key applied research in China. Now NSFC employs no more than 200 staff members with over 90% as professionals at the averaged age of 42. It has established a solid system to make strategic plans on key and basic research, evaluate various proposals, and assess R&D outputs strictly, fairly and scientifically. Since its foundation, the budget of NSFC has been increasing dramatically from RMB 80M in 1986 to 2000M in 2004, about 25 times higher. The projects sponsored by NSFC are now classified into the categories of major projects, key projects and general projects to be funded at different strengths and scales. Besides, special funds are launched for outstanding young investigators to promote their R&D excellence and for international exchange and collaboration.

In traditional electrical engineering area (i.e. heavy-current area mainly on power engineering), 6 key projects are sponsored during 1996-2000 at RMB 5.1M in total; while in 2000-2005, 6 major and key projects are sponsored at RMB 11.3M in total. The NSFC sponsored general projects are increasing from 40 projects and RMB 7.6M in 2001 to 98 projects and RMB 26.4M in EE subjects in 2006.

The NSFC major and key projects in electrical engineering focus on the significant R&D areas in power engineering, such as FACTS devices (TCSC) design, development, operation and simulation, non-linear robust control theory and its applications in power systems, fundamentals of power markets, super-conductor technology and its applications in power systems, basic theory and key technology for power system security control, etc. A major project on key technology for UHV ac/dc power systems is under planning.

In a key project jointly sponsored by NSFC and SGC, EPRI-China has successfully designed and constructed a prototype of TCSC (see Fig. 4). The TCSC was installed on a 220 kV ac transmission line in Gansu Provincial Grid and committed in December 2004. The compensation level was 50% of line reactance with the capacity at 95.4 MVar, which increased the transmission capacity by 33%.

Figure 4 TCSC developed by EPRI China

Although the funds for power engineering is about 1/20 of all funds for engineering and material science, and 1/100 of overall NSFC funds, it plays an important role to give preliminary support on basic and fundamental research and lay a solid foundation for further supports from industry. Actually some key projects are sponsored by the power industry in parallel, such as the project on multi-infeed HVdc transmission system reliability and control, etc. In addition, other departments of NSFC (such as information department, etc.) will also sponsor multi-discipline projects related to the applications of advanced technologies in power systems.

It should be mentioned that in parallel with NSFC as a “vertical” R&D source from the MSTC, there are two National Key and Basic Research Projects (so-called ‘973’ projects) on power engineering. One is “Vital Research on Collapse Prevention and Optimal Operation of Large Power Systems in China” (1999-2003) and the other is “Fundamental Research on Improving the Reliability of Large-scale Interconnected Electric Power System” (2004-2008). The project funds are RMB 50M and 30M respectively. The nation-wide experts of power engineering are working together for the projects and have made great contributions to the Chinese power industry.

The facts mentioned above show clearly the impacts of fast development of Chinese power industry on power system R&D. Actually the provincial governments, power companies and manufactures are all actively supporting R&D projects in power engineering so as to get benefits from the outputs.

IV. HIGHER EDUCATION ON ELECTRICAL ENGINEERING IN CHINA

The rapid growth of Chinese power industry also brings about fast development of high education in electrical engineering (EE) (or more accurately, in classical EE). In China, the classical EE course is mainly composed of heavy current subjects, such as power system and its automation, high voltage and insulation, electric machines and equipment, power electronics and drives, etc., with “power system and its automation” (PS&A) as the dominant and largest subject in EE.

For the undergraduate courses of EE, usually the freshmen can reach 50,000 per year in over 250 colleges and universities including two electric power universities in Northeast and North China. About 80 universities have the authority to admit master degree postgraduates (approved by the Ministry of Education) and admit about 2000-3000 master degree postgraduates per year in PS&A major; while the admitted Ph. D. degree postgraduates per year will be several hundreds also with the approval from the Ministry of Education in admission authority to ensure quality. Experienced full professors with good R&D records will be allowed to supervise Ph. D. degree postgraduates, and only qualified universities can award Ph. D. degrees.

Some research institutes, such as EPRI-China and NARI-China, also educate postgraduates and postdoctors but at small scale mainly for their R&D requests.

The Ministry of Education has formed a special committee to direct higher education with a sub-committee on EE course. Key issues in EE education will be discussed on its annual meeting. Special symposiums will be held to discuss key issues in EE course. In addition to that, there is an “Association of the leaders of electric power institutes in China”, which usually holds an annual meeting to exchange experiences and discuss key issues in higher education reform, management and R&D, etc. in the area of PS&A.

To promote education quality and R&D excellence in PS&A, the Ministry of Education organizes an assessment in every 5 years on the education quality and R&D outputs of the subject in individual universities. The top 5-6 universities will have their PS&A major entitle “key subject” and receive special fund from the Ministry of Education and the match fund from the corresponding universities. Such universities will have more opportunities to get key projects from NSFC and power industry. The competition is surely very severe.

The Chinese universities with PS&A major also hold an annual symposium on power systems and editor a high-quality journal on power systems as well. The annual symposium is similar to NAPS in USA & Canada. Till now, it has held for 22 times with average numbers of submitted papers and participants over 500 and 300 respectively in recent years.

It should be pointed out that a lot of ‘vertical’ projects (i.e. government, MSTC and NSFC sponsored projects) on power engineering are implemented solely or jointly by universities. It is clear that universities play a significant role in the R&D of power industry in China. Unlike the electric companies in developed countries, the Chinese electric companies have relatively week teams on R&D. Therefore the new products and technology will often be investigated by universities first through R&D projects, and the technology transfer will be conducted thereafter. Some universities even own the patents and organize their own companies to run business.

