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Blackouts: Remedial Measures and Restoration Practices – Asian and Australian Experience

Nikolai Voropai and Tom Hammons

***Working Group on Asian and Australian Electricity Infrastructure*[1]**

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Chairs: Nikolai Voropai, Energy Systems Institute, Irkutsk, Russia
Tom Hammons, University of Glasgow, UK

Track 1: Understanding and Responding to System–Wide Events

INTRODUCTION

Bulk electric power systems (EPS) experience tens and hundreds of thousands of disturbances yearly. Relay protection and emergency control devices eliminate most of the disturbances. Failures of these devices, personnel errors and some external factors may result in a cascading development of the emergency that is normally localized and eliminated by emergency control system. The insufficient efficiency and reliability of emergency control system as well as other related reasons lead to unique severe outages – blackouts – often with catastrophic consequences for EPS and consumers.

Liberalization in the electric power industry, power supply decentralization related to the expansion of distributed generation, and EPS globalization that implies increase in the size of territories covered by the systems, change essentially the EPS properties and complicate their emergency control. As a result the operating conditions of EPS become complicated, the probability of EPS operation at low margins of transfer capabilities increases, and the area of emergency control extends to the distribution electric network, which calls for improvement and development of the emergency control principles. Therefore the factors that leads to catastrophic development of emergencies become more diverse and the probability of cascading system emergencies increases.

Each country has its own specific experience in blackouts analysis and prevention. Therefore it is important to compare and generalize this experience considering:

- Analysis of factors which lead to heavy emergencies and blackouts,
- Remedial measures to prevent heavy emergencies and blackouts,
- Restoration practices after heavy emergencies and blackouts.

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[1] Document prepared and edited by T J Hammons

The Panelists and Titles of their Presentations are:

1. Nikolai Voropai and Dmitry Efimov (Energy Systems Institute, Irkutsk, Russia). Analysis of Blackouts Development Mechanisms in Electric Power Systems (Invited Panel Presentation Summary 08GM0656)
2. Yusheng Xue (Nanjing Automation Research Institute, China). Progresses of Defense Systems Against Blackout in China (Invited Panel Presentation Summary 08GM1002)
3. Subrata Mukhopadhyay (Sys. Engg.& Tech. Dev. Division, Central Electricity Authority, Ministry of Power, Government of India), Sushil K Soonee, S R Narasimhan, and Rajiv K Porwal. An Indian Experience of Defense Against Blackouts and Restoration Mechanism Followed (Invited Panel Presentation Summary 08GM1235)
4. Yunhe Hou, Shengwei Mei, Huafeng Zhou, and Jin Zhong (The University of Hong Kong, Hong Kong). Blackout Prevention: Managing Complexity with Technology in China (Invited Panel Presentation Summary 08GM0466)
5. John Clark and Kevin Small (Transpower, Wellington, New Zealand). Enabling the Appropriate Operation Response to Power System Events (Invited Panel Presentation Summary 08GM1653)
6. Xiaoxin Zhou (Chief Engineer) and Changyou Yan (Engineer), (China Electric Power Research Institute, Beijing, China). A Blackout in Hainan Island Power System: Causes and Restoration Procedure (Invited Panel Presentation Summary r 08 GM 1085)
7. Yuri Makarov (Chief Scientist Pacific Northwest National Laboratory, USA), Nikolai Voropai and Dmitry Efimov (Energy Systems Institute, Irkutsk, Russia). Complex Emergency Control System Against Blackouts in Russia (Invited Panel Presentation Summary 08GM0645)
8. Boming Zhang, Hongbin Sun, and Wenchuan Wu (Tsinghua University, Beijing, China). A New Generation of EMS Implemented in Chinese Electric Power Control Centers (Invited Panel Presentation Summary 08 GM0787)
9. 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 Nikolai Voropai (Director, Energy Systems Institute, Irkutsk, Russia) and Tom Hammons (Chair of International Practices for Energy Development and Power Generation IEEE, University of Glasgow, UK).

Tom Hammons and Nikolai Voropai will moderate the Panel Session.

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BIOGRAPHIES

Nikolai I. Voropai, Senior Member IEEE, was born in Belarus in 1943. He graduated from the Leningrad (St. Petersburg) Polytechnic Institute in 1966. N.I. Voropai received his PhD degree from the Leningrad Polytechnic Institute in 1974 and the Doctor of Technical Sciences degree from the Siberian Energy Institute in 1990.

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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.

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1. Analysis of Blackout Development Mechanisms in Electric Power Systems

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***Abstract* —** The paper suggests a-formalized technology for the analysis of developing emergency processes of a cascade character in electric power systems. The technology is based on classification of events and states in the system those are caused by these processes and determination of interrelations between them. The technology of analysis is illustrated on the example of analysis of two system emergencies.

***Index Terms* —** electric power system, cascade system emergency, mechanisms of development, technology of analysis.

1. Introduction

Bulk electric power systems (EPS) experience tens of thousands of disturbances yearly. Most of the disturbances are eliminated by relay protection (RP) and emergency control (EC) devices and normally are practically unnoticeable to consumers. Failures of these devices, personnel errors and some other external factors may result in a cascading development of the emergency that is localized and eliminated by emergency control system of a higher level. Here the EC action disconnects EPS elements, divides EPS into isolated subsystems and disconnects secondary consumers. These events do not lead to severe consequences for the system and consumers, and usually EPS is restored quite fast. However, the insufficient efficiency and reliability of EC as well as other related reasons lead to unique severe blackouts, often with catastrophic consequences for EPS and consumers (similar to the 2003 blackouts in North America and Europe and 2005 blackout in Moscow) [1].

Cascading emergencies in EPS are associated with system survivability which is defined as the ability of a system to resist disturbances not allowing their cascading development with severe disturbance of power supply to consumers [2]. Catastrophic development of emergency situation may take place due to the marginal state of EPS. This marginal state is determined by unacceptable values of system's operating parameters and unacceptable decrease in power supply to consumers [3]. In [4] the authors use an alternative notion – EPS vulnerability. In fact while survivability is an internal ability of the system and supposes some certain "activity" of the system in the sense of resistance to cascading emergency, vulnerability is a kind of "passive" attribute of the system.

Development of system emergencies in EPS has been systematically analyzed since the beginning of the 1960s. Gradually the events and states that occurred in the course of a cascading development of emergencies were classified, and schemes of occurrence and development of cascading emergencies were formed [1, 5-7, etc.]. In the 1970-1980s a systematic work was performed to analyze system blackouts in the Unified Energy System of the USSR [5, 8, etc.]. Similar analysis was carried out in other countries as

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well, and for some particularly large emergencies the processes of their development were modeled [9, 10, etc.]. Principal progress in understanding the mechanisms of development of cascading system emergencies was made after introduction of the notions “marginal state” and “triggering event”. The latter “triggers” an irreversible development of emergency situation [1, 6]. In fact triggering event takes place near the marginal state of the EPS.

The necessity to analyze the mechanisms of cascading blackouts is obvious. Along with specific pragmatic interest in the reasons and factors that lead to a catastrophic development of a certain emergency situation, knowing which it is possible to determine “bottlenecks” in the system and then eliminate them, generalization of system emergency development mechanisms allows one to make an attempt to reveal potentially possible ways of development of emergency processes by their modeling. Development of such models is extremely topical to reveal “bottlenecks” in electric power system that are potentially dangerous from the view point of a cascading development of emergency situation, upgrading the structure and setting of the emergency control system, etc. The attempts to construct such models have been made [11, 12, etc.].

Based on the previous studies the paper presents a formalized technique for analysis of cascading emergency processes in the bulk EPS. The technique is based on the classification of EPS states and events that stimulate transition from one state to another. Some stages of the analysis are exemplified by the states and events of some known blackouts. The suggested technique is used to describe two domestic system blackouts – the May 2005 Moscow blackout and the May 1975 blackout in the interconnected power system of North Kazakhstan.

2. SEQUENCES AND QUALITATIVE CLASSIFICATION OF EVENTS

A great number of events that differ in origin, qualitative and quantitative characteristics occur during EPS operation.

Conducting a retrospective analysis of the emergency situations normally we distinguish from the whole number of the events that occurred in the EPS some time sequence (a “chain”) of only those events that strongly affected the occurrence and development of the emergency situation.

This section presents some definitions. On the basis of these definitions all possible events can be divided into three groups according to their qualitative composition. Further these groups are described and their interrelation is generalized.

2.1 Definitions

Let us define the process of redistribution of active and reactive power flows in the network, which is directly and indirectly related to the change in the nodal voltages, and frequency of EPS as a “change in the EPS state”.

Introduce three gradations from the viewpoint of risk of emergency development of the change in EPS state:

- A negative change (deterioration) of state which implies decrease in the transfer capability margins of the main network and generation capacity reserves;
- A positive change (improvement) of the state which implies an increase in the transfer capability margins and increase in the generation capacity reserves;
- Imperceptible change (negligible) which means a minor change in the margins and reserves.

By the event we will understand the reason causing or hindering the change in the EPS state.

Each event will be assigned to three characteristics:

- A probability of the event occurrence;

- Direction of the event toward deterioration or improvement of the EPS state (to a negative or positive change in the EPS state);
- System effect of the event (the extent of its influence on the EPS state), – i.e. a quantitative measure of change in the EPS state under the influence of the event.

  Based on the above definitions all events taking place in EPS can be divided into three groups.

2.2 Group I: Accidental events

Let accidental events include the following:

- *Disturbances* – first of all transmission line short circuits, open-circuit faults, unplanned switching of EPS elements and drop/surge of load/generation. *Disturbance causes occasional change in the EPS state*.
- *Wrong actions* – i.e. false operation of RP and EC or wrong actions of personnel. *Wrong action causes deterioration* in the EPS state.
- *Faults* – i.e. nonoperation of RP and EC or personnel's failure to take necessary actions to change EPS state. Fault hinders change in the EPS state toward which a control action is directed.

Accidental event corresponds directly to a specific (generating, load or transmitting) element in EPS and leads to the change in its capacity – this is the way the local effect of the event manifests itself. Accidental event corresponds indirectly (via event of group III) to a change in the state of the entire EPS – which is manifestation of the system effect of the event.

2.3 Group II: Control actions (purposeful events)

These include correct and successful control actions at a planned change in the EPS state or in response to the events of groups I and III that improve the EPS state. Control actions are performed by RP and EC systems and by personnel by switching specific generating, load and transmitting elements of EPS – this is a local effect of the event (change in the capacity of an element). As well as an accidental event a control action corresponds indirectly (via event of group III) to a change in the state of the entire EPS. This is manifestation of its system effect.

2.4 Group III: Regular (natural) events

Regular (natural) events include actions of physical laws in EPS that manifest themselves in the form of its natural reaction to a set of all previous events. Regular events may *deteriorate and improve the EPS state*, as well as cause imperceptible (negligible) change in its state. An example of the local effect of the natural event is contingency of a line; an example of its system effect is changes in the voltages in EPS nodes.

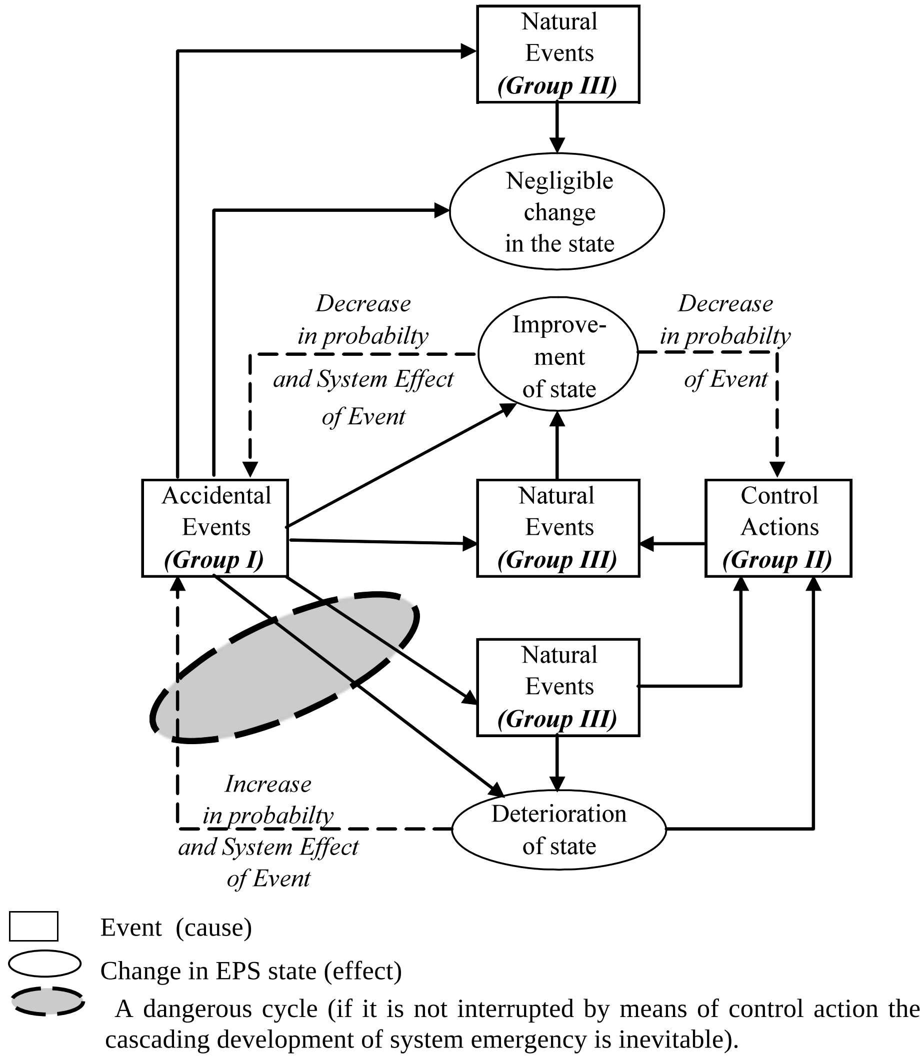

Fig. 1. Cause and effect relations between events and changes in the EPS state:

2.5 Generalization

Cause and effect relations of the above-described three groups of events are schematically shown in Fig.1.

Let us note that while the events of groups I and II affect individual elements in EPS the events of group III are a reaction of the entire system to these effects.

The events of the first two groups always cause the event of group III that are a direct cause of change in the EPS state. Thus the system effect of the event is caused by the event of group III.

The probability and system effect of the event are the values depending on the previous events, first of all on the events of group III that deteriorate the EPS state. These events cause:

- First, an increase in the probability of the events of group I (for example the probability of short circuit in the congested transmission line is essentially higher than in the transmission line operating with normal or lower load).
- Second, strengthening of a negative system effect of the events of group I (for example accidental redistribution of power flows in the operating conditions with a “large” load will cause larger overloading of a transmission line than similar redistribution in the operating conditions with a “lower” load).

The figure shows that the most dangerous (potentially deteriorating EPS state to a largest extent, i.e. increasing the risk of emergency) is combination of events of group I and group III that deteriorate EPS state. It is precisely this combination that makes possible a cause-effect cycle of events, which is a process of cascading deterioration of EPS state in time, i.e. a cascading development of emergency.

Occurrence of such a "dangerous cycle" means that the sequence of events at some instant of operation leads EPS to some marginal state where the next event becomes triggering, i.e. the event that triggers uncontrolled cascading process of further events (first of all, disconnection of EPS elements) with catastrophic consequences which is a blackout.

Thus, the triggering event divides the emergency development period into two parts: accumulation of events (not necessarily leading to a cascading emergency) and a sequence (chain) of events related to irreversible development of emergency [13].

3. A Generalized Scenario of Cascading Disturbances

Based on the analysis of sequences of events at development of system emergencies that have occurred in the past years in power systems of different countries we can suggest a generalized scenario of a cascading process of emergency development that contains cyclically repeating changes in the EPS state (Fig.2).

Below are short explanations to each of the states indicated in the figure and transitions between them. The data on recent emergencies in power systems of the world that are used as examples relate to the following blackouts and references:

- *The Italian blackout* – the September 28 2003 blackout in the power system of Italia [14, 15];
- *The American blackout* – the August 14 2003 blackout in the power system of the USA and Canada [16, 17];
- *The Scandinavian blackout* – the September 23 2003 blackout in the EPS of Southern Sweden and Western Denmark [18, 19];
- *Moscow blackout* – the May 24-25 2005 blackout in Moscow energy pool [20].

3.1 Normal (pre-emergency) or acceptable (after successful control actions) state of a system

In these state the operating parameters of EPS lie within acceptable limits. At the same time noticeable deviations of parameters were observed during the recent blackouts. They were not emergency but potentially weakened the system. These deviations were:

- *For the American blackout* – high power consumption, large power flows, decreased voltages and changes in frequency;
- *For the Italian blackout* – unplanned exceeding of the power flow from Switzerland to Italy;
- *For Moscow blackout* – higher electricity consumption (by coolers) due to unusually hot weather.

Besides in the American and Italian cases on the day of emergency some generators and/or transmission lines equipment were under planned repair.

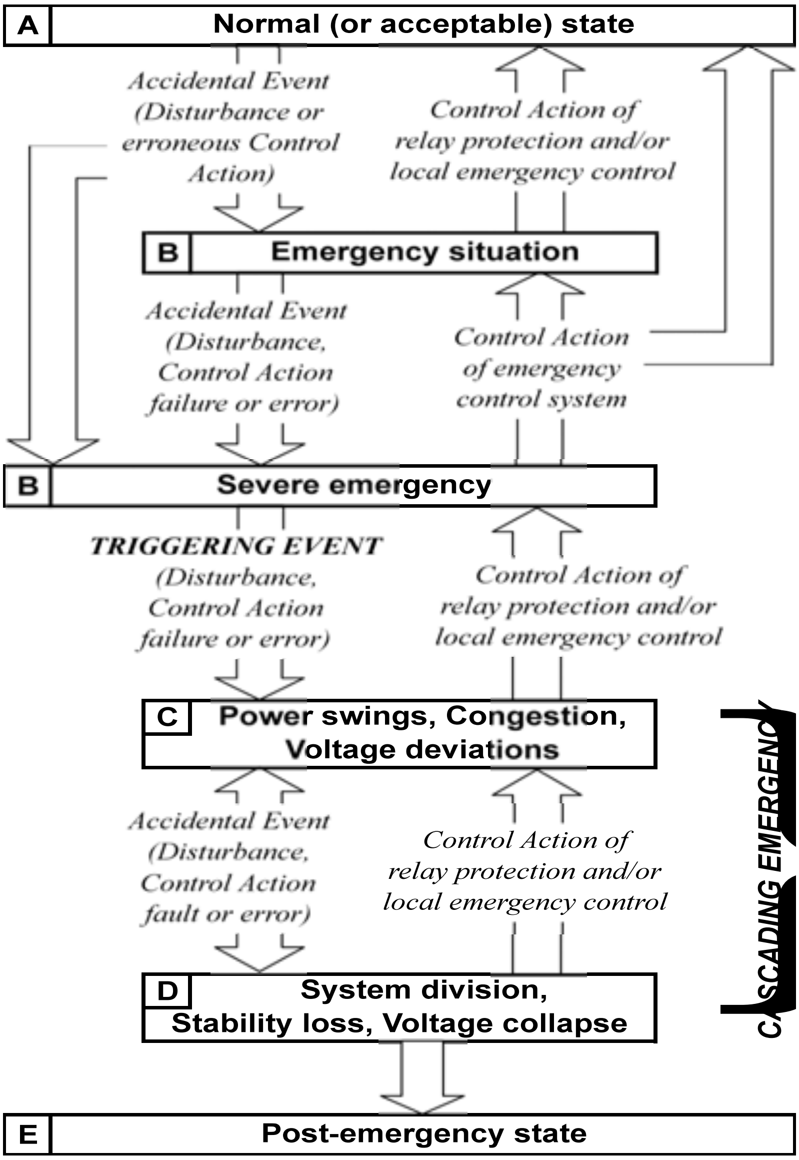

Fig. 2. A generalized scenario of cascading development of emergency

3.2 Emergency situation

Before the emergency power systems were additionally weakened by some events, namely:

- *For the American blackout* – disconnection of transmission lines in Indiana, energy unit at the Eastlake -5 power plant and 345 kV transmission line Stuart – Atlanta in Ohio;
- *For the Scandinavian blackout* – disconnection of a unit at the Oskarshamn nuclear power plant;
- *For the Italian blackout* – disconnection of the 380 kV transmission line Mettlen-Lavorgo in Switzerland;
- *For Moscow blackout* – operation of the Chagino substation at a lower capacity due to emergency repairs of the main equipment.