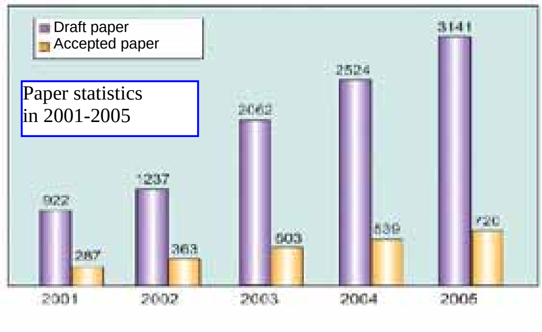
A Power System Research Institute (PSRI) at Tsinghua University Graduate School at Shenzhen (also entitled Shenzhen RI of National Key Lab on Power Systems) is running jointly by the University of Hong Kong (HKU) and Tsinghua University (THU), which will be used as an example to show the R&D outputs from the university in China. Under the leadership of Prof. Felix Wu (Chair Prof. of EE, HKU, Prof. of U.C. Berkeley, emeritus, IEEE fellow) and Prof. Qiang Lu (Prof. of THU, Academician of the Chinese Academy of Science, IEEE fellow), the Shenzhen RI has received R&D funds “vertically” from the two ‘973’ projects mentioned above and one key NSFC project; from the Shenzhen Government (since the RI is the first National Key Lab established in the former "Fishers Village" of Shenzhen) and from HKU. In the meantime, the RI received funds "horizontally" from the Dispatching Centre of the SGC, several regional grid companies, and manufacture companies including Panasonic (Japan) and Haier (China). In recent years, it conducts R&D work on power markets, power system planning and operation, power system analysis, stability and control, as well as the applications of power electronics in power systems, etc. and has published quite a lot of qualified papers [1-15] along with the implementation of the research projects. Fig. 5 shows a electronic device developed by the Shenzhen RI for real industry use.

Figure 5 A prototype of frequency-converter for central air-conditioning developed by the Shenzhen RI

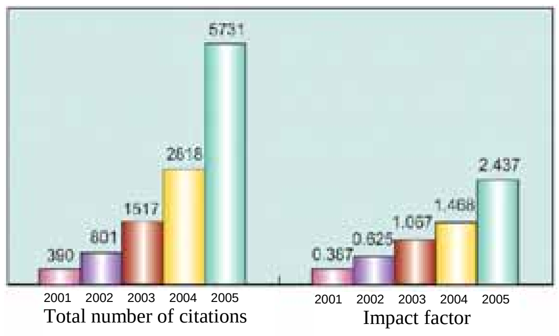
V. POWER SYSTEM JOURNALS AND PAPER PUBLICATIONS IN CHINA

Along with the growth of Chinese economy and power industry, technical papers, as one type of the R&D outputs, increase noticeably as well.

In 2005 there are 153,347 international science & technology papers published in the world. The top 5 countries with the largest number of international science & technology papers are USA, UK, Japan, China and Germany. In China there are 185 journals relevant to power systems with 37 entitled "Core Power System Journal". Among them the top 3 journals with largest impact factors (according to citations) are Proceedings of the CSEE, Automation of Electric Power System and Power Technology. Their papers are considered to be collected by EI. Using Proceedings of the CSEE as an example, Fig. 6(a) shows its annual received papers and published papers over the period of 2001-2005; and Fig. 6(b) presents the total number of paper citations and impact factors in 2001-2005. The fast growth of both submitted papers and qualified papers can be seen clearly in Fig. 6(a), which finally leads to the change of publication period from monthly to semimonthly for all the three core power system journals.



(a)



(b)

Figure 6 Data on paper publication and citation for Proceedings of the CSEE in 2001-2005

VI. ISSUES IN R&D ON POWER SYSTEMS IN CHINA

There are several issues which are critical to future R&D on power systems in China. The following points are considered important:

- International exchange and collaboration should be strengthened and such collaboration should be supported by both the government & electric power companies.
- Outstanding young investigators should be strongly supported to promote their R&D excellence. Besides they should not be given heavy load on management.
- The three sectors of education, research and application/production should collaborate closely and coordinate very well to yield high-quality R&D outputs at high efficiency. This collaboration can also educate superior experts with solid R&D capability in power engineering.
- Strategic planning on R&D of key technology for power systems should be conducted by prestigious experts thoroughly and systematically to promote power system R&D excellence and efficiency, and make even greater contributions to the sustainable development of power industry. Among all the potential R&D areas, the environmental protection, energy saving and efficiency improving in all parts of generation, transmission, distribution and end-user should be greatly emphasized.
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VII. SUMMARY

The fast development of electric power industry greatly promotes the R&D in power systems. In this paper the rapid growth of Chinese power industry is outlined at first. And then their impacts on power system R&D in China are described from three aspects, i.e. the NSFC sponsorship on power system R&D projects, higher education on electrical engineering and paper publications in core power system journals. The important issues in R&D of power systems in China are discussed as well.

VIII. ACKNOWLEDGMENT

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X. BIOGRAPHIES

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7. RELIABILITY COMPLIANT MARKET:INCENTIVES FOR LONG-TERM TRANSMISSION AND GENERATION CAPACITY ADEQUACY (PAPER 07GM0862)

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ABSTRACT – Electricity restructuring is centered on economic efficiency as well as grid reliability for both short and long terms. Successful markets are characterized with the common key elements. The key market elements include: locational marginal pricing (LMP), financial transmission right (FTR) and co-optimized energy and ancillary service market. As critical components of a successful market design, risk hedging mechanisms are presented including multi-settlement scheme, virtual bidding and bilateral contracts. Market mechanisms for long-term transmission and generation capacity adequacy are under development in the US several US markets and will be discussed in the paper. Examples are used to demonstrate the workings of the key market elements.

key words – Market design, locational marginal pricing, financial transmission right, ancillary service, capacity market and risk management, long-term transmission and generation investment.

I. INTRODUCTION

Electricity restructuring is centered around economic efficiency as well as grid reliability for both short and long terms. Experimentation with electricity restructuring in the last fifteen years or so around the world have witnessed successful and not so successful market designs. Experiences with successful markets have indicated that economic efficiency can be compatible with reliability requirements in terms of long-term transmission investment and generation capacity adequacy. The key to reliability compatible market design is to abide by the laws of physics and the principles of economics. As a general principle, market mechanisms should be adopted where possible. But in circumstances where conflicts between reliability and commercial objectives cannot be reconciled, they shall be resolved in favor of high reliability. This paper concentrates on the key elements of a successful market design with reference to several US markets in Mid-Atlantic, New England and Mid West regions.

The recent evolution of electricity market design has been shifting from its early focus on market liquidity which facilitates bilateral trading and pricing efficiency which facilitates congestion management to additional market design reforms that cater for long-term transmission investment and generation capacity adequacy. The early efforts to achieve liquidity and efficiency led to uniform or zonal marginal pricing (UMP/ZMP) in most early market designs. Uniform or zonal pricing requires pre-defining regions within which congestions are insignificant and hence prices can be deemed uniform. The UMP design is biased toward achieving market liquidity. The uniform pricing approach was adopted in several markets, such as the earlier England and Wales market, 1997 PJM market, the pre-2003 ISO-NE market and ERCOT zonal market. The uniform pricing approach would work if there should exist ample transmission capacity where congestions were of no concern. When this is not true, uniform pricing gives the wrong price signals and causes difficulties in physical system operation, which would put grid reliability at risk and often lead to command and control instructions, as experienced

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by the PJM and ISO-NE operators. The frequent exercise of command and control goes against the goal of competitive markets and reduces market efficiency with heavy uplift charges.

The development of the zonal pricing approach was an improvement over the uniform pricing model. In the zonal approach, it is assumed that transmission constraints are few, can be identified a priori, and can be used to delineate the network into several zones. A uniform energy price is then computed for each zone. However, practical experience has proved that the number of transmission constraints is not few, the congestion pattern is unpredictable, and that zonal price signals based on pre-delineated zones are helpless in relieving congestion.

Experiences with uniform marginal pricing and zonal pricing approaches led to the development of an alternative method: locational (or nodal) marginal pricing (LMP) based on a full transmission network model and determined via the security constrained economic dispatch (SCED). The LMP based method was implemented notably in the PJM RTO (Regional Transmission Organization) [1], New York ISO (NYISO), ISO-New England [2], and the Midwest ISO [3]. The LMP at a specific location reflects the marginal cost of serving the last MW of load considering the marginal production cost, the impact of locational injections on congestion constraints, and in some cases the marginal effect of transmission losses. The LMP method has proved its effectiveness in achieving congestion relief and market efficiency.

The unpredictability of transmission congestion implies greater uncertainty of LMPs, creating price volatility without appropriate financial hedging instruments. To address volatility and increase market liquidity, the point-to-point financial transmission rights (PtP FTR) was developed. An FTR is a financial entitlement that can hedge its holder against congestion charges incurred on a specific transmission path defined by its source and sink location. The economic value of an FTR is determined by the difference in the LMPs between its source and sink, independent of physical energy delivery. The FTR market in PJM has been in successful operation since April 1999. FTRs overcome the congestion-incurred price uncertainty and market liquidity problems that are otherwise impediments to the LMP method.

A robust, competitive market must also deal with ancillary services (AS) required to reliably operate the system. AS markets have been designed in different forms due to differences in operational practices and regional reliability standards between control areas (CA). The broader differences in AS market design also manifest the fundamental differences between energy and AS products. Despite these design differences, it is recognized that AS and energy markets are closely coupled as the same resource and same capacity may be used to provide multiple products when economics justifies. This capacity coupling between provision of energy and AS calls for joint optimization of AS and energy markets, though the exact form of joint optimization differs from market to market.

The reality that there exist lack of demand side response to spot market price signals and the application of energy offer price caps presents significant challenges that spot market alone would be able to stimulate sufficient incentives for long-term investment in generation and transmission expansions. A sustainable electricity market must therefore design mechanisms that can provide long-term price signals encouraging the right generation and transmission expansion investments necessary to meet reliability standards. On-going market design reforms in the US are on introduction a new capacity market design, such as PJM’s Reliability Pricing Model (RPM) and ISO-NE’s Locational Installed Capacity (LICAP) mode, and the demand curve model, such as in NY-ISO and Midwest ISO.

Central market’s provision of risk hedging products is another salient feature of a successful market design. In addition to FTRs, other risk hedging mechanisms include multi-settlement scheme, virtual bidding and bilateral contracts. Multi-settlement market typically consists of a day-ahead market and a real-time market. Day-ahead market is a financial market that allows participants to obtain price certainty for services scheduled to be delivered in real-time. A reliability commitment follows to ensure that generation resources are adequately procured to meet grid reliability needs. Virtual bidding is an important mechanism for the convergence of day-ahead and real-time market. This convergence improves price certainty in a forward basis. Bilateral contracts: Bilateral contracts may be constructed as financial or physical. A financial bilateral contract provides insurance of the price for delivered electricity and it does not impact grid dispatch. A physical contract guarantees physical delivery of service at a given price.

In the following sections, the LMP market design is described in Section II, followed with the discussion of FTR market features in Section III. Ancillary service markets are discussed in Section IV. Risk hedging mechanisms are discussed in Section V with references to markets with energy shortage conditions Section VI describes the current developments of market mechanisms for the long-term transmission investments and generation capacity adequacy.. The paper is concluded in Section VII.