At a certain moment of emergency situation development a *triggering event* occurred. For the blackouts at issue these events were:

- *For the American blackout* – disconnection of the 345 kV line Harding-Chamberlin in Ohio;
- *For the Scandinavian blackout* – disconnection of two bus bars at the 400 kV Horred substation;
- *For the Italian blackout* – tripping of the transmission line Silz-Soazza;
- *For Moscow blackout* – disconnection of transmission lines going from the Ochakovo substation.

Triggering event separates the period of accumulating multiple “indirect” (not causing directly the emergency) factors from the sequence of events that represent the course of emergency and have a direct cause-effect relation with subsequent phases of emergency. At the initial stages the cascading process develops relatively slowly and accelerates in the course of emergency.

3.3 Critical state of a system: large power and voltage fluctuations, congestion of transmission line

Triggering event and subsequent events of a cascading development of emergency cause considerable fluctuations of power transmitted along the lines, congestion of the lines and voltage problems. This, in turn, causes further emergency sequence events (including deviation of frequency at subsequent stages of the emergency unfolding).

Relay protection devices act both indirectly (at high power flow or low voltages due to short circuit) and directly – when the problems in the system result in real short circuits or instability. Relay protection isolates an element (or a group of elements) of the system from the remaining part (for example, trips lines, transformers, generators). This process may be accompanied by some load losses, which, in turn, again causes power swings, congestions, voltage problems, etc.

3.4. Division of system, instability, voltage collapse

At further stages of emergency development process there can be uncontrolled division of system, loss of dynamic stability and voltage collapse. As a result a considerable share of load can be lost.

3.5 Post-emergency state

Passing through the series of subsequent phases of development the emergency process finishes with some post-emergency state. This state is a starting point for the process of system restoration.

4. THE 2005 MOSCOW BLACKOUT

The presented approach to the analysis of emergencies development was exemplified by a sequence of events during the May 2005 blackout in Moscow EPS [20]. Detailed analysis is available in [13]. We describe below only the some points of the study.

After disconnection of the 220 kV overhead transmission line Kedrovo–Ochakovo due to short circuit, the situation became uncontrolled since the rate of event occurrence increased substantially and there was no time to make and realize decisions by both the operator and the personnel of energy entities. Thus, the mentioned short circuit was a triggering event, i.e. an event that initiated cascading emergency development.

After the triggering event, both the total disconnection of elements and the share of disconnection of generating equipment grew dramatically. In the aggregate these factors resulted in blackout of a considerable part of the Moscow, Tula, Kaluga and Ryazan EPSs.

The considered emergency development as a sequence of emergency events vividly illustrates that the increasing network overloads lead to essential growth of the probability of random events (first of all – short circuits), which should be taken into consideration at modeling and studying this stage of the process.

5. EMERGENCY IN THE IPS OF NORTH KAZAKHSTAN IN 1975

The system emergency in the interconnected power system (IPS) of North Kazakhstan on May 31, 1975 led to isolation of the Altai, Pavlodar, Tselinograd and Karaganda EPSs and violation of its parallel operation with the IPS of Ural and blackout of the Ermakovskaya condensing power plant (CPP) and the Pavlodar cogeneration plants (CP) #2 and #3. Power undersupply therewith amounted to 2.5 million kWh.

In 1975 the IPS of North Kazakhstan had the lowest stability level in comparison with all IPSs of the Soviet Union and constantly operated in a state close to emergency situation. It was seen from the facts that:

- Power from the Ermakovskaya CPP (amounting to more than 30% of the IPS power) was transmitted by weak ties.
- The automatic and emergency control system was in its infancy, i.e. was introduced in insufficient scale and without coordination of work of its individual parts.

Hence, any rather strong disturbance (such as tripping of any of the overhead transmission lines Ermakovskaya CPP – Altai, Tselinograd – Karaganda, Tselinograd – Kustanai, etc.) would lead to IPS instability.

The single-phase short circuit on the 220 kV overhead transmission line Ermakovskaya CPP – Rubtsovsk at 5:05 a.m. (local time) on May 31, 1975 was a triggering event for the cascading emergency. The sequence of events from the triggering one at the IPS to its blackout is shown in Figs. 3 and 4.

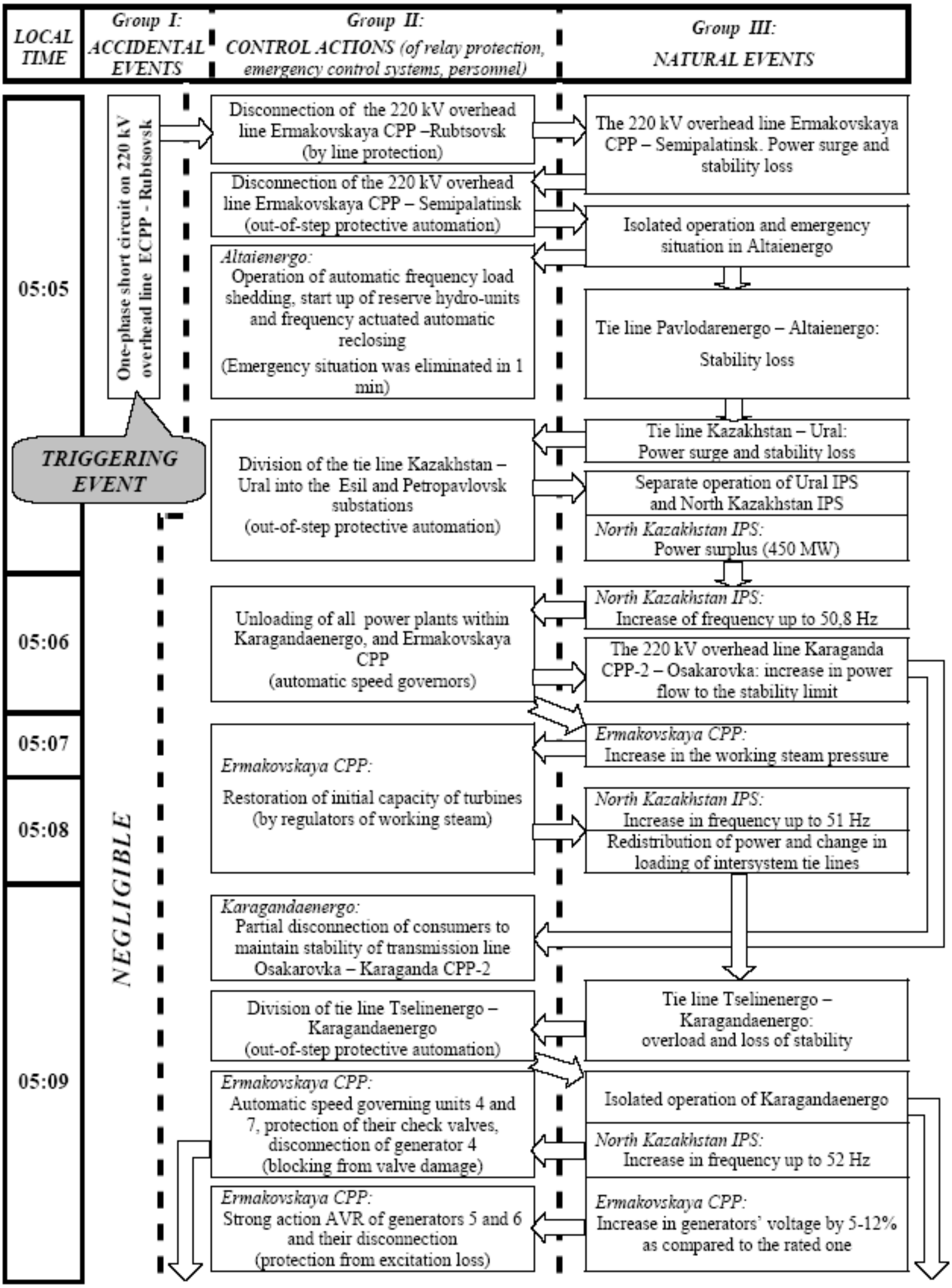

Fig. 3. Emergency in the IPS of North Kazakhstan on May 31, 1975: Beginning of the events.

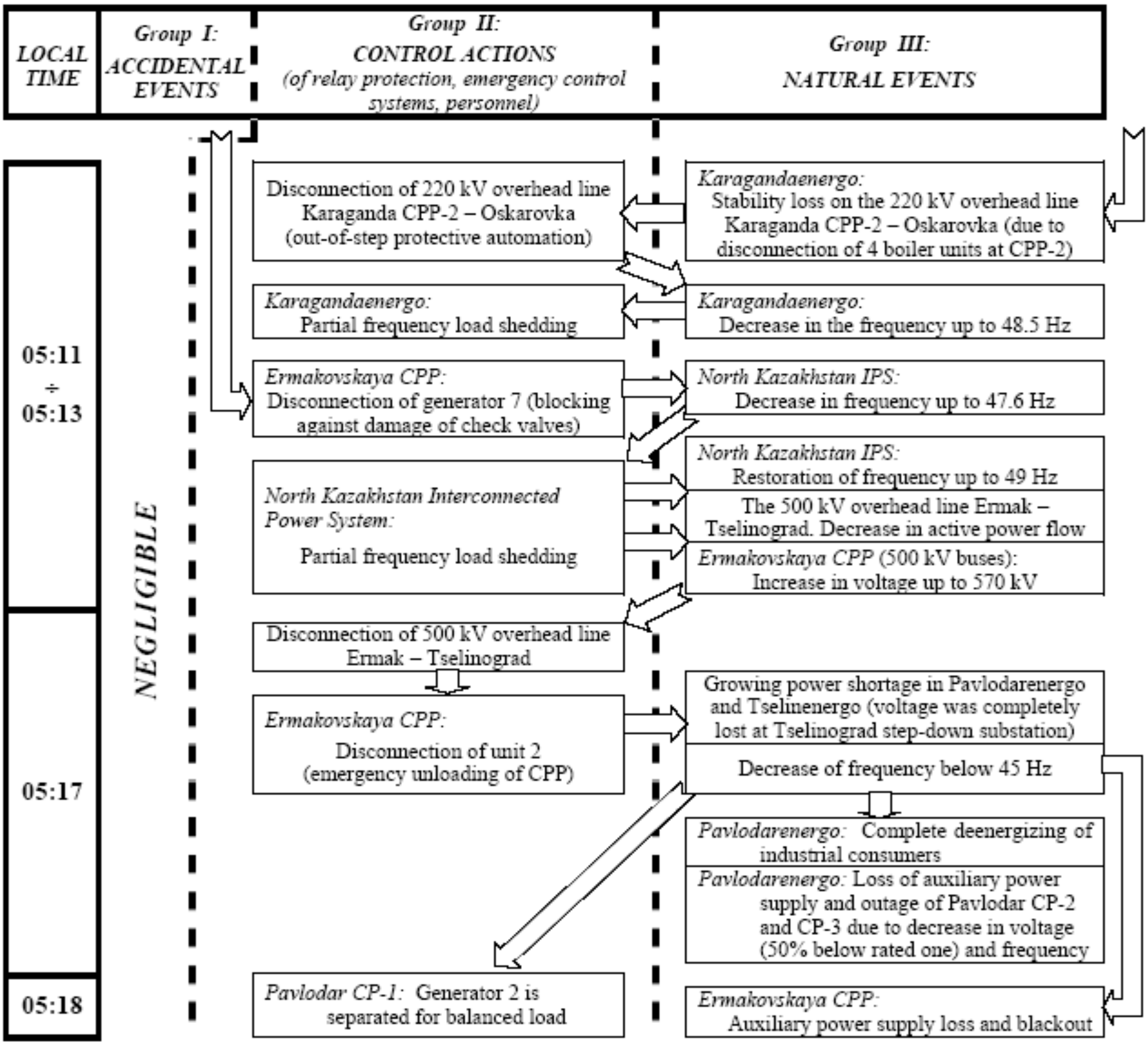

Fig. 4. Emergency in the IPS of North Kazakhstan on May 31, 1975: Blackout.

Non-coordinated actions of automatic devices at the plant became apparent especially from the fact that with the frequency rise in the IPS the speed governors of the Ermakovskaya CPP closed steam-in gates and the pressure regulators of working steam opened them again. As a result the plant was not practically unloaded and later two generators were disconnected. In so doing the plant's personnel either did not know other ("manual") methods of unloading the units or did not dare to use them, since these methods were not given in local regulations.

The absence of coordination in control and protection systems on generators of the Ermakovskaya CPP also influenced the work of voltage regulators, namely instead of limiting the minimum excitation, protection from excitation loss actuated, and as a result two units were disconnected (Fig. 3).

Because of absence of the reactor (was under repair) on the 500 kV line Ermak – Tselinograd and weak regulating capabilities of the operating units at the Ermakovskaya CPP the voltage rise in the network was not terminated, thus causing the mentioned line tripping and subsequent tripping right up to the blackout of the whole IPS (Fig. 4).

6. CONCLUSION

The presented technology for the analysis of mechanisms of system emergency development reflects adequately enough real events, states and processes in EPSs that occur at cascading emergency development. Efficiency of the proposed technology was demonstrated on the examples of blackouts of the Moscow EPS in 2005 and the IPS of North Kazakhstan in 1975. The structured information about these blackouts in itself is a contribution into emergency development statistics.

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8. Biographies

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2. Progresses of Defense Systems Against Blackout in China

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***Abstract* —** This paper investigates Chinese standards for power system security and the practices in the relevant strategy. Considering the cascading features of typical system-wide blackouts around the world, further emphasis is given to integration of various wide area measurements, trajectory-based knowledge extracting, on-line quantitative security analysis, and adaptive optimization of preventive control, emergency control, corrective control and recovery control, in order to upgrade the three-defense-line to an adaptive space-time cooperative framework. Functions, features and engineering experiences of such a framework in China are reported.

***Index Terms* —** blackouts defending, cooperative defense framework, quantitative stability analysis, adaptive optimal stability controls, developments and applications.

1. INTRODUCTION

With rapid growth of loads, transmission distances, HVDC and FACTS equipments in China, the dynamic behaviors of power systems are getting more and more complicated. Market-driven environment further highlights requirements for optimal operation and coordinative control.

A single fault is unlikely to destroy a modern power system, but information deficiency, hidden failures of protection relays, faults of other secondary automation systems or mistakes of human actions can bring about new disturbances. Under the strike of a series of cascading events, a system, however strong, may evolve into power calamity.

Cascading outages may happen between AC lines, between DC lines, between DC and AC lines, and between the sending area and receiving area. Its evolvement process can be divided into some of the five stages, namely a slow cascading outage stage, a fast cascading outage stage, a short stage of oscillation, a breakdown stage and a long stage of restoration.

How to hold out the disaster at each of the evolvement stages? This question has drawn wide attention in global defense frameworks [1-8].

Based on the lessons of many blackout disasters, it has been suggested that such a defense framework should advance the SCADA/EMS systems to dynamic category, realize on-line quantitative stability analysis and decision making, realize adaptive optimization of preventive control (PC), protection relays, emergency control (EC), corrective control (CC) and recovery control (RC) respectively, and coordinate them based on the concept of risk [9].

The so-called Wide Area Monitoring Analysis Protection-control, WARMAP for short, system is just such a space-time cooperative defense framework developed by Nanjing Automation Research Institute (NARI), China. It has been

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implemented and put into daily services in several power grids in China, and many other engineering projects are on the way.

Many essential techniques required by a WARMAP system, for example on-line pre-decision making technique for PC and adaptive optimization technique for EC, had already accumulated valuable experiences through engineering applications. This founded a strong base for WARMAP.

This paper reviews traditional techniques for stability analysis and control; reports the new techniques, especially the WARMAP system, and their applications in China.

2. TRADITIONAL STABILITY TECHNIQUES

2.1 A. Three-defense-line for Power Systems in China

The following actions can be used to defend blackouts: (1) PC actions shifting the operating point towards the stability domain, (2) Protection relays removing faulted elements, (3) EC actions switching on/off equipments immediately after detecting a preassigned fault, (4) CC actions such as out-of-step protection and load shedding; (5) RC actions to restore the supply of the shed loads. Reference [10] compares the characteristics of control laws of various stability controls.

The three-defense-line criterion has been a well-established security standard for power system planning and operation in China [11]. The first defense line consists of PC, grid strengthening (i.e. long-term PC) and protection relays to ensure system stability without load interruption under a non-severe contingency. The second defense line is armed with EC for severe contingencies. The third defense line is equipped with local EC for extremely severe contingencies.

Although having successfully avoided system-wide blackouts in the relatively weak grids of 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 operation.

2.2 . Current Techniques for Stability Analysis and Control

PC and EC have to apply predictive rules, which were stored in decision tables in an EMS or a special protection system (or called as system protection scheme, SPS for short). Because of its explosive combinations of operating conditions and cascading events, the traditional fashion of off-line pre-decision for setting up the tables is becoming a bottleneck. For modern power grids, on-line pre-decision should be adopted. Moreover, the pre-decision nowadays is based on some exhaustive trial-and-error fashions. Obviously, this is unacceptable for applying the concepts of adaptation, optimization, coordination or risk management.

3. NEW TECHNIQUES AND APPLICATIONS

3.1. The Unique Method for Quantitative Stability Analysis

Extended Equal Area Criterion (EEAC) performs numerical integration to the full models as detailed as preferred, and then maps the resultant trajectory into a set of time-varying one-machine infinite-bus planes. The stability analysis can be quantitatively performed for the image OMIB systems with time-varying parameters. The stability control decision can be optimized with the sensitivity analysis technology. The rigorous proof can be found in Ref. [12].

3.2 Adaptive Optimization of PC

Advanced on-line transient stability assessment functions in Guangxi Grid's EMS have been put into normal operation service to support PC since Sept. 2003. The most important techniques are the assessment of stability margin and the decision-making fashion of "on-line pre-decision, real time matching" [13].

3.3 Adaptive Optimization of EC

An adaptive EC scheme was proposed to automatically refresh the decision table in a quasi-real-time fashion [14]. It 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.