II. LMP BASED ENERGY MARKET

The LMP based market model starts with the requirements for real-time grid operation. It has been an industry practice that the SCED algorithm produces dispatch solutions that conform to efficient and secure real-time grid operation. The SCED provides grid operators with the capability to manage changes in load, generation, interchange and transmission security constraints simultaneously in real-time operation. Transmission system security is continuously monitored and analyzed with the state estimator (SE) and contingency analysis (CA) functions in the EMS using detailed network models. Potential transmission security breaches are resolved through redispatch with the SCED algorithm. Evidently, incorporating modeling details that are consistent with the physical network into the SCED is critical to the efficiency and effectiveness of the redispatch, which has ultimate impact on network security.

While sufficient confidence has been built in the SCED derived MW (and Mvar) redispatch signals, it has been practically proved that the counterparts of the MW redispatch controls, that is, LMPs, can also serve as control signals for real-time secure grid operation. The key to the substitutability of the LMPs for MW redispatch controls hinges upon the requirements that LMPs and MW redispatches be fully consistent. In mathematical terms, the LMPs must be determined with the true dual solution of the SCED problem. In this case, the duality theory dictates that the LMPs and the MW redispatches are both the optimal solution to the same constrained optimization problem, but expressed in different forms. It is no surprise that the LMP based energy markets have achieved its current successes and is being considered for other markets.

Take a 2-generator single-line system (Fig. 1) as an example to demonstrate that the LMP market provides consistent MW dispatch (reliability) and price (commercial incentives) signals. Assume that system loads are concentrated at bus B and most generations are located at A far from load center B, transmission systems are designed to meet a normal load of 200MW at bus B and a gas turbine unit is built adjacent to the load center at B to serve additional load above 210MW. When the load at bus B is normally less than or equal to 200MW, there is ample transmission capability to transfer power to the load center. The marginal cost to serve the system load is $20/MWh corresponding to the generation at A. Since there is no congestion, LMPs at A and B are the same, i.e., $20/MW. In this scenario, grid operators may send the MW dispatch signals of 200MW and 0MW to units A and B respectively; or, grid operators may communicate the $20/MW price signals. In the latter case, the generators would, based on the $20/MW real-time price signals, derive the same MW dispatch values of 200MW and 0MW for their generators.

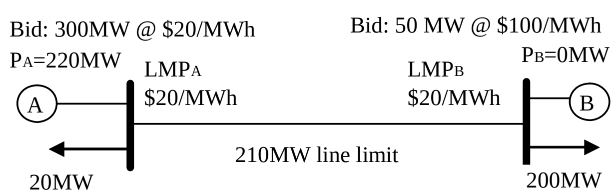

Fig. 1. MW and price consistency without congestion

Now assume that the load at B increases above 210MW, say 220MW at a peak hours. The 220MW load at B cannot be fully served with the cheap generation at A due to the limited transmission capability of 210MW. In this scenario, the more expensive generation at B has to be dispatched to meet all the loads. The resulting dispatch and LMPs are shown in Fig. 2. In this congestion case, the two generators at locations A and B are paid their respective LMPs of $20/MW and $100/MW respectively under the LMP market. Under the LMP scheme, either the MW dispatches or the LMPs may be used as real-time generation control signals, and either will lead to the same system reliability.

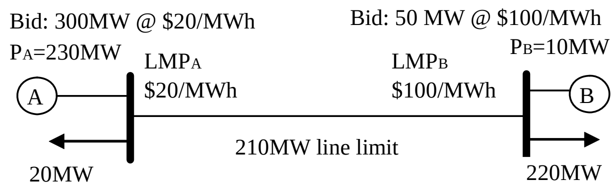

Fig. 2. MW and price consistency under congestion

The MW dispatches and real-time prices are used as real-time generation control signals in some LMP based markets in the US. In the PJM market, zonal dispatch rates (ZPR) derived from real-time LMPs are communicated every five minutes to local control centers that control generators within their zones. In the ISO-NE market, desired dispatch points (DDP), the MW dispatches derived from the SCED algorithm, are sent to generators. No matter either DDPs or LMPs are used as control signals, the key is that generators' real-time productions shall be paid at their respective LMPs, or generators' respective LMPs must be used to determine their real-time DDPs, and that the consistency between MW and LMP calculations must be maintained in order to achieve grid reliability and market efficiency.

It is worthwhile to note that alternative market designs may reduce either grid reliability or market efficiency. For instance, under the uniform marginal pricing (UMP) scheme, generators at A and B are both paid the same UMP of $93.04/MWh and the loads at A and B are both charged the UMP. Generator A with a marginal cost of $20/MW is satisfied with the UMP, and will indeed be rewarded for more production, though additional generation from unit A would aggravate the congestion. Generator B will not be satisfied with a UMP lower than its marginal cost of $100/MW, and thus would reduce its generation output when and where it is most needed. Apparently generators A and B cannot be allowed to respond to the UMP price signal, and thus inevitably, command control will have to be applied to both generators. An uplift payment, $6.94/MW in this case, will have to be paid to generator B to at least make up the shortage of its short-run marginal cost. This uplift payment is shared among the loads in the form of uplift charge, which reduces market efficiency.

The LMP based real-time market may be settled in terms of ex-ante or ex-post LMPs. In the ex-ante LMP based real-time market settlement real-time actual generations and consumptions are paid and charged the LMPs that derived from the 5-minute look-ahead SCED solutions based on projected very-short-term demand forecast and transmission conditions. For this ex-ante scheme, settlement rules must be in place to deal with uninstructed deviations. In the ex-post LMP based settlement method, real-time market settlement LMPs are re-calculated after the fact in accordance to generators' compliances with ex-ante DDPs and real-time actual transmission congestion. Generators with excessive deviations from DDPs may be disqualified for participating in setting marginal price and become price takers in the ex-post LMP calculation. The ex-post LMP based settlement scheme is more transparent and encourages generators to follow dispatch instructions. This is also the approach recommended in FERC's SMD. The ex-post LMP real-time market design is in operation in the PJM, ISO-NE and MISO markets.

The LMP based market settlement produces the following basic cash flows for generators and loads:

- Generations at buses A and B are paid $4,600 and $1,000 respectively.
- Loads at buses A and B are charged $400 and $22,000 respectively.
- Total settlement residue: $16,800, called congestion rentals.

These LMP market settlement results have important implications on the behavior of market participants:

- Generation and load responses to LMPs lead to reliable grid operation.

- LMPs serve as short-term signals for generation investment. In the example of Fig. 2, the \$100/MW LMP_B clearly indicates the need for new generation at bus B (load center).
- LMPs give explicit valuation of scarce transmission capacity, \$80/MWh (= LMP_B - LMP_A) in this example, which serves as short-term market signals for transmission investment.

However, LMPs create price volatility associated with network congestion activities. Congestion rentals must also be allocated appropriately. Both issues are dealt with using the FTR mechanism, which will be discussed in the next section.

III. FINANCIAL TRANSMISSION RIGHTS

An FTR is a financial entitlement that can hedge its owner against congestion charges incurred on a specified transmission path. The FTR path is defined by the transmission reservation from the point where the power is scheduled to be injected onto the grid (source) to the point where it is scheduled to be withdrawn (sink). Once determined, the FTR is in effect for the predefined period whether or not energy is actually delivered and offsets the congestion cost for the FTR's owned MWs.

An FTR's economic value is based on the MW reservation level multiplied by the difference between the LMPs of the source and sink points. These LMP differences reflect opportunity costs of the transmission paths. FTRs are financially binding and can either be a benefit or a liability to the holder. They are a benefit when the designated path is in the same direction as the congested flow. This occurs when the sink node LMP is greater than the source node LMP. FTRs are a liability when the inverse occurs. The holder of an obligation FTR must pay for holding the FTR when the sink node LMP is less than the source node LMP.

FTRs may be acquired in different ways depending on the market design. In the PJM and ISO-NE markets, transmission service customers who pay the embedded cost of the transmission system have the right of requesting network or firm point-to-point transmission service FTRs. FTRs can also be acquired through the centralized FTR Auction market. All FTR requests submitted (whether through transmission service requests or the auction) must pass the simultaneous feasibility testing (SFT) prior to being approved. The SFT analysis ensures that the financial entitlements granted through approved FTR requests can be simultaneously honored within the existing capability of the transmission grid. Therefore the SFT analysis ensures that the revenue from transmission congestion rentals is adequate under normal system conditions to pay FTR credits.

Below the previous 2-bus example is used to explain the FTR auction (or allocation) process. Assume the following PtP obligation FTR purchase bids:

- Participants X bids to buy 300MW @ \$5/MW from bus A to B
- Participants Y bids to buy 20MW @ \$1/MW from bus B to A

Line A-B is limited to 210MW. The FTR auction market solution is shown in Fig. 3. The 230MW injection and withdrawal at buses A and B correspond to FTRs awarded to X. The 20MW injection and withdrawal are FTRs awarded to Y. With bus A as the reference, LMP_A=0 and LMP_B=\$5/MW determined by the marginal FTR bid of participant X. Participant X pays \$1,150 to receive 220MW FTR from A to B. Interestingly, participant Y is paid \$100 for the 20MW FTR awarded from B to A. It is worthwhile to point out that the proceeds from FTR auctions are allocated to market participants who pay the embedded network cost through the transmission tariff payment using an auction revenue right mechanism.

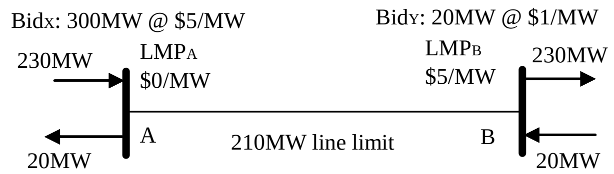

Fig. 3. Obligation FTR Auction Market Solution

When the FTR ownership shown in the above figure is applied to the LMP market in Fig. 2, participant X would receive the FTR credits determined as the product of its owned FTRs of 230MW and the LMPs of the energy market, which is $18,400 (=(100-20)*230). On the other hand, participant Y would have to pay $1,600 (=(100-20)*20), as the FTR from B to A is a liability in this case. The total FTR credit is $16,800 ($18,400-$800), which is exactly equal to the congestion rentals collected from the LMP market settlement. This balance of congestion rentals with FTR credit requirements, called revenue adequacy, is not coincidental. The key to achieving revenue adequacy is to ensure that the grid model and reliability standards (such as SFT analysis) are consistently applied for FTR allocation or auction and the physical market operation.

If participant X owns the energy transaction between generation A and load B, then participant's X net settlement amount would be equal to 220MW Load*$100/MWh–230MW Gen*$20/MWh–230MW FTR*$(100–20)/MWh)=$1000, which implies net credit of $1000 due to its FTR benefit. Similarly, if participant Y has a transaction from generation B and load A of 20MW, the net settlement for this transaction is 20MW Load*$20/MWh–10MW Gen*$100/MWh–20MW FTR*$(20–100)/MWh)=$1000, which implies a net charge of $1000. However, when the amount of owned FTRs matches the amount of energy transactions, the net settlement will constitute a perfect hedge leading to net settlement of zero dollars.