3.4 Adaptive Optimization of CC

The optimization of low voltage (frequency) load shedding includes placement, set points and activation time [15]. The set points optimization has been successfully applied to Liaoning Grid, Northwest Grid, Sichuan Grid, etc. The placement optimization has been also applied to Jiangsu Grid, etc.

Research projects on intelligent out-of-step protection are under way [16].

3.5 Coordination of PC and EC

An optimization method for coordinating PC and EC was proposed [17], where the task is formulated as a nonlinear hybrid-programming problem with both discrete and continuous control variables. The objective function is the sum of the daily cost for PC and the probability-weighted cost for EC.

4. THE WARMAP FRAMEWORK [18]

4.1 Three Essentials of the Integrative Defense Framework

Three essentials for effectively preventing blackouts are: wide-area static and dynamic measurements, quantitative analysis of security and stability, optimization and coordination of the controls.

WARMAP integrates and coordinates wide-area data, which are of widely different time scales, including static data from SCADA systems, real-time dynamic data from PMU/WAMS, transient data from fault recorders and data from stability control devices etc.

PMU data should be put in order with the unified timestamps to form the swing curve; however this information is not easy to be understood by engineers.

WARMAP upgrades the information to the knowledge (understanding) level, even to the wisdom (decision-support) level (Fig.1). Its functions include on-line quantitative stability analysis and pre-decision, based on risk concepts, adaptive optimization of PC, EC, CC and RC, coordination among various defense lines, and that between security and economy.

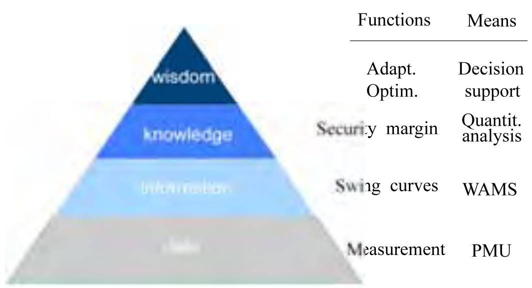

Fig.1. Not only data and information, but also knowledge, even wisdom are required

4.2 An Integrative Information Platform

In order to assess transient security and stability in an on-line fashion, it is required to build a unified open platform and integrate all wide area data and simulation results.

Simulation is indispensable for investigating a postulated contingency and assessing the effects of assumed control actions.

4.3 An Integrative Analysis Platform

The analysis sub-system should realize the following functions (see Fig.2): (1) direct analysis of static SCADA data and dynamic PMU data, 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 suppression 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.

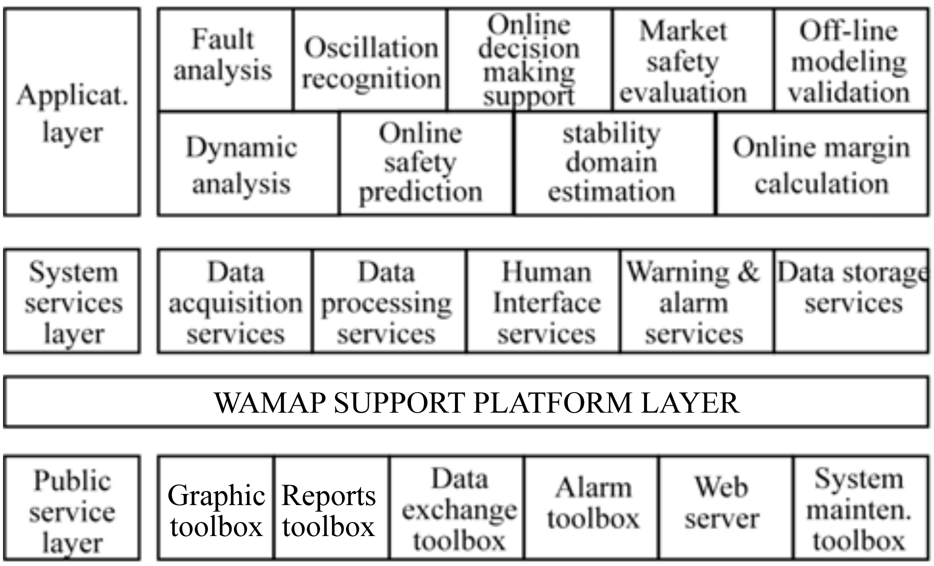

Fig. 2. Software configuration of WARMAP

4.4 An Integrative Decision-making Platform

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

4.5 WARMAP System

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.

WARMAP upgrades the relevant techniques from static category to dynamic one, from qualitative to quantitative, from offline to on-line, from typical-case-based to adaptive, from conservative to optimal, from certainty-based to risk-oriented, and from isolated to cooperative.

Combining with model-based simulations, WARMAP coordinates different defense-lines in a global viewpoint, coordinates system 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.

WARMAP system offers early warning, supports on-line decision making and integrates various defense-lines, based on dynamic, adaptive, quantitative, optimal, risk-oriented and coordinative views.

5. QUANTITATIVE ANALYSIS

A very small shift in a parameter space can make a stable case unstable if the original condition is close enough to the stability boundary. However, numerical integration methods cannot distinguish this very marginal stable case from rather stable cases. Moreover, sensitivity analyses have to be based on reasonable index and the critical mode has to be correctly identified.

Therefore, margins for angle, voltage and frequency stabilities, which are basis for optimization and coordination, are valuable information.

Stability domain in the power-injection space might be the most straight foreword knowledge on transient stability. Afterwards, load limits and interface flow limits etc. can be easily obtained via load flow. Both dangerous and safe reloading directions can be identified.

Supported by a quantitative stability analysis method, a novel optimization algorithm and distributed parallel processing, WARMAP can periodically refresh the decision tables in a sub-real-time fashion.

Sensitivity analysis can directly estimate the limits of certain parameters instead of exhausted try-and-error. This property is also very important for on-line assessment and tracking system changes (Fig.3).

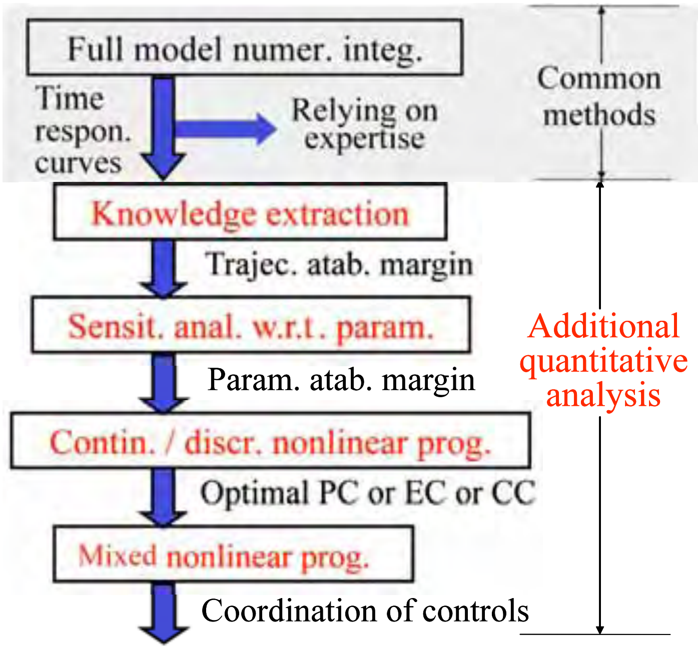

Fig. 3. Quantitative algorithms are one of the essentials of WARMAP

6. MULTIFOLD COORDINATION

WARMAP fulfills integration and coordination in many aspects, such as data of different time scales, communication networks, control equipments, secondary systems, analysis functions, decision and control, display.

6.1 Coordination of Wide-area Information

As a wide-area measurement based defense scheme, WARMAP integrates information acquired by using RTU, PMU, fault recorder and protections and information resulting from model-based simulations. Then, profound knowledge on system's dynamic characteristics, which is the basis for both adaptive optimization and coordination, can be extracted from the time response curves. The information platform is seamless (Fig. 4 and 5).

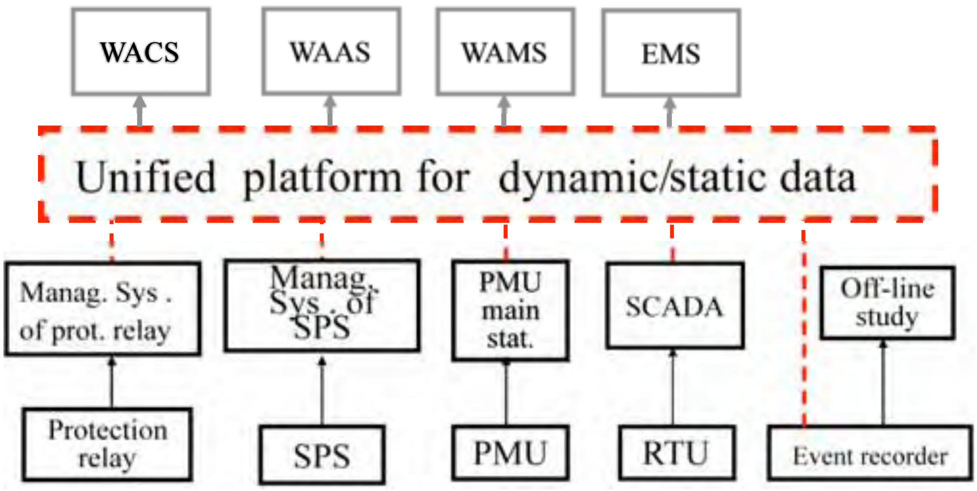

Fig. 4. Unified platform for transient-dynamic-static data

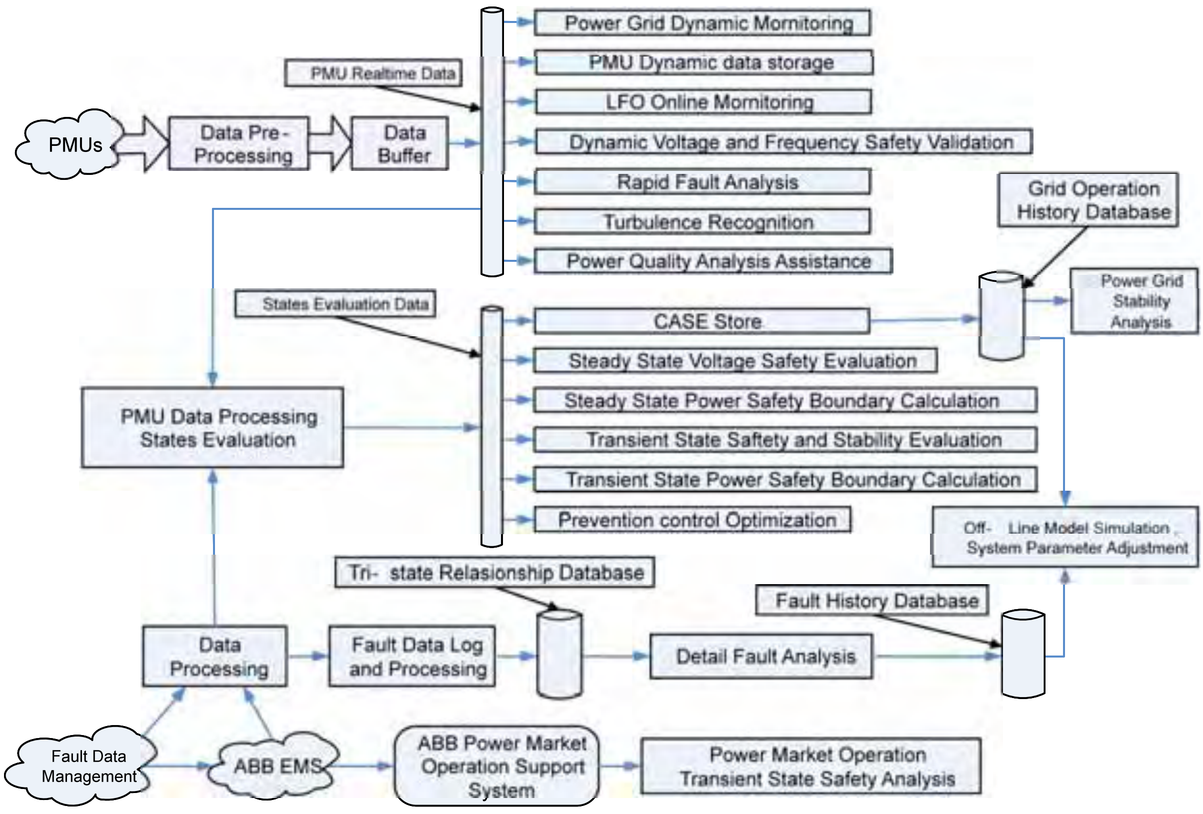

Fig. 5. Data flow of WARMAP

6.2 Coordination of Various Stabilities

Angle, amplitude and frequency are three essentials of AC voltage (or current and power). At present, they are studied separately and most of tools cannot tell the distance to the stability limits.

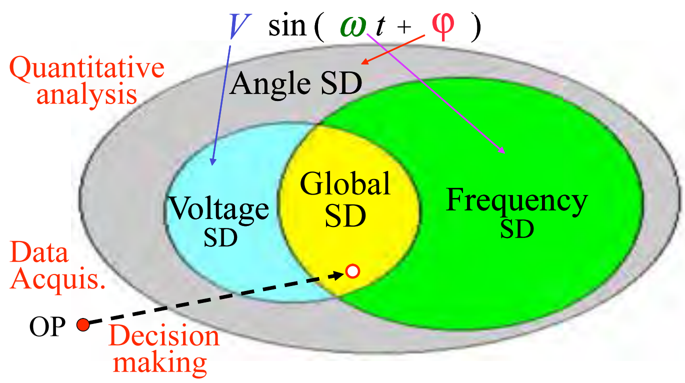

Fig. 6. The global stability domain

WARMAP integrates the above dynamic stability problems with the thermal one to identify the global stability domain (SD), see Fig. 6.

6.3 Coordination of Decision Space

If faults occur at 2 areas corresponding to different control stations, every original SPS can only react to one fault and disregard others. Therefore, the interaction between the faults cannot be considered.

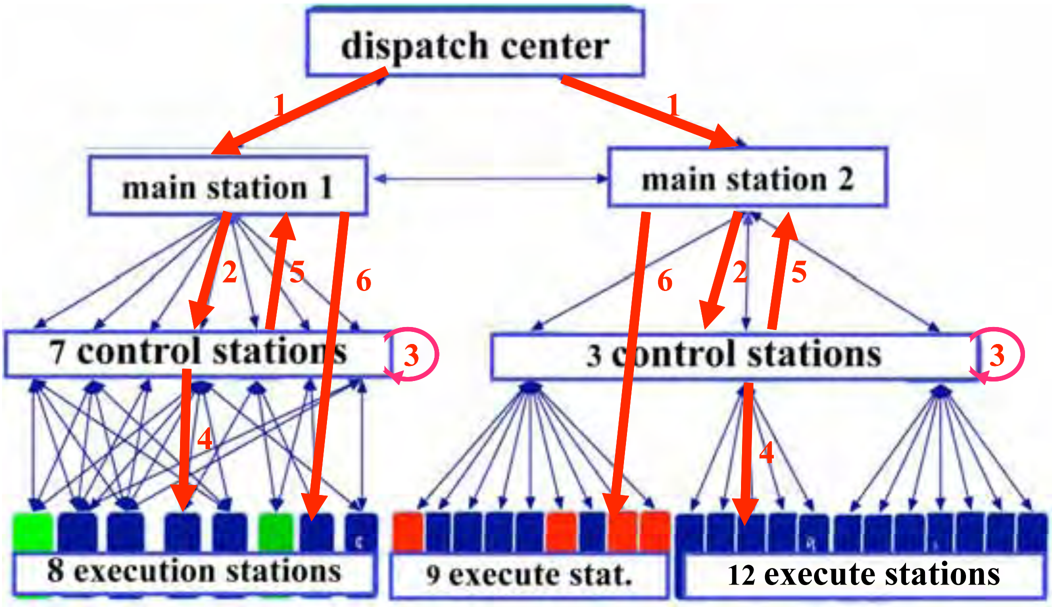

Fig. 7. The coordination of EC in Jiangsu Grid

WARMAP overcomes such limitation by exchanging information between main stations. Fig.7 shows the actual scheme, which has been serving well in Jingsu Power Grid.

6.4 Coordination of Activation Time

During the evolvement of a blackout, control actions can be activated at different stages to hold out blackouts. (1) Before contingency occurrence, PC actions can be activated. (2) After the occurrence of a contingency, the faulted equipment should be removed selectively as well as quickly. (3). After identifying preassigned faults, EC actions can be performed. (4) Once insecure dynamic behaviors are detected, CC actions can be taken to prevent the expansion of the blackout area (5). After a blackout, RC actions should be taken to restore the supply of shed loads.

These controls have different physical features, as well as different cost property. Moreover, they interacted with each other closely (Fig. 8) therefore coordination is helpful.

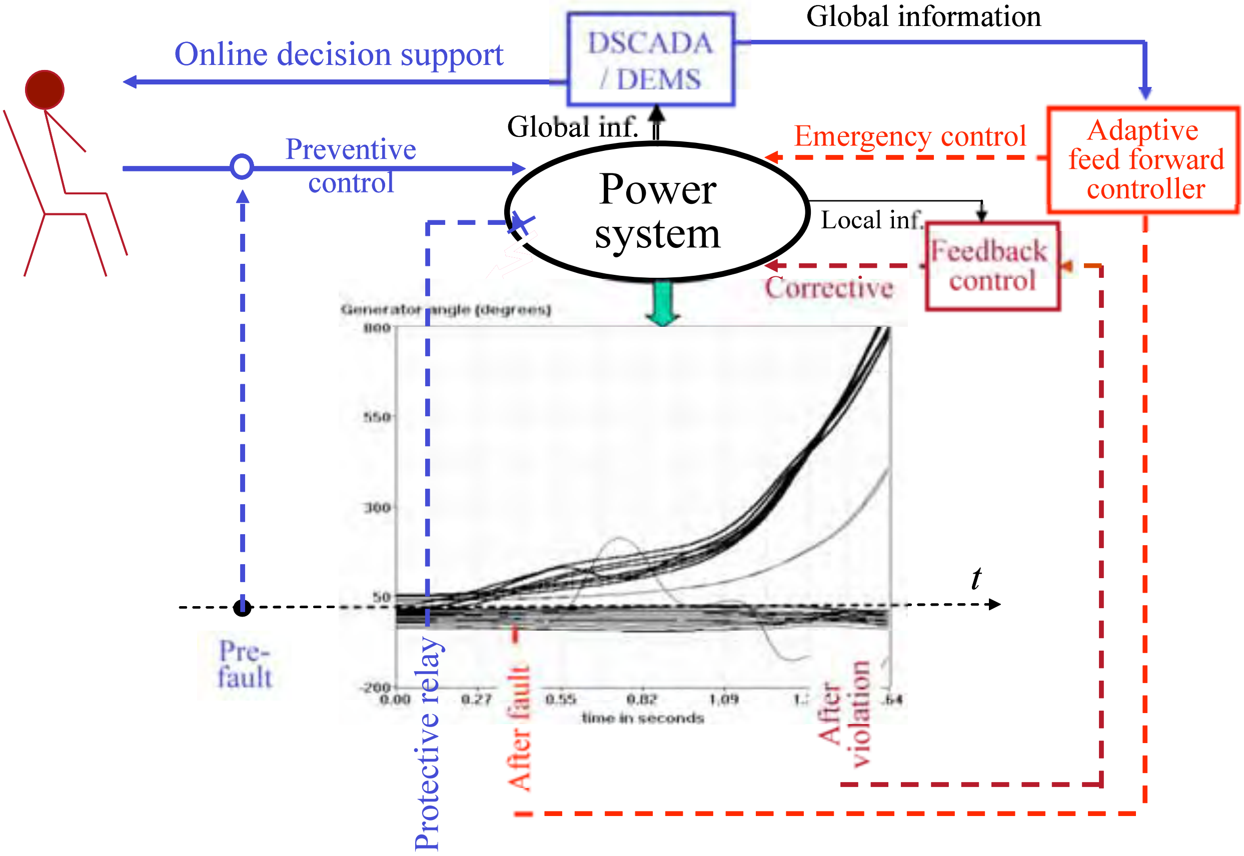

Fig. 8. The coordination of control time

6.5 Coordination of Various Control Rules

PC affects the dynamics from the beginning of a fault, thus fully uses activation period. However, it is not applicable for PC if generation reserve is not sufficient. Moreover, it cannot secure the system alone if different contingencies ask for contradictive actions. PC actions are open-loop control issued by experienced operators (Fig.9).