The above result indicates that the energy transactions of A-B for participant X and B-A for participant Y in the example are fully hedged against the congestion associated price volatilities. When FTR MW as well as its source and sink points matches the energy transaction MW and its injection and withdrawal points, the FTR constitutes a perfect hedge and the energy transaction owner is indifferent to congestion related price risks. This hedging capability addresses the market liquidity concerns with LMP and enables the CfD type of bilateral transactions to be reasonably conducted under the LMP market.

FTR's financial hedging function for congestion price can be extended as a financial instrument to protect long-term transmission investment and incremental transmission improvements rendered possible by certain generation additions.

IV. ANCILLARY SERVICE MARKETS

Ancillary services (AS) are necessary for secure and reliable grid operation. Competitive market processes have been developed for provision of ancillary services. In the development of AS markets, different market designs have been attempted. Compared to the development of energy markets, AS market designs tend to have more variations from market to market due to different reliability standards, operational practices, and mixes of resources able to provide these ancillary services. AS market differences lies in the approaches to energy and AS dispatch as well as operational philosophies.

The following three approaches to energy and AS dispatch have been attempted:

- Independent Merit Order Dispatch: Independent merit order based market clearing ignores the capacity coupling between energy production and supply of ancillary services. Each product is cleared separately from other products based on a separate merit order stack. This approach is simple, but it easily leads to solutions that are physically infeasible.
- Sequential Market Clearing: The sequential approach recognizes that energy and reserves compete for the same generating capacity. In essence, a priority order is defined for each product. Available capacity of a resource (e.g. generating unit) is progressively reduced as higher priority products are

dispatched from that resource. The degree of sophistication of recognizing the coupling varies from market to market.

- Joint Optimization: In the joint optimization approach, the objective is to minimize the total cost of providing ancillary services along with energy offers to meet forecast demands as well as AS requirements. The allocation of limited capacity among energy and ancillary services for a resource is determined in terms of its total cost of providing all the products relative to other resources. The effective cost for a resource to provide multiple products depends on its offer prices as well as the product substitution cost. Product substitution cost arises when a resource has to reduce its use of capacity for one product so that the capacity can be used for a different product (leading to an overall lower cost solution). The product substitution cost is determined internally as part of the joint optimization. This product substitution cost plus its bid price reflects the marginal value of a specific product on the market. The marginal value, which is typically the market clearing price, represents the price for an extra unit of the product that is consistent with the marginal pricing principle for the energy product. Joint optimization of energy and AS market has been accepted in many electricity markets, including PJM, New York and ISO-NE markets.

AS markets also differ in the time frame in which AS assignment decisions are made. In the PJM market, AS market including regulation and ten-minute spinning reserve services are operated during the time frame from two-hours to thirty-minutes ahead of real-time. At two-hours ahead of real-time, an SCUC and SCED based look-ahead analysis is conducted which projects the amount of remaining capacities available from partially loaded on-line units and the remaining transmission capabilities of critical transfer interfaces. These projected quantities are used by grid operators to determine the AS requirements for the system and import-constrained local zones. The same information also helps generators prepare for offering AS services. At thirty-minute ahead of real-time, the AS dispatch is performed based on the projected real-time grid conditions by minimizing the total cost of energy and AS bids to meet system demand, system and local AS requirements. PJM's AS market clearing is conducted ahead of real-time as a separate process from the real-time energy dispatch. This is because fast response combustion turbine generators are major resources providing the required spinning services and advance notification is considered necessary for regulation unit to prepare for regulation services. In the ISO-NE and MISO market, spinning services are mainly supplied from on-line partially loaded generators due to its existing resource mixes. As a result, ISO-NE chooses to jointly optimize energy and AS dispatches five minutes ahead of real-time in the real-time market dispatch every five minutes.

V. RISK MANAGEMENT MECHANISMS

Central market's provision of risk hedging products is another salient feature of a successful market design. In addition to FTRs, market mechanisms for risk hedging purposes offered in the PJM, ISO-NE and MISO markets includes: multi-settlement scheme, virtual bidding and bilateral contracts. They are discussed below.

A. MULTI-SETTLEMENT SCHEME

Multi-settlement market consists of a day-ahead market (DAM) and a real-time market (RTM). Day-ahead market is a financially binding forward market that allows participants to obtain price certainty for services scheduled to be delivered in real-time. A reliability commitment follows to ensure that generation resources are adequately procured to meet grid reliability needs. The real-time market settlement on real-time deviations form day-ahead schedules creates incentives for participants to follow dispatch instructions, thereby enhancing grid security and reliability.

The LMP based DAM is intended to achieve the following objectives:

- Enhance reliability: Demands are encouraged to reveal their realistic load consumptions for each hour of next day. Generators are encouraged to follow ISO's/RTO's real-time dispatch instructions.

- Provide price certainty: Energy bids/offers are settled against day-ahead LMP, which shields the participants from real-time prices to certain extent or fully if the day-ahead schedules are followed through in real-time. The FTR hedging instrument reduces exposure to congestion-incurred LMP volatility.
- Provide market liquidity: Commercial trading locations, such as hubs, zones, and aggregated price nodes, are created with requests from market participants. Compared to individual bus LMPs, LMPs at hubs, zones and aggregated price nodes are more stable, encouraging bilateral trading.

The DAM is a voluntary bid-based, financially binding forward market. DAM schedules are settled against the day-ahead LMPs and any real-time deviations from day-ahead schedules are settled against real-time LMPs using an ex post pricing algorithm.

Market participants have multiple choices to participate in the day-ahead energy market. These choices include the following.

- Internal generation: Submit energy offers indicating the price above which the generator is willing to produce. Generators may submit start-up, no load costs, min-down and min-run times for the day-ahead commitment. Generators may also self-commit or self-schedule.
- Internal Load: Submit projected fixed demand bids by LSEs (Load Serving Entity). Loads can also be price-responsive indicating their willingness to reduce consumption when market price is above its specified price.
- External resources: Offered the same choice as internal resources. They participate in the day-ahead market in the form of external transactions: spot purchases/sales, or bilateral transactions. Spot purchase and sale transactions are equivalent to the internal price-responsive loads and generators. For bilateral transactions, participants are allowed to specify a willing-to-pay congestion price above which the transaction is willing to be curtailed.
- Virtual incremental/decremental bids: Virtual bidding is important mechanisms for participants to manage their risk. These virtual energy bidding can be at any location on the system for which an LMP is computed. They are not necessarily backed up with physical resources.

Based on participants' bid/offer data, a security-constrained unit commitment (SCUC) is conducted in order to commit sufficient resources to meet the fixed demand bids and RTO/ISO-determined reserve requirements as well as reactive interface constraints. The SCUC is followed with SCED and simultaneous feasibility testing (SFT). The combination of SCED and SFT is to guarantee that hourly generation dispatch schedules are operationally N-1 secure and that LMP-based settlements are revenue adequate to honor FTR entitlements. Due to the DAM nature of financial bidding, the DAM cleared demands may be lower than the RTO/ISO projected demand conditions for next day operation. In this case, the DAM is followed with a reliability commitment through which the RTO/ISO procures additional resources in the form of incremental reserve capacities to meet RTO/ISO demand forecasts and reserve requirements by minimizing startup and no-load costs of additional physical resources.

The RTM is operated using the same SCED algorithm and the LMP method as the DAM, except that virtual bids are not allowed. The RTM includes two main functions:

- The real-time SCED computes zonal dispatch rates (energy price signals) and generator desired dispatch points (DDP);
- The ex-post LMP calculator performs the after-the-fact LMP calculations based on the zonal dispatch rates, actual transmission congestion, state estimator (SE) calibrated real-time generation outputs and generators' compliance.

The examples in Fig. 1 and 2 are used to illustrate that how the two settlement scheme provides price certainty and reliability enhancements. Assume that the results in Fig. 1 represent the DAM results and the results in Fig. 2 are what happed in real-time operation. With the multi-settlement market design, we have the following settlement results:

- For load B: Net charge=DAM_MW*DAM_LMP+ (RTM_MW-DAM_MW)*RTM_LMP=200*20+(220-200)* 100=$6000. This result indicates: (1) By scheduling 200MW load in the DAM, 91% of load B's actual demand is locked in at the DAM LMP, $20/MW. This is a huge benefit compared to the $100/MW RTM LMP. (2) Load B would have benefited more if it had increased its DAM demand bid. Loads therefore have the incentive to reveal their true demands for next day, which improves the DAM resource schedules. This outcome enhances grid reliability.
- For unit B: Net payment=Same formula as for Load B above=0*20+(10-0)*100=$1000. Even though unit B was not scheduled in the DAM, the RTM LMP is sufficiently high that it is willing to follow the dispatch instruction to meet the load increase.

The above example may be flipped that the results in Fig. 2 represent the DAM and those in Fig. 1 the RTM. We have the following settlement results:

- For load B: Net charge= 220*20+(200-220)*100=$2400. This result indicates: (1) By scheduling 220MW load in the DAM, 100% of load B's demand is locked in at the DAM LMP, $100/MW. This is a huge risk compared to the $20/MW RTM LMP. (2) Load B would have benefited more if it had decreased its DAM demand bid. Loads therefore have the incentive to reveal their true demands for next day, thereby improving the DAM resource schedules. This outcome enhances grid reliability due to improved scheduling.
- For unit B: Net payment=Same formula as for Load B above=100*10+(0-10)*20=$800. Even though unit B was scheduled at 20MW in the DAM, the RTM LMP is sufficiently low that it is willing to follow the dispatch instruction to shut itself down, which still leads to $800 revenue. This outcome creates incentive for unit to follow dispatch instructions.

B. VIRTUAL BIDDING

Virtual bidding is allowed in the DAM and it is an important mechanism for the convergence of DAM prices and RTM prices. This convergence improves not only price certainty on a forward basis, but the DAM resource schedules as well.

Assume that the results in Fig. 1 represent typical DAM bidding patterns and the results in Fig. 2 are the actual RTM results. In this case, an arbitrage opportunity exists between DAM and RTM. Since virtual bidding is permitted, participants who realize this opportunity, even though they may not have physical load at B, will be able to submit virtual decremental bids up to the DAM 10MW remaining capacity on the transmission line. Say, a participant submits a 15MW decremental bid at $50/MW. The 10MW decremental bid will be awarded. The LMPs are now $20/MW at A and $50/MW at B respectively. Apparently, the virtual bid will not consume in RTM. This means that it sells back to RTM its 10MW cleared in the DAM and receive the RTM price of $100/MW, making a profit of $500. Similar arbitrage opportunity exists when loads over-bid demand in the DAM, which encourages incremental offers that benefit from selling at DAM higher prices and buying back (virtual incremental offers do not deliver) at lower prices in RTM.

Participants' taking advantage of DAM and RTM arbitrage opportunities creates convergences of the DAM LMPs to the RTM LMPs. When DAM and RTM LMPs converges, the DAM resource schedules will better reflect the project real-time operational needs.