EC is close-loop feed-forward control. The later the control action is taken, the worse the control effect will be. Without increasing the system's normal operating cost, EC can raise the transmission capacity. Since emergency actions are activated only for a short period of time just after the occurrence of a specific contingency, the problem of contradiction between different contingencies are not serious.

CC is initiated by power system dynamics and applies feedback control rules, such as multi-stage load shedding, to improve the precision of control.

WARMAP lays a foundation for further coordinating the PC in a continuous space with contingency-specified EC and dynamics-driven CC in a discrete space.

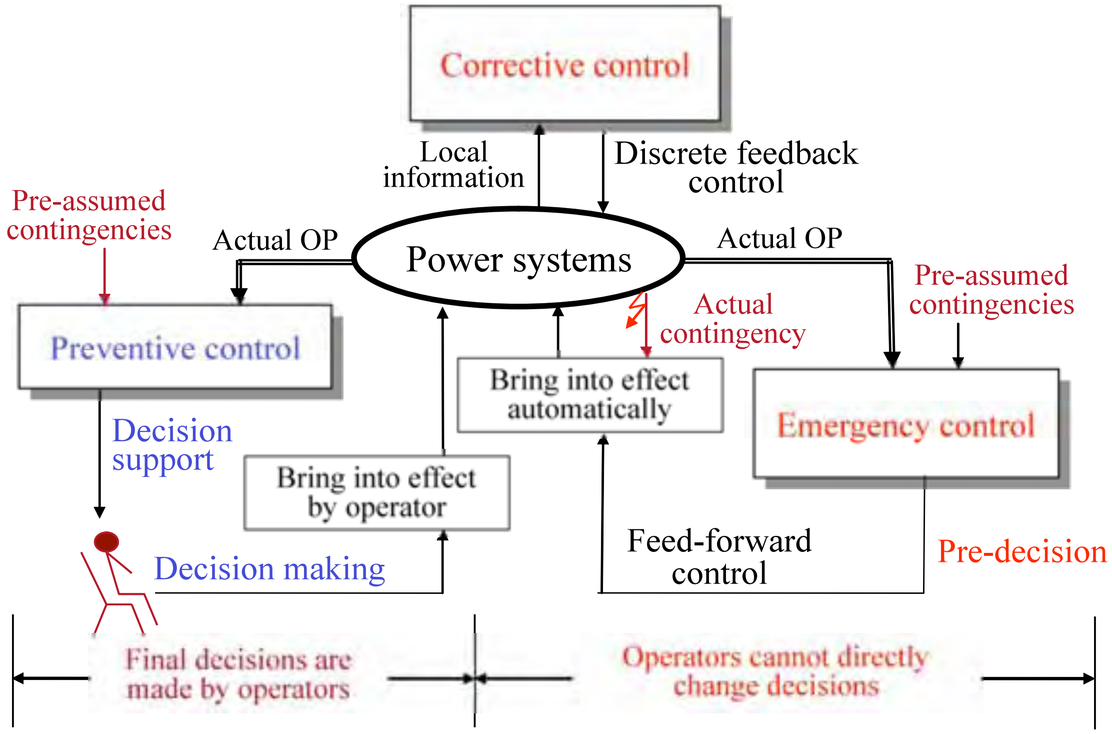

Fig. 9. The different control rules defending blackouts

6.6 Coordination among Decision Layers

In a hierarchical grid, coordination among different decision levels is required, especially for defending multi-fault or cascading contingencies, which occur in the different layers.

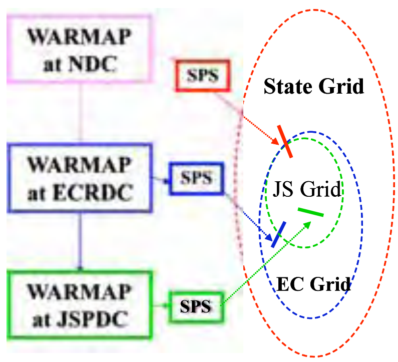

Fig. 10. Three layers of the hierarchical decision-making and stability control

7. SOME ENGINEERING EXAMPLES OF WARMAP IN CHINA

Table 1 lists the engineering projects that apply the quantitative stability algorithms, namely EEAC, in China since 2000.

The WARMAP system has been put into daily operation in a two-layer power grid in China, which consists of East China Regional Grid and Jiangsu Province Grid.

East China Power Grid is the largest regional grid in China and coordinates its 5 provincial (or metropolis) grids, namely Jiangsu, Zhejiang, Fujian, Anhui and Shanghai. Jiangsu Power Grid is one of the largest provincial grids in the country.

TABLE 1
ENGINEERING PROJECTS SINCE 2000
APPLYING THE QUANTITATIVE STABILITY ALGORITHM

Grid	On-line analysis						On-line decision			Operational planning			EMS platform	Comput. platform
	P	ΔT	T	V	f	PMU	PC	EC	CC	PC	EC	CC		
Guangxi			√	√									NARI	Windows
Sichuan	√		√				√			√			NARI	Windows
Yunnan						√							/	Windows
Shanxi						√							/	Windows
Fujian			√	√			√						/	Windows
Jiangsu	√		√	√	√	√	√	√		√	√		NARI	Unix
East China	√		√	√	√	√	√			√			ABB	Windows
Northwest						√							NARI	Windows
Guangdong	√		√	√	√		√	√		√	√		NARI	Unix
Anhui						√							NARI	Windows
Shandong	√		√					√					/	Windows
Ertan			√					√					/	Windows
Yuebei	√		√					√					/	Windows
Henan	√		√					√					CAE	Windows

There are 26 PMU units in Jiangsu Power Grid and 38 PMU units managed by East China Power Grid at present. Among them, 6 units have direct data links to both Dispatch Centers.

The WARMAP system in East China Power Grid (called as WAMAP by the utility) includes the following functions for Project Phase-I: 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. The functions fulfilled for Project Phase-II are: 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 frequency security; verification of transient stability of system operations in power market environment; security and stability analysis of operational planning. All these functions have been in daily operation since 15 June 2007 [19].

The WARMAP system in Jiangsu Power Grid (called as EACCS by the utility) is set up on a unified platform integrating EMS, WAMS, AVC, AGC and various stability control systems to implement global alarming and stability control. One of the additional functions is the adaptive optimal EC, which coordinates 2 main control stations, 10 sub control stations, 8 generator tripping control stations and 21 load shedding control stations for power system stability.

This adaptive optimal EC function has been put into service in June 2007, which is 6 months ahead of the original schedule, to be ready for defending blackouts during the summer peak load period. In fact, it has correctly responded to two hurricane disasters up to now.

Two other provincial grids in East China Power Grid, namely Fujian, Anhui provincial grids, as well as several other grids in China are ready now to implement WARMAP system.

NARI, cooperating with other institutions, is also involved in building a defense scheme for the highest layer of State Grid Corporation of China.

8. CONCLUSIONS

The reliability of power systems in China is still facing great challenges resulting from rapid growth of loads, nation-wide interconnection, ultra-high voltage transmission and power market development. In order to effectively reduce risk of cascading blackouts, transitions of operating conditions should be tracked, early warning should be issued timely, and space-time decision-making of various defense-lines should also be adjusted in time.

Based on valuable experiences on PMU, WAMS, SPS and on-line pre-decision of PC and EC separately accumulated via engineering projects for years in China, a space-time-cooperation blackout defending scheme, named as WARMAP, has being developed by NARI.

WARMAP has been implemented and put (or partially put) into daily services in three layers, namely State, regional and provincial Grids, of State Grid of China to ease the risk of cascading blackouts and give optimal solution to both economics and security.

However, there is still a big gap between the expectation and actuality. Besides improving the available functions, the further efforts include: (1) risk-based early warning of cascading events; (2) extension of the coordinated stability control onto the State Grid level; (3) quantitative stability assessment of a stable trajectory given by PMU data without using network models [20].

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BIOGRAPHY

Yusheng Xue (M'1987) 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. An Indian Experience of Defense Against Blackouts and Restoration Mechanism Followed

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Abstract-- In this paper with the background of evolution of regional electricity grids in India aiming at the formation of National Grid, Indian experience of running the electricity grid with the procedure established to safeguard the system against possible blackouts has been detailed. This has been followed by the restoration measures adopted earlier in the event of such occurrences and as envisaged for future, particularly in the context of four out of five regional grids operating in synchronism and the remaining one connected asynchronously with the rest.

Index Terms-- Black out, black start, fog, islands, load crash, restoration, synchronization.

1. NOMENCLATURE

CIGRE: International Council on Large Electric Systems
ERS: Emergency Restoration System
FGMO: Free Governor Mode Operation
RLDC: Regional Load Dispatch Center
SPM: Suspended Particulate Matter
SPS: System Protection Schemes
SVC: Synchronous Var Compensator
TCSC: Thyristor Controlled Series Compensator
UFR: Under Frequency Relay
UVLS: Under Voltage Load Shedding

2. INTRODUCTION

Power system in India developed from distributed small systems to state grids. In order to derive benefits of interconnections, the state grids were interconnected to form regional grids. In sixties five regional grids were planned for the country based on various operational, technical, geographical and political considerations aiming for at least regional self-sufficiency. However, soon need arose for to and fro exchange of power under contingencies between the self-sufficient regional grids. Fulfilling such a requirement without bringing much change in operational, technical and commercial principles of regional grids, the asynchronous HVDC back-to-back interconnections were put in place starting with Vindhyachal HVDC back-to-back station connecting the Northern and Western grids in 1990. Diversity in terms of time, festivals, weather, availability of resources and thus crop pattern, industrialization effecting ultimately load pattern, brought in focus the issue of optimization of resources at national level and thus the need of a National Grid. Therefore, number of high capacity AC and DC interconnections were planned and executed. The North Eastern and Eastern grids started operating in synchronism since October 1990 followed by East and West grid in March 2003 and North and East grids in August 2006. Therefore presently, India has two synchronously connected large grids namely Northeast-North-East-West or NEW grid of approx 100 GW capacity and south grid of approx 40 GW capacity with asynchronous transmission capacity of 4.5 GW with the NEW grid. The operation of each of these regional grids is coordinated by the Regional Load Dispatch Centers (RLDCs) [1].

3. UNIQUE FEATURES IN THE CONTEXT OF GRID OPERATION IN INDIA

Indian power system is growing at a very fast pace. Such a high growth scenario brings up new and challenging technical, operational, commercial and regulatory issues very often. In this context some of the unique features are named below [2].

- A statutorily permitted floating frequency band of 49.0 to 50.5 Hz
- Non-enforcement of mandated primary response, absence of secondary response by design and inadequate tertiary response.
- Limited market mechanisms to complement reliability and absence of an explicit ancillary services market
- Resource inadequacy leading to high uncertainty in adhering to maintenance schedules
- Pressure to meet demand even in the face of acute shortages
- Freedom to deviate from the schedules
- Operation without adequate operating reserves
- Haulage of power over long distances

All the above features have a bearing on grid operation under normal, alert, emergency as well as under restorative conditions.

4. SAFETY NETS

The operational procedures and safety net provided help in safe and secure operation of the grid. The regional system operators, i.e., RLDCs are mandated to keep power system under safe and secure conditions and restore the system after any eventuality. To carry out above responsibility, the system operators are required to develop the “Operating Procedures” and “System Restoration Procedures” and review these documents periodically along with all stakeholders. These documents are available at respective RLDC’s website [1]. Major safety nets available are described below.

4.1 Under Frequency Relay (UFR) Load shedding

Flat under frequency, rate of change of frequency load shedding and islanding schemes have been the backbone of defense plans. These plans have also evolved and have been modified as per the requirement. After the formation of NEW grid, the set points for under frequency relays and quantum of load shedding have been modified. The present setting of UFR are given at Fig. 1 below.

Northern & Western grids	Stage	Initiating Frequency	Time Delay	Load Relief (MW)	
		(Hz)		NR	WR
	1st	48.8	Instantaneous	800	960
	2nd	48.6	Instantaneous	1000	960
	3rd	48.2	Instantaneous	1250	1280

Eastern grid	Stage	Initiating Frequency	Time Delay	Load Relief (MW)
		(Hz)		ER
	1st	48.5	Instantaneous	300
	2nd	48.2	Instantaneous	300
	3rd	48.0	Instantaneous	410

Fig.1. Present UFR settings.

4.2 Rate of change of frequency [df/dt]

The relays based on rate of change of frequency change give early indication of the event. However, careful planning is done to correctly set the rate of frequency change. After synchronous operation of 4 grids in India, stiffness has increased and thus rate of change of frequency fall is not very sharp (less than 0.1 Hz/sec in most of the cases). This safety net is also important when islands are formed and stiffness of the island reduces. Therefore, different rate settings for different block of loads are essential.

Synchronization of the regional grids has brought about a paradigm shift in selecting the UFR relay and df/dt relay locations in order to avoid the secondary problems such as enhanced line loadings in some pockets due to UFR action.

4.3 Under Voltage Load Shedding (UVLS)

Though not extensively used currently, stakeholders are being encouraged to have these relays installed so as to make the entire grid secure in case of any contingency.

4.4 Islanding Schemes

Earlier philosophy of islanding system in smaller islands during contingencies has not worked well due to smaller stiffness of the small-islanded systems and non-availability of free governor mode of operation (primary response). Therefore, most of the islanding schemes have been dispensed with except those with sensitive loads such as large metro cities and or very sensitive generation such as with nuclear power stations.

4.5 System Protection Schemes (SPS)

The System Protection Schemes have been provided at few places. These are to take into account credible contingencies leading to outage of more than a single element. Schemes to take care of outage of load center based power station leading to loss of more than 800 MW are in progress. Scattered ownership of such generators spread across several utilities poses a great challenge as far as installing and commissioning of SPS is considered. The need for including such schemes at the planning stage itself for high capacity transmission lines and mega power stations has been highlighted by the system operator.

4.6 Static Devices

Static devices such as Synchronous Var Compensators (SVCs), Thyristor Controlled Series Compensators (TCSCs) and HVDC controllers have also been employed in Indian system. However, no phase shifters are employed in the Indian grids so far.

5. RESTORATION

Fortunately, in India due to efforts of grid operators and support from all stake holders including regulators, planners and Government, major black outs have not been experienced in the last 5 years. However, minor burnouts and emergency or restorative situations have arisen many a times due to number of factors. Some of such events and consequent challenges faced are being discussed in subsequent sections.

5.1 Philosophy of revival

'Top down' and 'bottom up', 'Sequential' and 'Simultaneous' philosophies of restoration are being used. These have been elaborated in 'System Restoration Procedures' of each regional grid in India [1, 3].

5.2 Priorities

The guiding principles of priorities for extending supply are on account of human safety, equipment safety, minimization of restoration time after black starting and / or getting supply from healthy islands. Major priorities of restoration have been given in [3]. However, there are few regional peculiarities that affect human safety. These are given top priority, such as supply to collieries in eastern grid, railways and hospitals etc. These have also been well documented in the CIGRE working group report [4]. Emergency supply is also restored on priority to nuclear power stations from safety considerations, as these would be depending on only the local back up from the diesel generating sets. Apart from these, the next priority is to thermal power stations that can be revived quickly and ramped up.

6. SPECIAL EVENTS AND OPERATING CONDITIONS

Some of exceptional events are discussed below.

6.1 Extreme weather conditions

6.1.1 Fog in northern part of India

Every year northern part of India is severely affected by dense fog along with biting cold weather during the months of December / January. The pollution deposited over insulator strings coupled with fog becomes killer smog for the transmission lines that start auto-reclosing due to flash over. Repeated flash over can result into insulator puncture and line break down. Such incidents have been on the rise due to high Suspended Particulate Matter (SPM) levels and the number of days that the electricity grid was adversely affected is illustrated graphically at Fig. 2. A sample of tripping that occurred on the night of December 22/23, 2005 is indicated in Fig. 3. Part of the systems had separated and collapsed on December 23, 2005. Fig 4 indicates such tripping for January 27, 2007.

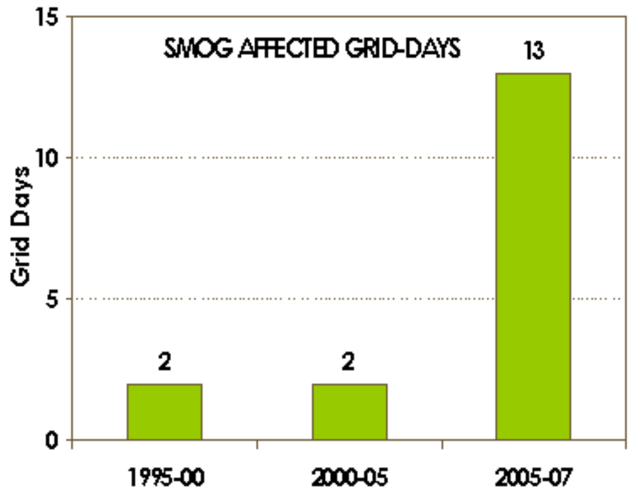

Fig. 2. Major fog affected days.

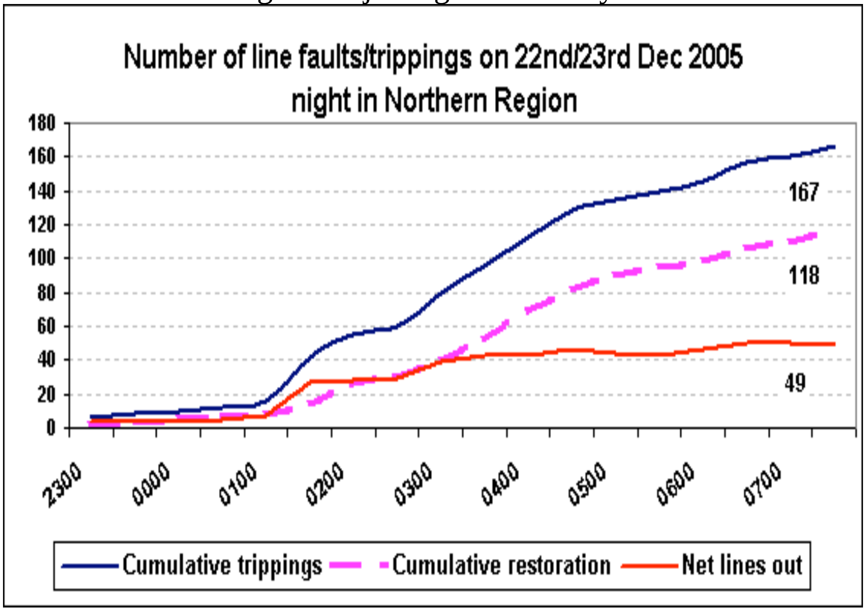

Fig. 3. Line tripping on December 22/23, 2005 due to fog / smog.