C. BILATERAL CONTRACTS

Bilateral contracts may be constructed as financial or physical. A financial bilateral contract provides insurance of the price for delivered electricity and it may not impact grid dispatch. A physical contract guarantees physical delivery of service at a given price. Physical delivery guarantee can be implemented by submitting self-scheduled generation and load bids to the DAM and RTM, in which case the parties are the price takers. The commonly utilized bilateral energy contracts are in the form of contract for differences. CfD can be a one-way or two-way hedge. In the one-way CfD, energy sellers provide purchaser with assurance of a certain strike price. When the market price is higher than the strike price, the sellers pay the purchasers the difference between the market and the strike price. In the two-way hedge, the purchasers also pay the sellers the price difference so that the strike price is guaranteed for both parties. While it is straightforward to utilize CfDs in a UMP market, they, along with FTRs, can also be used to an LMP market.

Assume that the load at B and the generation at A have a CfD of 200MW at a strike price of $25/MW and the load also has 200MW FTRs from A to B. The CfD strike price of $25/MW is accomplished as follows:

- Load B energy charge for 200MW: $100/MW*200MW= $20,000.
- Load B FTR credit: $(100-20)/MW*200MW=$16,000.
- Load B net charge for 200MW: $4,000.
- Generation A revenue for 200MW: $20/MW*200MW=$4000.
- Load B pay Generation A per CfD: $5/MW*200MW=$1,000.
- Load B pays net price $25/MW for 200MW and Generation A is paid $25/MW for 200MW. The CfD is accomplished.

With the use of FTR hedging against congestion prices, a physical bilateral contract can be fulfilled the same way.

V. MARKET DEMCHANISMS FOR TRANSMISSION AND GENERATION INVESTMENTS

While the LMP based market design along with FTRs and ancillary services provides the key elements necessary for secure grid operations in the short-term, the deregulated market must also maintain long-term grid reliability by encouraging timely and cost-effective investments in generation and transmission expansions.

In a perfectly competitive market, spot market short-run prices would provide sufficient incentives to signal the needs for generation or transmission investments at appropriate locations. A perfectly competitive market requires complete elasticity from both generations and loads. As price responsive loads are increasing, it is not sufficient to allow the market to discover the “true” value of electricity services. The incomplete competition of today’s market is the cause for application of bid caps in most existing markets. The existence of bid caps implies that spot market prices only are not sufficient to incur new investments or even sustain existing generation facilities.

The need for market mechanisms that can provide guidance for long-term transmission and generation expansion investments is recognized in recent years. The new market design reform efforts are developing along two paths:

- Capacity market redesign: PJM and ISO-NE is on this path.
- Energy-only market supplemented with scarcity pricing: MISO is working on this model. ERCOT will likely to pursue in the same direction.

Such market mechanisms are intended to achieve the following objectives:

- Provide additional revenues required to sustain existing capacity resources and to maintain grid reliability;
- Provide price signals that encourage long-term investments to meet projected grid reliability requirements in terms of both generation and transmission capacities;
- Reflect locational valuations by recognizing projected grid congestion.

Based on experiences with installed/unforced capacity markets, the existing capacity market mechanism is undergoing a major redesign in the US. The redesigned capacity market construct is proposed to include the following features:

- Demand curves: The demand curve is constructed in terms of projected resource requirements and the cost of adding new capacity expansion in the future. The shape of the demand curve reflects the value of capacities meeting varying levels of reliability.
- Fungibility: Locational capacity requirements must account for projected major transmission congestion.
- Reliability contribution: New capacity additions with greater contribution to maintaining reliable grid operation shall receive a higher valuation.
- Equitability for generation and transmission expansions: Generation and transmission expansions shall be treated equitably when either investment will provide the same resource adequacy.

However, it is worthwhile to note that not all potential transmission expansions can be conducted through a competitive process. Potential transmission expansions may be characterized as economic or reliability expansions. An exact delineation between economic and reliability expansion is hard to be drawn. In general, when a transmission expansion will potentially impact large number of participants in an excessive geographical region, it may better be classified as reliability expansion. It is considered appropriate that reliability expansions be handled as a coordinated planning process subject to due regulatory procedures, as this type of investments may be considered for public good. However, for economic transmission expansions, beneficiaries can be identified explicitly due to its impacts on limited number of participants within a well defined geographic area. Economic transmission expansions should be conducted using a market based mechanism.

VI. CONCLUSIONS

A successful market design starts with meeting secure real-time grid operation requirements. The SCED based real-time dispatch and its dual LMP solutions support secure and reliable grid operation. LMP based market design with primal dispatches and dual prices harmonizes the requirements for grid reliability and market efficiency. Provision of FTRs allows participants to manage congestion risks and they may also be used as means to protect transmission rights derived from transmission expansions. Joint optimization of energy and ancillary service markets makes it possible to meet demand and reserve requirements in accordance with reliability standards at least cost.

Risk management mechanisms are also necessary for a successful market design. These mechanisms used in existing markets include the multi-settlement scheme, virtual bidding and bilateral contracts. New mechanisms may be created. But addition of new mechanisms should not conflict with grid security requirements.

A successful market design must support long-term grid reliability by guaranteeing long-term resource adequacy. Similar to the AS market design, it is expected that the capacity market design details may vary from market to market due to differences in load growth, resource mixes, strategic policies on fuels and others.

A successful market design must also include an independent market monitoring unit to identify design flaws and recommend mitigation rules. Once identified, market flaws should be cured with structural solutions or behavioral mitigation measures.

VII. REFERENCES

[1] Check http://www.pjm.com for PJM market.
[2] Check http://www.iso-ne.com for ISO-NE market.
[3] Check http://www.midwestiso.org for MISO market.

VIII. BIOGRAPHY

Xingwang Ma received his B.S. from Hefei University of Technology, China and his M.S. from the Graduate School, EPRI, China in 1983 and 1985 respectively. He worked with AREVA T&D from 1996 to 2006. He founded Electricity Market Consulting Inc providing independent consulting services on the design and implementation of electricity market and market operation systems.