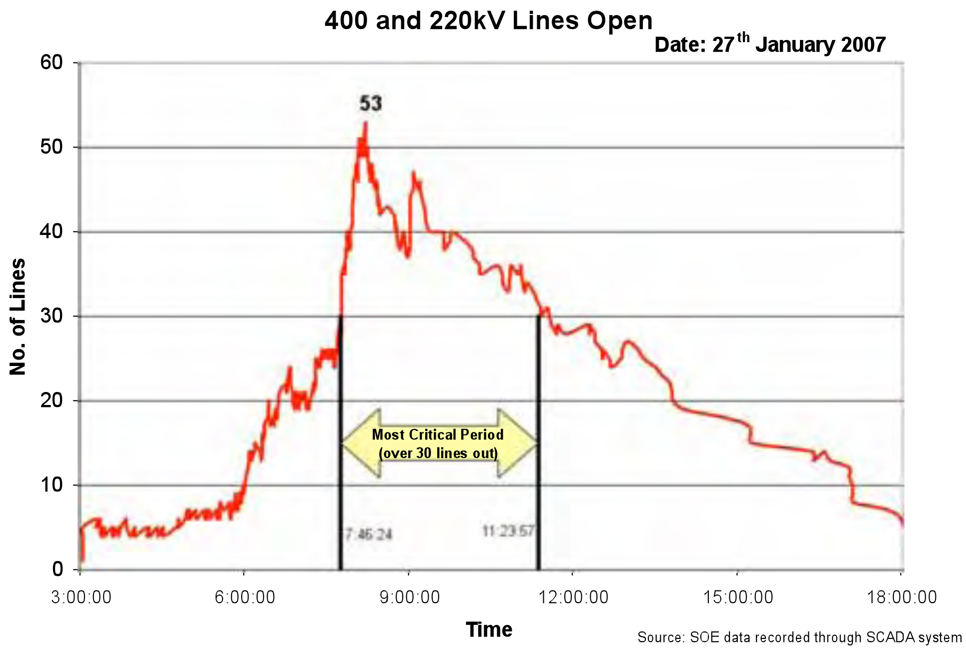

Fig. 4. Line tripping on January 27, 2007.

Under these circumstances, keeping the system interconnected remains the greatest challenge as transmission corridors get depleted. The system separation under such situations would invariably result into collapse of the smaller island. Reviving the island would have its own problem and has to be revived as per island approach or sequential approach based on the collapsed area and availability of black starting units in the area. As the problem occurs during winter when hydro generation is low, delay in synchronizing the system might result in a setback to the restoration process, as the hydro generation would get depleted.

Black start of hydro stations and islanded operation of station poses a major challenge as power stations are not familiar with operating their units on primary response (FGMO). Frequency excursions of Salal hydro station during islanded mode of operation after the tripping on December 23, 2005 is depicted in Fig. 5. It is clear from above that FGMO operation is completely off and therefore, unit were not able to operate in islanded mode.

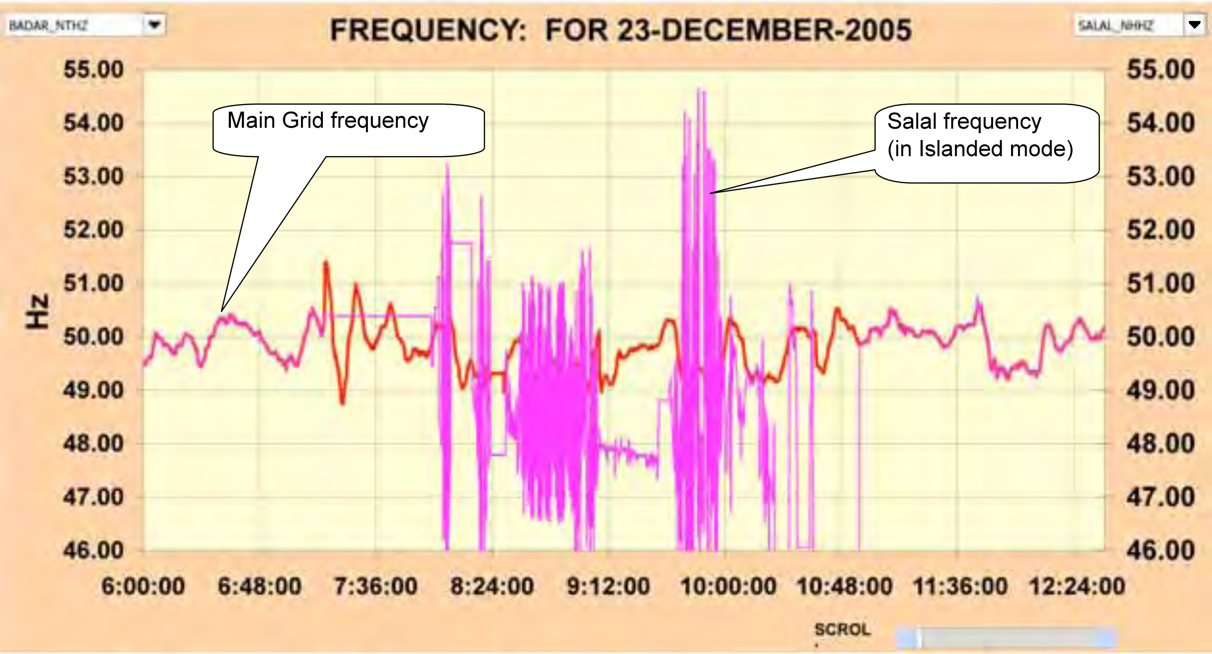

Fig. 5. Islanded operation Salal unit on December 23, 2005.

The incident highlights the requirements of technological solutions for fighting the ‘killer smog’. A committee of experts has decided for hotline washing of insulators and change of insulators based on pollution level [5]. Fog forecasting and assessment of the impact of environmental conditions on the performance of power system would also provide insights to the pressing problem. Following are the major concerns during such events.

- Information overload at control centers (see Fig. 6 below)
- Dilemma on whether to keep single pole auto-reclosing in service or not
- Black start of hydro units and capability to charge a long 400 kV line for build-up of system.
- Planning of line shutdowns between October December every year for pre-winter maintenance.

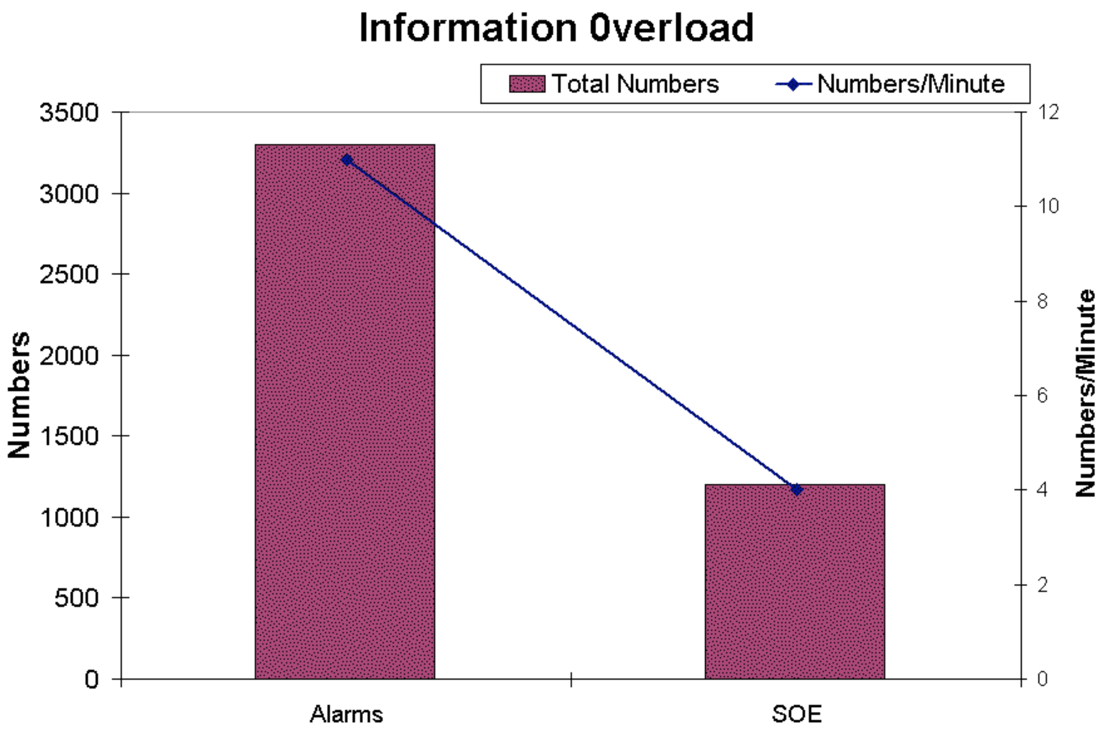

Fig. 6. Alarms and Sequence of Event data received at NRLDC on January 27, 2007.

6.1.2 Snowfall

Kashmir valley in Northern India receives heavy snowfall during the winter months every year. In February 2005, Kashmir valley received 12 meters of snowfall, which was the highest snowfall in the last 30 years (previous highest snowfall of 4.5 meters was recorded in February 1967 in Gulmarg). As a result of heavy snowfall accompanied with rains at isolated places there were landslides / avalanches at many places. At 18-32 hours of February 08, 2005, the towers of 220 kV Kishenpur-Pampore double-circuit line collapsed and Kashmir valley plunged into darkness as the power supply totally was cut-off. The tower location was inaccessible due to heavy snowfall. Line restoration through Emergency Restoration System (ERS) was ruled out due the risk of avalanches. The closure of the Jammu-Srinagar highway compounded the problems and made the restoration and relief work almost impossible.

For nearly a month, Kashmir valley (with demand of 800 MW) was operated in isolation (at a restricted load of 200-250 MW) or through a weak 132 kV interconnection with rest of the Northern Grid. The longest period of islanded operation was two hours and fifteen minutes on February 13, 2005. With a weak 132 kV interconnection, up to 300 MW load could be met in Kashmir valley.

6.2 Load Crash

There are winter rains and summer dust storms in India. During such events very high load throw-off takes place due to 1) natural dependency of load on weather parameters for agriculture, domestic and commercial loads, 2) tripping / collapse of distribution system, 3) switching-off of the feeders by distribution utilities for safety reasons. The load pickup is also very sharp during such event. This uncertainly plays heavily on the mind of system operators during decision-making process under these events. One such situation occurred during the night of June 9 / 10, 2005 (Fig. 7) when electrical load in the western part of the North grid crashed by more than 7,850 MW within a short span of time.

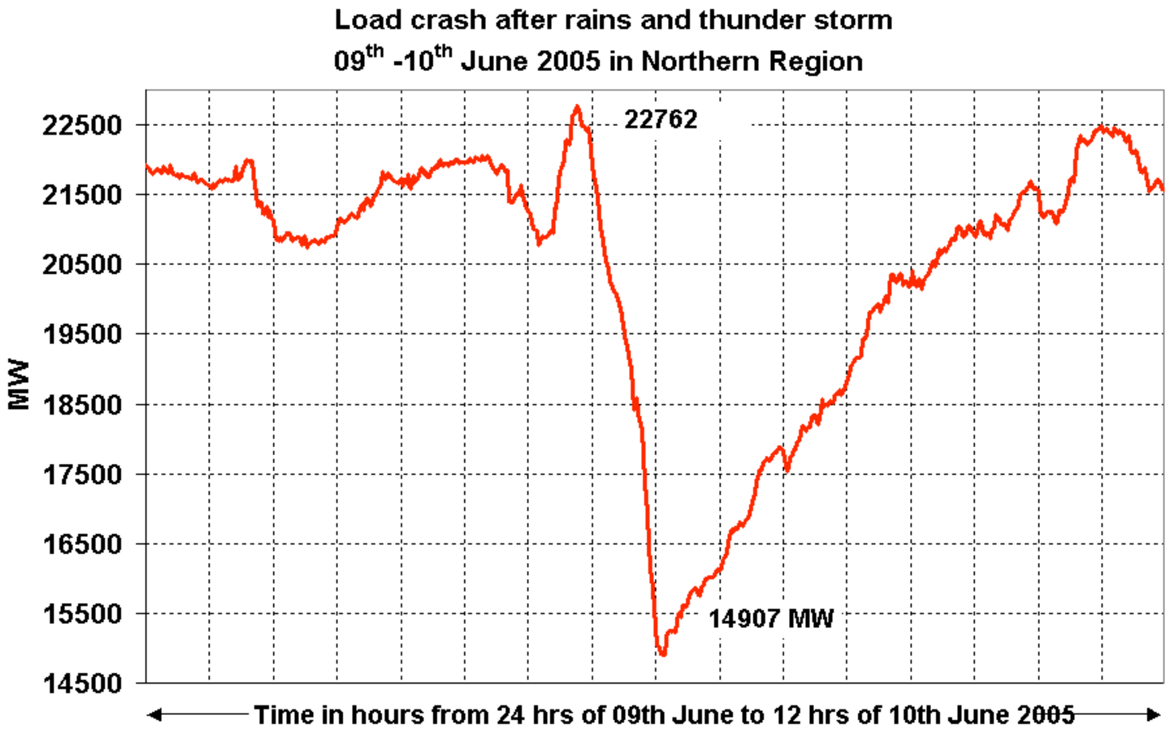

Fig. 7. Load crash on 09th – 10th June 2005.

Similar situation occurred in February 2007 (Fig. 8) when the demand of Northern Grid fell from 20 GW to 9.4 GW within a few hours. One of the highlights of this event was that a 210 MW coal-fired unit at Dadri Thermal Power Station operated on house load for three hours and twenty minutes.

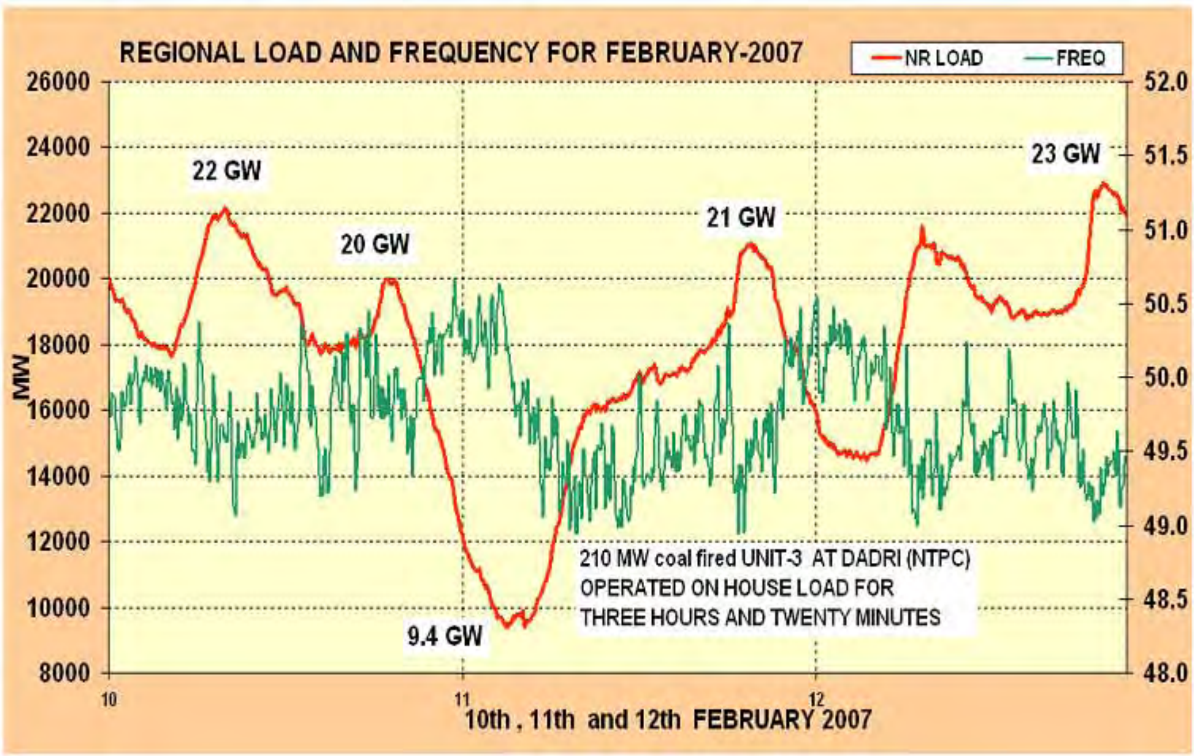

Fig. 8. Load crash on February 11, 2007.

In both these occasions generation in large thermal / reservoir based stations was minimized in the areas having low demand. Still major transmission corridors got overloaded in the direction opposite to their usual flow. Large number of EHV transmission lines tripped on high voltage and the power export to the neighboring regions also could not be maximized due to the overloading of transmission lines. Generation was backed down at gas stations, reservoir-based hydro and load center-based thermal stations. Even the run-of-the river hydro stations were forced to spill water.

Similar load crashes take place whenever there are dust storms or thundershowers in the region and the intriguing part of these load crashes is that the load bounces back to normal level within a few hours. The only plausible explanation for this phenomenon could be the traditional practice of manual switching of distribution feeders by the distribution companies to avoid collateral damage. This puts a lot of pressure on the system because the boxed up generating units take a long time to revive and hence the practice of opening distribution feeders at the slightest hint of rains/ dust storms needs to be revisited at the state utility level.

6.3 Extreme Contingencies

Power system operator has to tackle a number of grid emergencies during real time operation. Northern Region has seen several instances of complete power station trip and entire 400/220 kV substation trip since December 2004. Apart from these there have been several system threatening multiple contingencies. However, most of them could be managed due to the robustness of the grid and the swift actions by the power system operators while a few resulted into interruption of power supply from the EHV level. Each incident is unique and interesting with its twists and turns but the incident that occurred on July 6, 2005 needs special mention (Fig. 9).

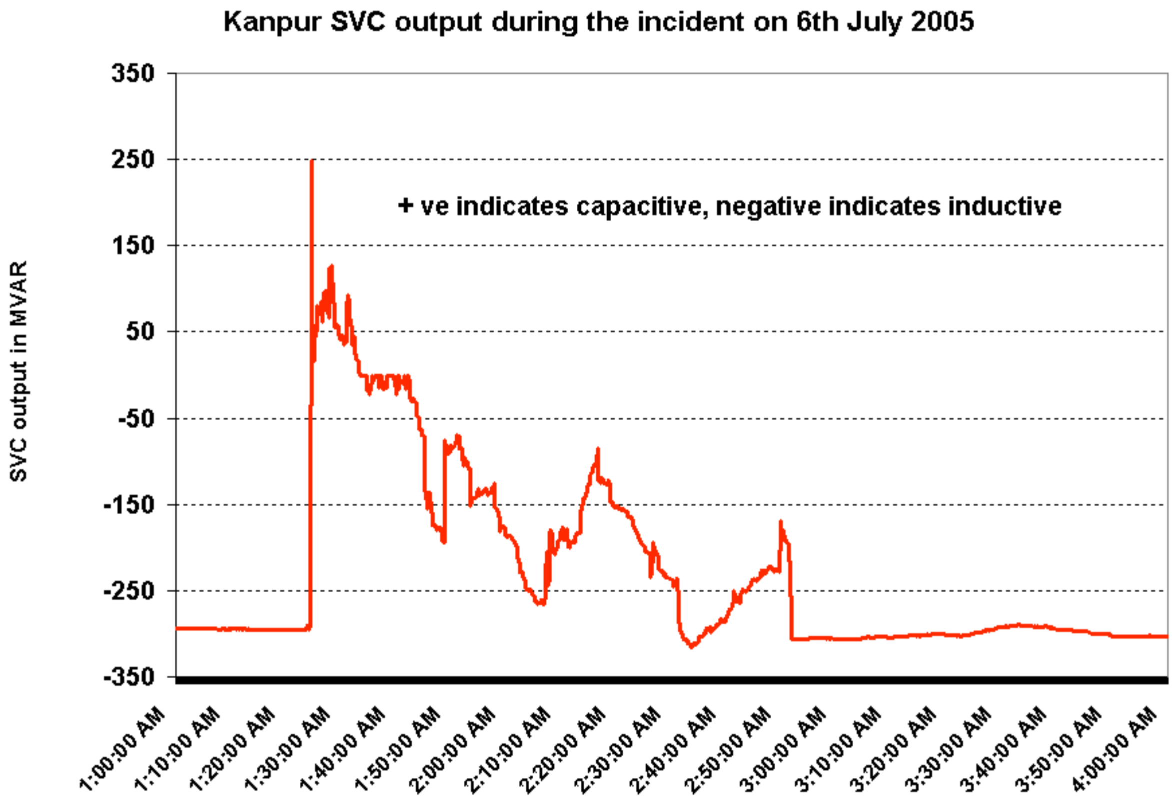

Fig. 9. Output of SVC at Kanpur during the fault.

At 01-23 hours Northern Grid was subjected to a stress test of the worst kind. Simultaneous outage of vital transmission elements in the interconnected grid resulted into wild fluctuations in the grid parameters, like, frequency, power flow on trunk lines interconnecting major subsystems and voltages at several nodes for more than an hour. Rapid corrective actions were taken by the power system operators to prevent the system from degenerating and as a result the grid was held together.

A thorough investigation following the event revealed that a fault occurred on a single 400 kV transmission element, which was not isolated from one end leading to failure of other elements in its vicinity. The unhealthy section remained firmly connected to healthy system (as it was beyond 3^{rd} zone reach of any distance relay and many utilities did not have a back-up earth fault protection in 400 kV system) causing an unprecedented assault on the physical network. The fault was fed for nearly 63 minutes before it got cleared through manual opening of a circuit breaker on the adjacent section. Such a situation was unprecedented and the system operator could get only the following clues that something was amiss.

- SCADA data from 400 kV Agra (UP) substation was not getting updated. The fault on 400 kV Agra-Muradnagar line was cleared from that end but not from the other end.
- Negative sequence alarm appeared at some power stations.
- One coal fired station at Dadri (4 x 210 MW) which tripped due to back up protection on the Generator Transformers (GTs) found it extremely difficult to start their auxiliaries during this 63-minute interval when there was an un-cleared fault.
- Mal-operation of a protective system led to tripping of one 400 kV bus at Dadri which further confused the system operator as he had to wait for a confirmation from the power station that it was indeed a mal-operation before carrying out any switching operation.
- The operator could see MW values intermittently on 400 kV Agra-Muradnagar line at Muradnagar end which led to the assumption that the line was in service.

To prevent recurrence of such events in future greater emphasis is required in protection systems. The voice communication between the operators of adjacent stations and between the field and the load dispatch centers is crucial for improving situational awareness. Subsequent to this event, the visual displays at the Control Center were modified to indicate a bus outage at any 400 kV substation to draw quick attention of the operator.

6.4 Social recreation such as kite flying

The independence day being a public holiday, traditionally people enjoy the day by engaging in activities, like, kite flying in and around Delhi. Thicker metallic thread / string used now-a-days for better strength plays havoc on electrical power system by resulting in transient faults (Fig. 10)

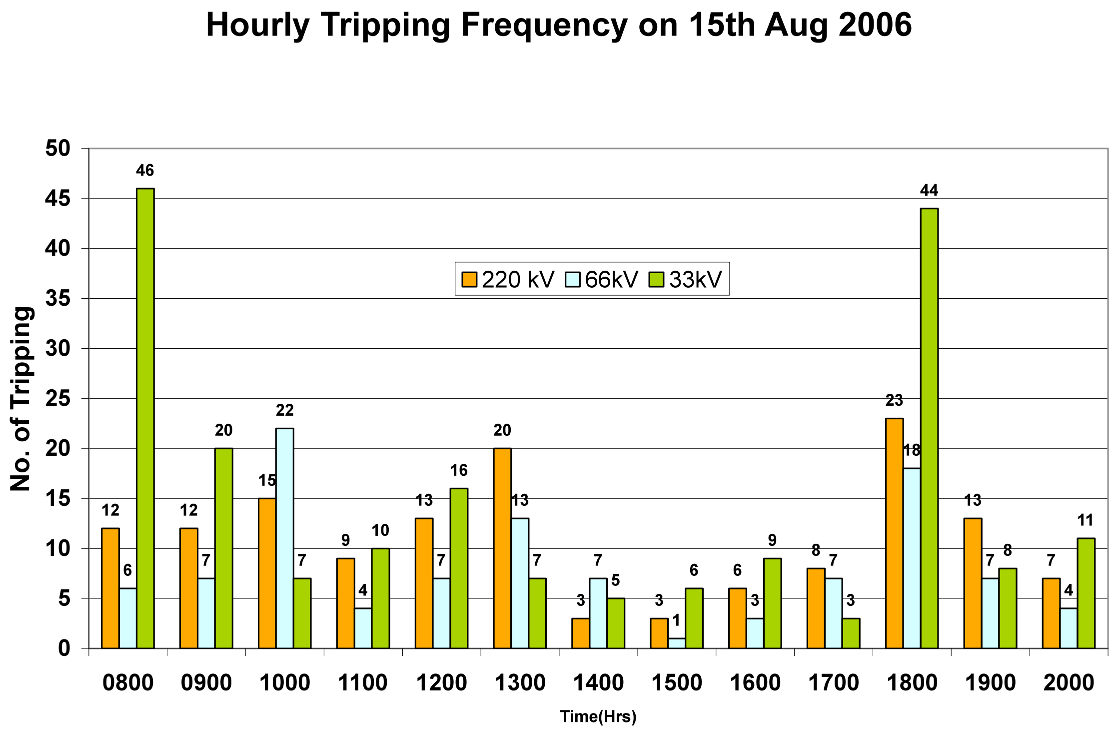

Fig. 10. Tripping in Delhi system on August 15, 2006 due to kite flying.

An extensive awareness drive launched through print / visual media prevented any such happening in August 2007.

6.5 Hydro generation reduction due to high silt content

Northern Grid experiences maximum demand during the period from June to August due to irrigation requirement of the paddy crop. Of course hydro generation also goes high during this period on account of high rainfall and water inflows. However high silt content in the Himalayan Rivers such as Sutlej results in frequent outage of the power station and the system has to handle such contingencies. An example of Jhakri hydro power station generating 1,500 MW going out frequently whenever the silt content exceeds 5000 ppm is indicated in Fig. 11 below.

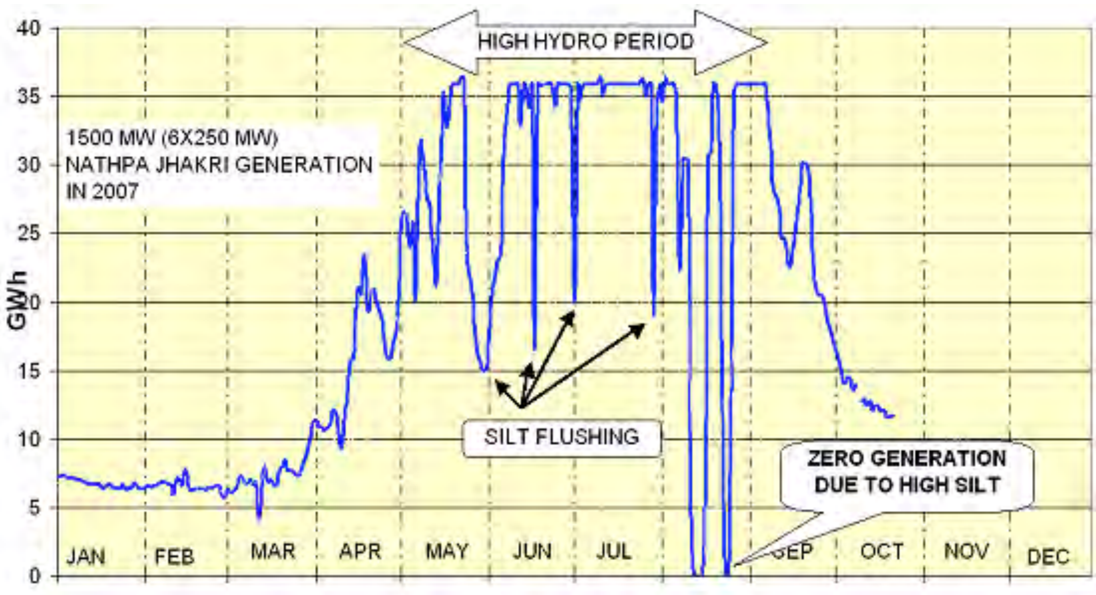

Fig. 11. Outage of Jhakri HEP during high hydro conditions.

7. IMPROVEMENTS INITIATED

Normal and abnormal events faced in power system are learning opportunities. The Indian electricity grids faced several major disturbances in the past (Fig. 12). The reduction however has a flip side that while earlier operators were frequently trained in real life system restoration, the same had to be now done in a simulated set-up. In this context it is worthwhile to refer to the saying of power system guru Charles Concordia that 'a weaker system that has a well tested plan for emergency procedures and for restoration may be more reliable than a stronger system with no such plan' [6].

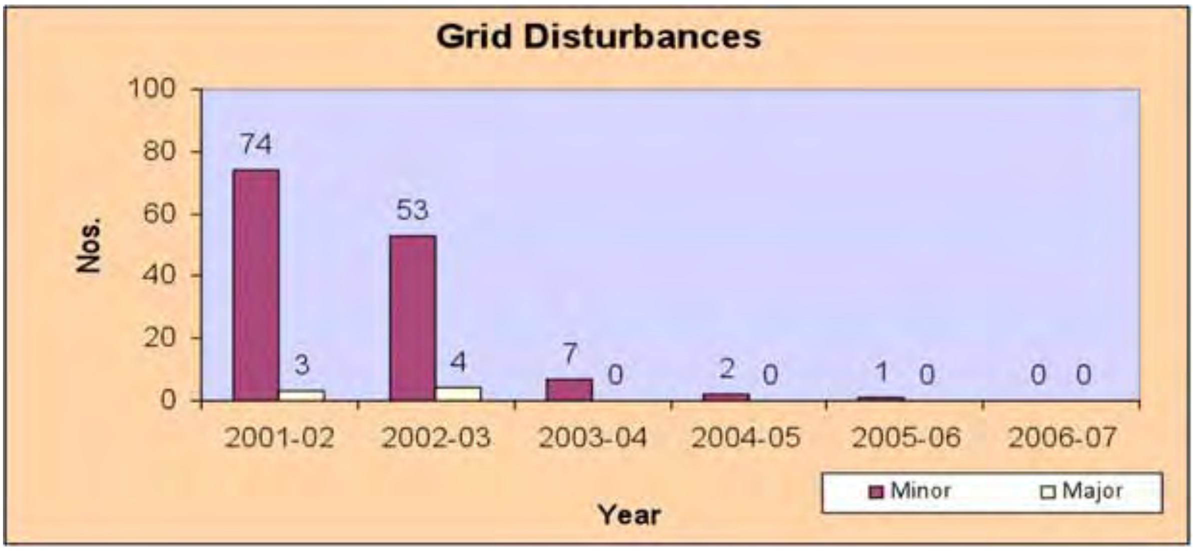

Fig. 12. Reduction in grid disturbances

Improvements initiated to minimize disturbances are as under:

7.1 Visualization and Situational Awareness

Visualization and situational awareness are the most important factors during contingencies and restorations and greatly help on comprehending the problem and decision-making. The following has been put to use in control centers [7].

7.1.1 Displays

In tabular, geographical, summary, graphical displays, the concept of layers is being utilized to access relevant information with ease and in time. In order to avoid mixing of supplies and extent of energizing, de-energizing, indicator such as color changing, width changing, flashers and style (dotted, firm), etc. is being used extensively (Fig. 13).

Fig. 13. Geographical display

7.1.2 Angular Measurement

Angular difference calculation and angular measurement is being extensively used in Indian power system to understand the vulnerability of the system. The angular measurement is also being used as a signal for integrated / islanded operation (Fig. 14).

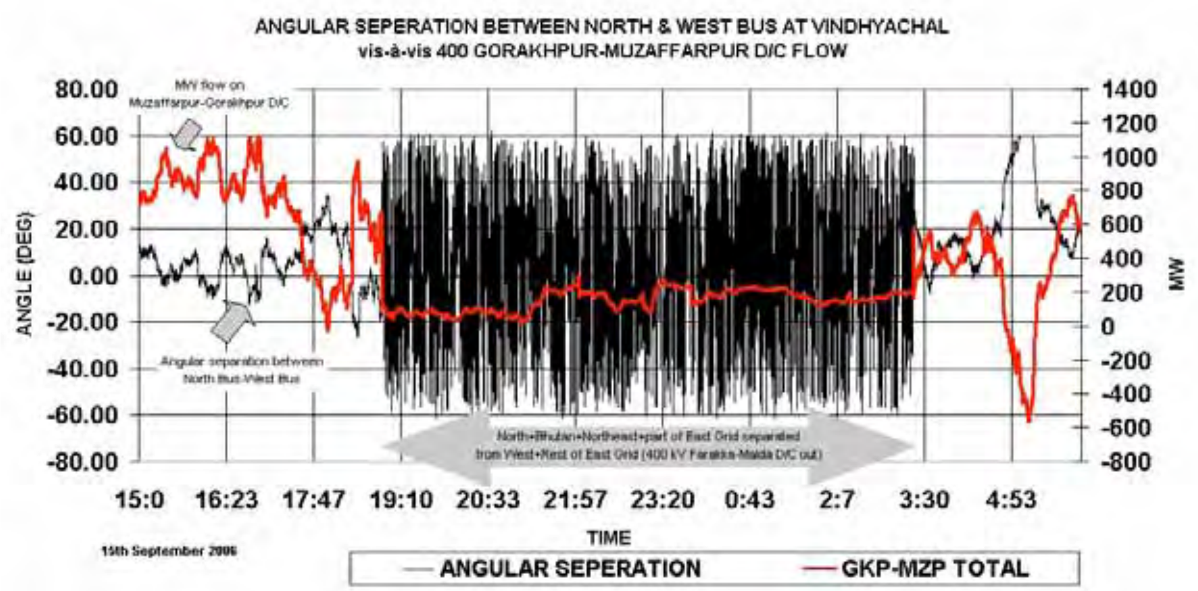

Fig. 14. Angle measurement.

7.2 Mock Drills

Frequent mock exercises for black start of hydro power station and extending supply to local loads, building up the network and synchronization are being done on a regular basis by segregating one 220 kV bus at a couple of substations.

8. FUTURE REQUIREMENT

The situations described above pose a great challenge to system operators and further improvements would help in tackling the situation in future. Some of these are given below [8 - 11].

- Explicit Ancillary Service Market in the form of black start facilities, reactive power support etc.
- Primary response from generating units
- Under Voltage Load Shedding (UVLS)
- More System Protection Schemes (SPS) to correct outages of generation / transmission lines and prevent cascading notwithstanding the number of agencies involved in making such a scheme functional
- Synchronizing facilities at major substations and availability of trained manpower
- Improved situational awareness at Control Centers

9. CONCLUSIONS

The society is becoming increasingly dependent on electrical power and it expects reliable, uninterrupted, secure and affordable supply. Power system engineers have designed an elaborate system to fulfill that desire. However the real test of any system is its ability to handle emergencies. The issues highlighted above assume greater importance with increasing size of the power system and regional / international interconnections. Any blackout in the Indian power system would have much larger socio-economic and political impact than earlier days when the systems were limited in size and complexity. It is expected that new tools and techniques, requisite training and the right attitude would help the system operators in discharging this onerous responsibility.

10. ACKNOWLEDGMENT

The authors acknowledge the efforts of all the power system operators in running the real time power system and providing their valuable feedback. Encouragement and support by POWERGRID management and power system fraternity at large is also acknowledged.

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12. BIOGRAPHIES

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4. Blackout Prevention: Managing Complexity with Technology in China

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Abstract—With the development of electric power grid in China, some experiences in blackout analysis and prevention have been obtained. The experiences show that the security operations of bulk electric power systems depend not only on the technologies of system operation, analysis and control, but also on the management of power systems. This paper reviews the strategies of prevention cascading failures in China, and then discusses an emerging technology based on self-organized criticality theory for analyzing the cascading failures in the viewpoint of macro-scale. A framework of the future power system control centers to avoid blackouts is also described.

Index Terms—Blackout prevention, cascading Failures, three defense-line, self-organized criticality, power system control centers, Grid services, PMU

1. INTRODUCTION

Reliability is one of the key issues in the power system planning and operation. The recent blackouts brought us attention to the understanding of the interdependence between policy, economic, and engineering developments [1]. As a developing country, the installed generation capacity in China has reached 600 GW at the end of 2006, with annual production of 2,187 TWh, making it the second highest in the world [2]. With the rapid development of electric power grid, some experiences in blackouts analysis and prevention have been obtained. This paper reviews the strategies of prevention cascade failures in China, and also introduces the emerging technologies for blackout prevention.

The criterion of three defense-lines has been a well-established security standard for power system planning and operation in China [3], [4]. The criterion defines strategies for regular pattern of the blackout evolvement. For a non-severe contingency, the strategies ensure system stability without load shedding. For a severe or extremely severe contingency, the emergency control and corrective control are employed to avoid system-wide blackout. As a defense framework for preventing cascading failures, it successfully avoided system-wide blackout in the relatively weak grids in China [5].

For a complex power grid, the traditional analysis methodologies are facing great challenges in constructing accurate models on the microcosmic level with differential algebraic equation set. The self-organized criticality theory, which focuses on the system evolutions from macro-scale viewpoint, is a new approach to study blackouts of power systems. With the theory, the critical characteristics of an interconnected power grid could be analyzed and corresponding countermeasures could be given at the beginning of blackout as well.

The strategies preventing the system from cascading failures demand for the supporting of future power system control centers, which should be more decentralized, integrated, flexible and open. Grid technology provides coordinated and secured sharing of computing resources among dynamic collections of individuals, institutions and resources. It has been used for developing the framework of future control centers [6]. Case study demonstrates the feasibility of the proposed architecture.

This paper is organized as follows: Section II provides an account of three defense-lines security standard of power system. Section III presents the blackout modeling and analysis based on self-organized criticality. Section IV describes the architecture of the power system control centers for preventing cascading failures. The last section draws a brief conclusion.

2. BLACKOUT PREVENTION: STRATEGIES OF CHINA

2.1 General Process of Cascading Failures

The Blackout prevention is a key issue for developing future power grids. Suffering from a series of cascading events, even a strong system can become fragile and may evolve into a disaster. It pointed out, after analyzing the Jul 1, 2006 Blackout in Central China Grid [7], the Sep 26, 2005 Blackout in Hainan Grid of China [8], the Aug 14, 2003 blackout in USA and Canada [9,10], the Aug 28, 2003 blackout in London, U.K. [11], the Sep 23, 2003 blackout in Sweden and Denmark [12], the Sep 28, 2003 blackout in Italy [13], and the May 24-25, 2005 blackout in Moscow, Russia [14], that cascading failures may occur due to the loss of generating units, breaker failures, common tower and common right-of-way circuit outages, combination of system conditions and events. The common cascading processes consist of system state before blackout, cascaded events, and post-blackout state. The following stages are suggested for those cascading processes [15].

The first stage is system state before blackout. Generally, system parameters are within the normal operating reliability ranges with no indication of the approaching blackouts. However, some potential deviations, such as weak grid, heavy power flow, depressed voltage, and frequency variation, etc., weaken the system before the actual blackouts occurring. The second stage is triggering events under contingency conditions. If the operating point is outside the stability domain in the first stage, the system under contingencies will be even weaker. After occurrence of triggering events, the operating point moves out of the stability domain. The third stage is subsequent events. Cascading events may cause a series of problems, such as power flow surges and overloads. With some defined control strategies, a group of equipments are isolated by protection relays, accompanying by some load losses. This may make the situation even worse. The fourth stage is system separation, instability, and voltage collapse. It is possible that uncontrollable system separation, angle instability, or voltage collapse occurs during blackouts, which may lead to the loss of significant loads. Finally, the system will reach the post-blackout state, which is the beginning of system restoration process.

2.2 Three defense-lines for power system in China

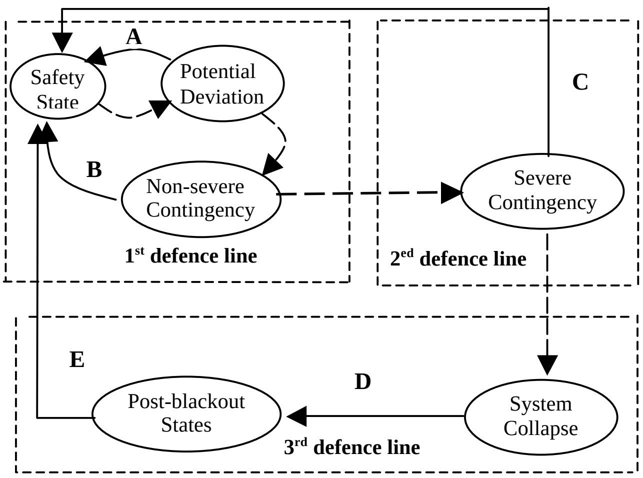
The security operations of bulk electric power systems depend not only on the technologies of system operation, analysis and control, but also on the management of power systems. It is revealed that, after analyzing the regular pattern of the blackout evolvements, there are opportunities to avoid the disaster in different stages during the blackout evolvement with a good knowledge of the mechanism of a system wide blackout cause by an occasional contingency. With the rapid development of electric power grid in China, some experiences in blackouts analysis and prevention are obtained. The three defense-lines has been a well-established security standard for power system planning and operation [3] - [5].

Considering the criticalities of faults, and the probability of faults taking place, the three defense-lines are established in China. (see Fig.1.)

States	Strategies	Defense line
● With enough stable margin	● Grid strengthening	1
● Potential unsafety ● Potential unstable states ● Potential deviation	● Preventive control	
● Non-severe contingency	● Protecting relay ● Reclosing relay	
● Controllable load shedding ● Controllable separation	● Fault clearance ● Emergency control	2
● Loss of synchronization ● Voltage collapse ● frequency collapse	● out-of-step separation ● Under voltage load shedding ● Under frequency load shedding	3

Fig. 1. Sketch map of three defense lines

The first defense-line consists of grid strengthening, preventive control and protection relays to ensure system stability without load shedding under a non-severe contingency. The second defense-line is armed with remote emergency control for severe contingencies. The third defense-line is equipped with local corrective control such as out-of-step islanding and load shedding for extremely severe contingencies [4]. Fig 2 shows states transfer of the system with the three defense-lines.



1. A: Preventive control B: Protecting relay & Reclosing relay
1. C: Emergency control D: out-of-step separation, UVLS & UFLS
1. E: Recovery control

Fig. 2. States transfer under the three defense

The following actions are considered: 1) For the system without a contingency, the stability region is extended by grid strengthening strategy. 2) After potential deviation being detected, preventive control tries to maintain the operating point within the stability domain. There are no equipments removed by these two actions. 3) After the occurrence of a non-severe contingency, the faulted equipments should be removed selectively and quickly by protection relays. If operating point returns back to the stability region, the first defense-line is done (i.e., the system ensuring stability without load shedding). Non-severe contingency could be eliminated by this defense-line. 4) For a severe contingency that is not eliminated by the first defense-line, the second-line works. The emergency control moves the stability domain towards the operating point by controllable load shedding and separation. 5) Once subsequent events occur, actions of third defense line, 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. 6) Recovery control actions are adopted to restore the supply of the shed loads as soon as possible.

According to these defense framework, the frequency of faults of power grid is decreased, although the size of grid and load level of China are increasing rapidly. Tab.1 reveals this tendency [5].

TABLE I
STATISTICS OF ANNUAL POWER GRID FAILURE RATE CAUSED BY DIFFERENT REASONS FROM 1981 TO 2000

Reason of faults	1981-1990 (Times/Year)	1990-1995 (Times/Year)	1996-2000 (Times/Year)
Natural disaster	2.5	0.6	0.4
Equipment damage	2.0	1.0	0.6
Human error	1.6	1.6	1.2
protecting relay accident	0.9	0	0.4
Indefinite reason	1.1	0.6	0
Total	8.1	3.8	2.6

3. BLACKOUT ANALYSIS: SELF-ORGANIZED CRITICALITY

3.1 Blackout modeling based on self-organized criticality

After recent blackouts, it becomes clear that the blackout triggering events may happen more frequently than they are expected. The modern power systems are becoming much more complex. They consist of tremendous components, which are couplings and interactions due to different physical laws. A fault can lead to the transient process at generator nodes and load nodes, especially at the induction motor nodes. Then, the power flow transfer will happen, and protective relaying will isolate some components. These actions may lead to cascading failures or even large-scale blackouts. It is difficult to construct accurate models on the microcosmic level with differential algebraic equation set and to minimize the risk of large-scale blackouts as well. How to model and analyze the blackouts of power system will be a challenge.

The self-organized criticality theory, which focuses on the system evolutions from the macro-scale viewpoint, is a new approach to study blackouts of power systems. The historical data of power system failures denote that the blackouts such as the restoration time, energy unserved, power of loss, and number of customers unserved has the power law characteristic, rather than normal (Gaussian) distribution [16,17]. One of the system evolution mechanisms behind the power law characteristic is self-organized criticality theory. With the theory, the critical characteristics of a complex system, such as an interconnected power grid. The countermeasures could be given at the beginning of blackout.

The main point of this theory is that the operation and evolution of any system are determined by two kinds of dynamics: long-term dynamics and short-term dynamics. During the long-term dynamics, the system continuously adjusts its state to absorb the external energy and then dissipate. During the short-term dynamics, the external force can be considered as constant, therefore the system is autonomous, i.e., state is governed by its own property and the initial value. Besides, the system state may be deviated from the norm and become critical by random events. Correspondingly, there are two kinds of variables in the system, i.e., fast variables and slow variables. These variables are also called internal and external variables, respectively. Once the two variables satisfy certain condition, the system will arrive at a critical operation state. In this situation, any disturbance, even small, may cause unpredictable change.

According to self-organized criticality theory, the evolution of power system can be described in three time scale dynamics, i.e., the slow dynamics, the fast dynamics and the transient dynamics [18], as shown in Fig.3.

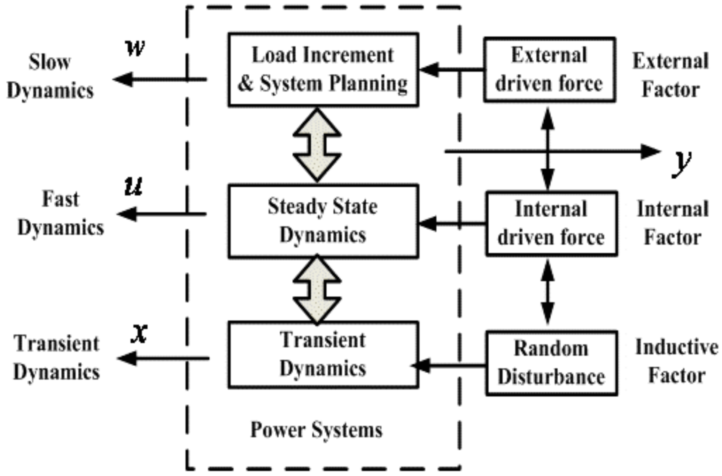


Fig. 3. Physical description of power network evolution

The slow dynamics *w*, describing the increment of load and system construction (including network and generation planning and construction in monthly or yearly time scale). This is the external driven force of power systems. The fast dynamics *u*, representing the internal driven force of power systems, describes the internal load flow dynamics ranging from several minutes to hours (e.g., the line outage, load flow transfer, and even the low-voltage load shedding and low frequency load shedding). The fast dynamics always happens in the case of load level exceeding the maximum transfer capability of the grid (i.e., the system in a potential deviation state). The transient dynamics *x*, which is triggered by random disturbances, represents the system's successive transient dynamics suffering from a large disturbance from several milliseconds to seconds (i.e., the protection dynamics and the emergency control dynamics such as generation tripping and load shedding). These successive transient dynamics may cause the abrupt change of load flow and the outage of heavily loaded lines. System output is denoted by *y*.

3.2 Analysis of self-organized criticality in power system

The blackout modeling based on self-organized criticality theory is summarized: with the development of the power system, the system generation, load and line flow are continuously increased. When the line flow exceeds its upper limit, it may cause an outage. Furthermore, it may trigger the outage of other overloaded lines due to load flow transfer, so that the cascading failures would happen. On the contrary, the overloaded lines are improved to augment their transfer capacity and security level. Several models based on self-organized criticality theory are employed to analyze the blackouts of power systems. They are the OPA model based on DC optimal power flow [19], [20], Manchester model based on load shedding and AC power flow, and the blackout models based on OPF and OTS based on OPF with transient stability.

In these models, the OTS can model the line outage, redispatch of generators, FACTs devices, as well as preventive and emergence control. Fig 4 and Fig 5 show the results of the fast dynamics of OTS model in the IEEE 30 bus system, and Northeast Grid of China, respectively.

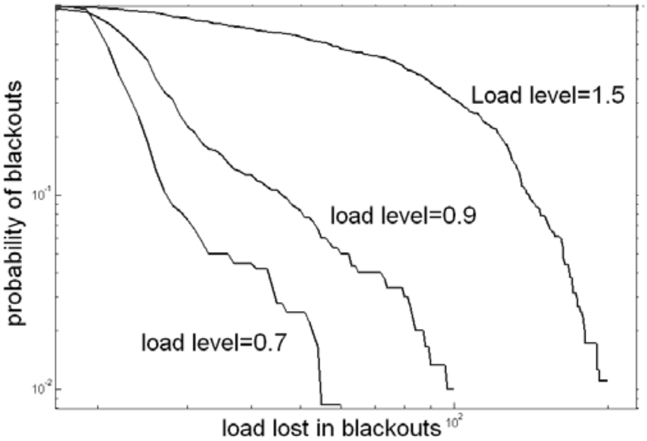


Fig.4 Blackout distributions of fast dynamical process in IEEE 30 system at different load levels

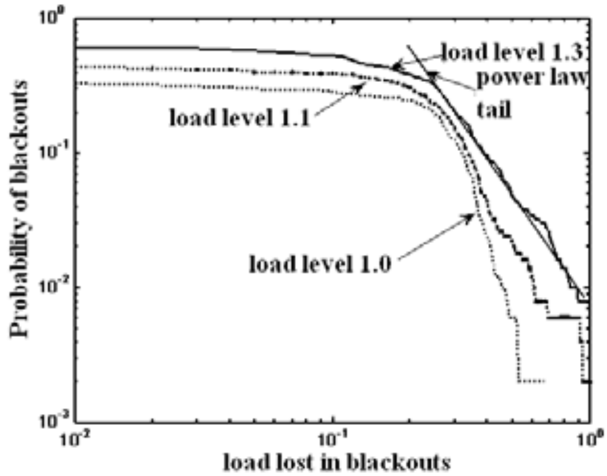


Fig.5 Blackout distributions of fast dynamical process in northeast grid of China at different load levels

With appropriate loads level, the blackout distributions of these systems represent the power law tail. Although the global characteristics of system blackout distribution are far from the power law, the power law still appears in the curve tail, which means that the failure distribution in large scale has the power law property.

These models can capture the general scenario of cascading failures and blackouts, reveal the self-organized criticality in power system and propose countermeasures to blackouts. However, due to the complexities of power systems and limitation of current simulation devices, there are still a lot of problems in this field, such as a detailed description of the transient process of power system with the protection systems and the specific counter measures to the power system blackout. On the other hand, with the rapid advancement of computer technology (such as Grid computing), the improvement of power system technology, and the theoretical development of the subject of complexity theory, they could be used to understand the mechanism of self-organized criticality in power system more deeply.

4. BLACKOUT PREVENTION SUPPORTING SYSTEM

The demand for preventing cascading failures challenges the architecture of the current power system control centers, from 1) the need for a stable, open and flexible data acquisition and processing platform, which supports both SCADA and PMU data and satisfies the system’s various requirements for data, 2) the support for the accessing of a variety of dispersed market participants; 3) the capability of transparent data sharing and cooperation between interconnected power grids, 4) the support for operating and controlling of a large number of distributed generators, and 5) the need for better scalability of the system and seamless cooperation between different systems. The future control centers should be more decentralized, integrated, flexible and open.

Grid technology offers dependable, consistent, and pervasive access to resources irrespective of their different physical locations or heterogeneity, using open standard data descriptions and transport protocols. In a Grid service environment, everything is a service. It provides an open, flexible and scalable solution for power industry to develop the future control centers, meeting the challenges that are usually met in an incremental fashion.

A framework of Grid-based future power system control centers has been proposed [21], using the emerging technologies. The framework indicates the general direction of the development of future control centers. The Globus Toolkit is widely regarded as one of the key enablers of Grid technologies. It is a collection of software components that provide many of the building blocks (services) necessary to create a Grid-based application [21]. The Globus-based control centers design is based on a multilayered architecture, as shown in Fig. 6 [22]. The layered design of complex system is made tractable by hiding the details of the lower layer design in the higher layer abstraction. On top there exists a client layer, representing the consumers of Grid systems, typically Web browsers and Personal Digital Assistants (PDAs), which interact with the portal via HTML form elements and use HTTPS to submit requests. Beneath it is a portal layer, which consists two sub-layers: application portals and portal services. Portal services are a collection of grid services that shorten the distance between users and low-level GT services. Application portal consists of the portal-specific code itself. Logically there are several portals have to be developed for different users. The portals run on standard Web servers and process the client requests and the responses to those requests. On the bottom is a backend services layer called Globus layer that acts as a middleware and manages distributed resources. The control center services are located between portal layer and Globus layer. According to their different functions, they could be roughly separated into three components [22,23]. Supported by IP-based high-speed power system communication network, Data service is a virtual service that provides a general data processing and delivering platform, which is open and standard, supporting SCADA, PMU or maybe other even finer data in future [24]. Application service is not just moving the traditional functions of EMS to the Grid environment. Considering their different requirements for computation, communication, storage and information security, the solutions are provided for 1) basic service, 2) data-intensive service, 3) computation-intensive service, 4) communication-intensive service, 5) interactivity and scalability, 6) online and offline, 7) the equilibrium of security, efficiency and reliability, and 8) workflow of complicated functions [22]. Security has become a primary concern for all enterprises exposing sensitive data and business processes through a shared environment. For control centers, security service is a complete information security platform, including accessing controls, communication protocols and permission managements. It could be built from the aspects of authentication, authorization, privacy, integrity, auditing, and etc.

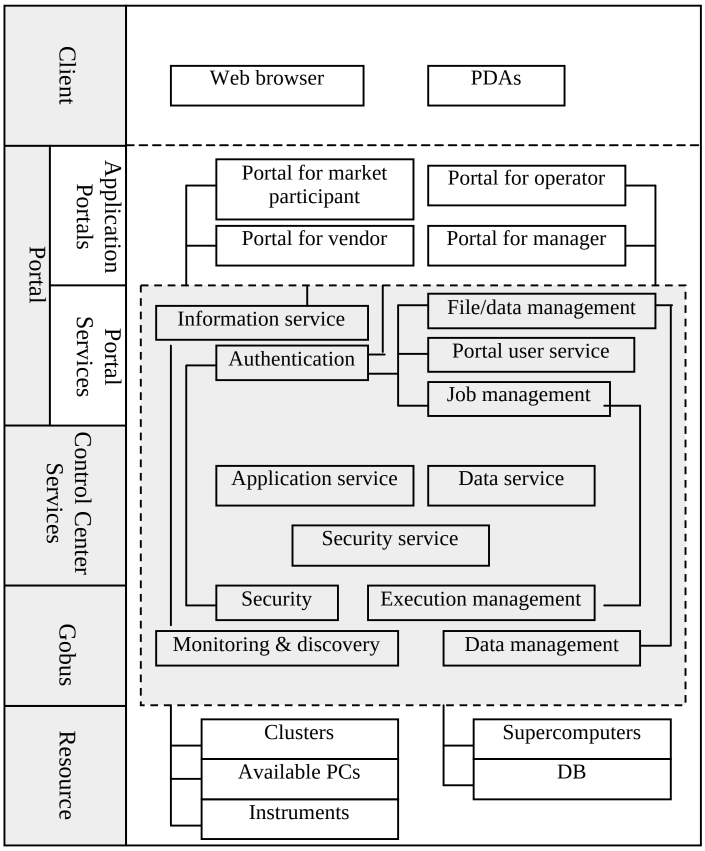


Fig.6. Grid-based control centers architecture

A test bed for demonstration has been constructed, initially including seven Linux PCs/Servers with GT4.0.1 installed and a computing cluster with PBS. It simulates Portal Server, Data Centers, Application Centers, Registry Center, CA Center and High Performance Computing Node of two control areas, respectively. In order to evaluate the feasibility of the framework, a dynamic state estimation (DSE) service has been designed and implemented using GT4.0.1 to explain, to some extend, how the application services work. The service consists of five participants (topology data advertiser, calculation module advertiser, computing node advertiser, DSE user and DSE broker), four usage cases (advertising/revoking resources, finding resources, running service and result display), several services (resources advertising services, DSE operating service, DSE broker service, data transfer service, and so forth), and multiple security strategies (password control, GSI transport, authorization for certain data, data privacy and integrity, and logging). To make it a real system, other issues have been considered. For an example, resource lifecycle management is offered by WS-Resource Lifetime, including immediate destruction and scheduled destruction. For another example, it supports notification, offered by WS-Notifications, notifying some parts of the software the changes that happen in one of the other parts.

This work is the very first step. Grid service technologies are suggested for constructing the infrastructure of distributed systems. In order to keep moving forward on the research of the design and implementation of future control centers, we offer the following recommendations:

- Work out a set of standards for power systems data formats, application service interfaces, information security mechanisms;
- Develop a power industry-specific middleware, which is located over the low level Grid layer, such as GT;

- Research should always keep following with the advancement of Grid and Web service technologies and standards other than the toolkits.
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5. CONCLUSIONS

This paper reviews the experiences in blackout analysis and prevention of China, and introduces the work on the self-organized criticality of blackouts. A framework of grid-based future power system control centers is also discussed.

The three defense-lines criterion is a well-established security standard for power system planning and operation in China. According to their different criticalities of the contingencies, various strategies are implemented to avoid system collapse, and maintain the operating point within the stability domain. Although system-wide blackouts have been successfully avoided in China, the defense-lines are facing great challenges from rapid load growth, nation wide interconnection, and industry deregulation. It is difficult to construct accurate models on the microcosmic level to minimize the risk of large-scale blackouts. The self-organized criticality theory presents an approach to capture the general scenarios of cascading failures and blackouts in macrocosmic level. To prevent blackout, power industry is requiring for a more open, standard and flexible control centers. The architecture of Grid-based future control centers has been suggested to be an ideal design. The architecture of a Grid-based control centers using GT4.0.1 is discussed. Case study demonstrates the feasibility of the proposed framework.

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BIOGRAPHIES

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5. Enabling the Appropriate Operation Response to Power System Events

John Clark and Kevin Small (Transpower, Wellington, New Zealand). Enabling the Appropriate Operation Response to Power System Events

Abstract: On 12 June 2006 operators had to manage multiple simultaneous system issues across the New Zealand power system including:

- an equipment failure causing a loss of supply to New Zealand's largest city equivalent to a third of system demand in the North Island,
- a one in 20 year snow storm causing widespread faults and multiply loss of supplies across the New Zealand's South Island and,
- the disruption to the primary gas supply threatening the loss of all gas fired generation.

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Power system operators were able to successfully manage these events and keep all market functions operating through the combination of the technology provided to operational staff, the contingency planning and training systems along with the flexible resourcing arrangement with a "virtual control center"[3]. Together these factors all contributed to ensure operators had sufficient situational awareness to understand the situation, were equipped with the knowledge to make good timely decisions, and enabled the rapid deployment of additional operators to manage the coordination of these multiple events within the control room.

This paper describes the recent changes by the New Zealand's market and system operator, Transpower that enabled both operators and management to successfully respond to extreme system events.

1. BACKGROUND TO THE NEW ZEALAND ENVIRONMENT

The New Zealand Power System has a winter system peak of 6,500 MW with an annual electricity consumption of 37,000 GWh/year. There are two main Islands linked by a 1000 MW HVDC link. There is no interconnection to any other power system.

About 80% of New Zealand's population of four million resides in the North Island and a third of that in the wider environs of New Zealand's largest city, Auckland at the top of the North Island. Electricity generation is predominantly hydroelectric (65%); another 25% of the generation mix is gas fired thermal plant. Core grid voltage is 220 kV; the power system was developed during the 1950's through to 1980's largely to enable the transfer of hydroelectric generation from the South Island to the major load center in the top of the North Island.

As well as its role as system and market operator, Transpower is also the owner of the New Zealand national grid. Supply to end consumers from grid substations at low voltage (typically 66 kV and below) is via some 30 individual local distribution utilities with seven major consumers directly connected to the grid.

2. DEREGULATION

Since the early 1990's New Zealand has progressive de-regulated the electricity sector. In 1992 the grid owner and system operator, Transpower, was separated from the central generation and transmission utility. In 1996 wholesale market arrangements including one of the first Locational

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[3] Reference IEEE PES GM 2004 panel paper - The implementation of a single "virtual" control centre to manage the New Zealand power system.

Marginal Pricing (LMP) markets were introduced. By 2000 there were five major competing generating companies operating. At this time the electricity retail function had been transferred from the local distribution utilities to separate retailers. The generation companies largely own these retailers.

Since the early 1990's New Zealand's approach to governance of the electricity sector has been one of "light handed regulation" under the approach of using market arrangements wherever possible and regulation as a last resort. In 2004 an industry regulator was appointed to put in place a formal framework for achieving needed transmission investment. More formal rules for market and system operation were also formally codified. The role of system and market operator was formally established as a "service provider" under the regulators rules.

In addition to the electricity sector reforms the labor market was itself deregulated, while individuals retained the right to organize, unions and employers lost the right to make union membership compulsory or to insist on collective negotiation of wages and conditions. Employees became free agents to promote themselves and their best interests.

3. POWER SYSTEM AND NETWORK CONTROL

Market and system operation is delivered from two control centers operating as one virtual control center. As the System operator, Transpower receives offers from generators and information on grid configuration and carries out a merit order based dispatch. The system operator's objective is to dispatch the system at lowest cost to consumers while acting as a reasonable and prudent operator to avoid cascade failure of the power system. The formulation of the LMP market model achieves the first point while various rules and policies cover RPO (word better).

Routine operational communication with generators is achieved through the issue of electronic dispatch instructions. The operational management of the grid including switching of equipment is delegated to three regional operating centers. These three centers are also the prime operational interface with the local distribution utilities.

The system operator only has very limited powers to direct the operation of the market. The requirement is to dispatch the system within the generation and transmission made available by market participants and the grid owner. However in the "Grid emergency" it can direct the regional operators and local distribution utilities to shed demand if required to maintain system integrity.

4. A CHANGING OPERATIONAL ENVIRONMENT

Changes in technology and de-regulation and have created an operational environment barely recognizable from the one 20 years ago.

Change 1: Field automation has de-manned all substations and area control sites, and the vast majority of generation stations. A few people in this layer have been absorbed but most have grayed out and disappeared from the industry altogether, more importantly this layer of the industry traditionally feed the system operator function and without this important feed experienced operators are simply not there to be recruited.

Change 2: To manage risk within the market as well as the need to manage the power system being operated closer to the extreme end of its capability IT systems have had to advance well beyond the simple SCADA observe and control functionality. The skills to operate and interpret these tools can be very different to the traditional operator skill set; there use is key to identifying issues before they happen and to understanding and resolving them in a timely way when they do. In many cases the operational staff are needed to help design and build these tools and must be able to not just 'use' but develop, diagnose issues and know when the tool itself is at its limits in terms of producing a correct answer.

Change 3: A successful restoration in a deregulated environment means more than just the safe and timely restoration of grid equipment. Information provision is vital to enable participants in the market to communicate with their customers, to enable them to meet their contractual requirements, to manage their risks, and allow them to make decisions that can assist the system operator in restoring supply. To succeed here an operator needs good communication skills and the ability to speak and understand in the language of commercial operators and economists as well as that of station and network operators.

Change 4: The creation of a regulatory function in New Zealand changed the matrix of accountabilities and responsibilities, and has created a need for additional support and communication from system operations.

Change 5: Many operators found the new environment to be not the role they wished for and have left or gone to more suitable positions. In an area where traditionally people had decades of industry experience, we were confronted with a mean experience of only a few years.

The result of all these changes is depicted graphically below in figure 1. Demand on the system operator has grown in terms of both the volume and the complexity of the work while at the same time our capability to meet that demand was diminishing both in the number of people available and the competencies they possess.

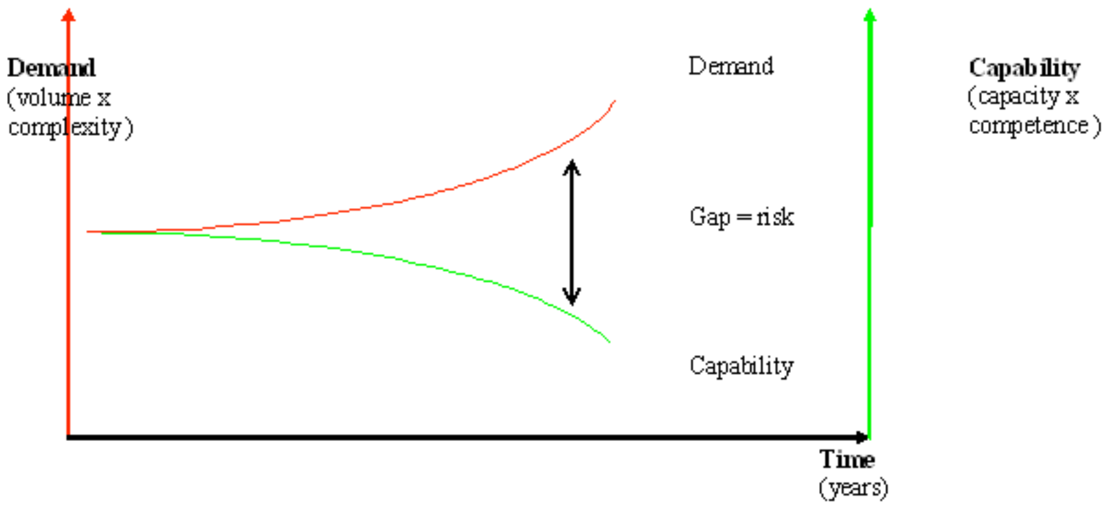

Figure 1

5. ORGANISATIONAL RESPONSE

Transpower launched a project to understand the issues facing it and to implement systems to address them. The issues creating the risk are permanent and therefore the fixes could not be ‘one off’ events, they had to change the way we did business.

- A different type of recruit was required, simply put persisting with finding people with field experience who were now in other parts of the industry was not working, it was incorrectly valuing experience above all else and leading to a lowering of standards.
- The new recruit is a very different person with different expectations toward career and job tenure. People now want rapid career growth and seldom see any job as one they will be doing in 5 years, therefore strategies are needed that will encourage staff to stay in the role for an appropriate amount of time and also career strategies to help them move, hopefully within the organization.

- Significant change has happened in the area of training; new ways of training were needed, as was ways of providing experiential learning systems to replace the years of hands on experience. The old training technique of getting an old operator to 'tell' the young ones what to do was not working and could not work, professionals with learning and development expertise were brought in to build and run a complete training programme, a second training simulator was constructed and importantly additional operating staff were recruited to account for the extra weeks that all staff would spend each year in the training environment.
- Control room roles were changed to create broader more interesting roles and to allow the operational management team to step back from detail operations and increase the people management aspects of their role.
- A new and more rigorous approach to contingency planning was introduced.

Transpower has put significant effort into working with suppliers to further develop existing technology systems to manage issues such as voltage stability, and also to develop it's own tools where none are available such as a visualization systems that uses color and graphics to represent data (figure 2) which maintains the operators situational awareness and their ability to take in large amounts of information very quickly.
….Figure 2 shows two alternative ways of viewing the power system using information from the market. One shows a traditional schematic diagram overlaid with price and information feed from the SCADA system contingency analysis program. In a nodal price market changes in price can represent physical constraints that should match the results from tools looking at our N-1 capability. Less obvious is the bottom view which examines the expected flows on circuits and transformers for the next day based on generation cleared in the market, operators are quickly aware of which parts of the system will be heavily loaded and where infeasibilities may occur. (Y scale = time, X scale is equipment A-Z)

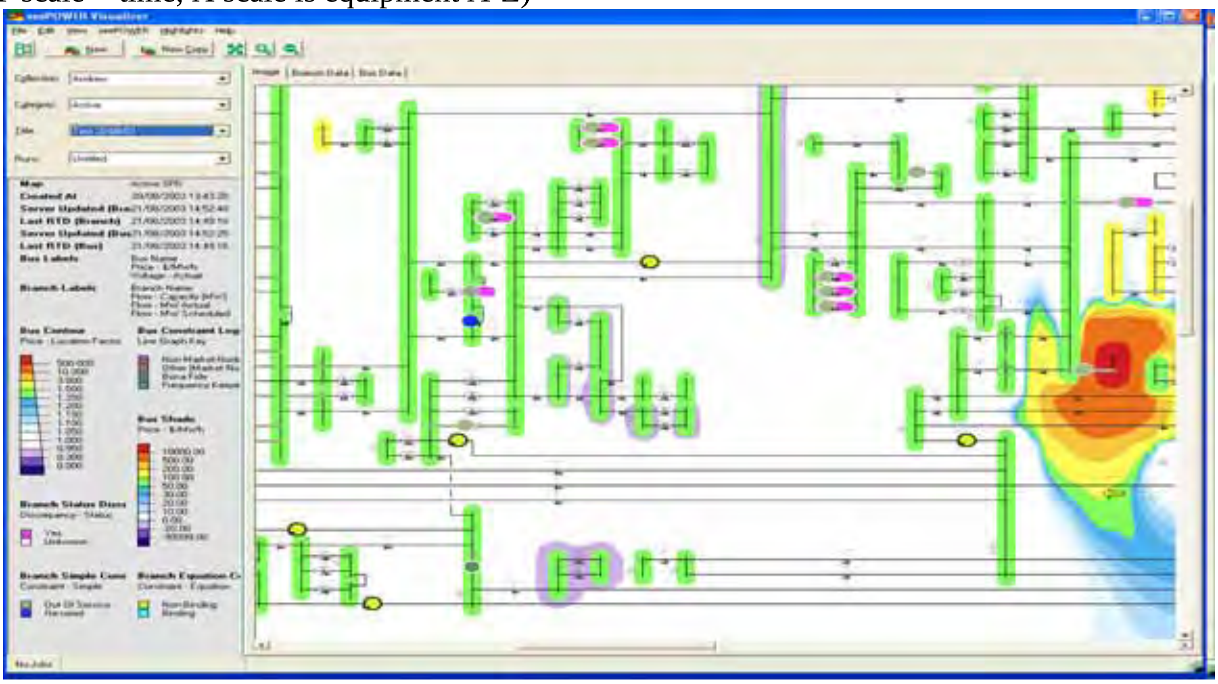

Figure 2

6. EVENTS OF 12 JUNE 2006

In the early hours of 12 June the expected southerly weather pattern hit New Zealand's South Islands bring freezing temperatures and snow to sea level, by 06:00 the system operator staff had responded to a fault on grid equipment on average every 6 minutes, a number of lines had suffered permanent damage and a large number of rural communities were without power, some would remain so for up to 14 days. With no sign of the storm abating a decision was made to reinforce the control room. A system co-coordinator was pulled off project activities and put in the control room, the workload was divided so that one team could manage the events in the South Island and the other could manage the North Island.

No sooner had this been done than events took hold in the North Island at 08:29 a phase one Gas Contingency was declared meaning a reduced supply to gas fired plant was likely then at 08:32 two overhead earth wires failed and fell across the four 110KV bus sections at the Otahuhu sub station in Auckland nearly 25% of the North Island demand was lost either through direct disconnection of adjoining substations or the resulting voltage depression (3939 MW fell to 3000 MW). While the South was bearing the brunt of the bad weather the North Island was also suffering high winds clearly restoration was going to take time. New Zealand’s commercial center was without power, many businesses were forced to close, traffic lights were out with the resulting chaos on the roads, people were trapped in lifts in high rise buildings and the focus was quickly on Transpower to put things right. The estimated financial impact of the outage is between NZ $50-70 million.

Once again further resource was brought in, an operations manager entered the control room to assist the team leader but not to run the situation, an emergency room was staffed with managers, engineers and customer liaison staff to both assist the restoration by providing advice and take on some of the communication workload. At no time was any operational authority removed from the operational staff.

The situation was now almost comical had these scenarios been put together as a training exercise it would not have been considered realistic, yet the individual components of the event had been thought through and practiced. A contingency plan for a rebuild of the Auckland system was on hand and was quickly modified; preparations for restoration began within minutes of knowing what had caused the fault.

While it took until late afternoon for restoration to be complete an independent review found no fault in the restoration and no obvious manner in which it could have been safely completed quicker.

During the restoration the SCADA and Market Systems started to fail, both these systems were ageing and projects were underway to upgrade these yet the operators had to make do, at times of stress even minor tool failure can be enough to cause a loss of focus and start breaking a team down however this was another practiced scenario from our business continuity planning and was properly dealt with by staff.

By the time supply was restored to Auckland the situation in the South island was still playing out, the loss of a 220 KV feed into the top of the South Island meant the evening peak demand would be above the voltage stability limit for the region. The fact that staff who had been constantly busy since the start of a 12 hour shift had managed to retain sufficient situational awareness to see forward in time was quite remarkable. Industry participants in the area were contacted and demand management plans put in place, close communication was maintained with field staff to ensure priorities were correctly set and developments quickly reflected into plans. Thankfully the circuit could be restored in time to prevent customer disruption but for the control room the work had been done.

The situation in the gas supply had got worse as well and plans for load management across the North Island had to be put together, again supplies were restored before any consumer disruption took place, but again not before the control room had done its job.

7. ORIGIN OF SUCCESS

All but one of the staff on duty that day had five or less years of experience, the two-team leaders included. Success on the day was clearly then not born from having staff with decades of experience and a detailed knowledge of each piece of equipment on the system. The electricity market was unaffected by the events in that there was no need to put aside market rules or reduce or curtail the information flows.

Our success came from a number of factors including:

1) Our ability of staff to learn and the organizations ability to teach. Staff are selected for their aptitude and attitude, recruiting managers know the standard candidates must meet and know to walk away from the recruitment process empty handed rather than select a second rate candidate. In turn candidates know from day one what skills and competencies each role requires and when and how they will be obtaining these. In this way over time we aim to develop a reputation that will assist with recruitment and retention of staff.
2) Our ability to rapidly expand. Career and staff development strategies lead to having operational staff seconded to projects and other engineering teams within Transpower, these staff can be rapidly redeployed back to the control rooms. A second team leader was brought in off a project developing our new market system to manage the South Island storm events and allow the roster team lead to manage the North Island's day to day issues and gas supply problems. After the Otahuhu event staff were again redeployed into supporting roles.
3) The two center 'virtual control room design means we have two control rooms both capable of managing the whole system independently in effect this means a team lead or support role can be done from either control room or both, having this capacity (desks, SCADA terminals, market interface etc) allowed this additional staff resource to be effectively utilized without sharing desks and computer equipment
4) In addition control room staff that have moved on in their careers are now present in the engineering and market teams who provided support on the day.
5) Knowing what to do. Contingency plans and business continuity plans are developed by operational staff and management, they are kept refreshed and most importantly they are trained on. Training within the simulator is professional and realistic, there is time for discussion and improvement suggestions and events are often repeated on the request of staff knowing they can do it better. Thus high professional standards expected of the trainers are matched by a high standard operators expect of themselves and their team.
6) Communication. While we didn't get 100% customer satisfaction for our communication, complaints were very few and the issues minor given the complexity of a deregulated environment. Ensuring that the operators maintain accountability for the events mean the operation management can have a wider focus including ensuring communications is happening. In addition staffing the emergency response room allowed many people to participate in the communications effort without jeopardizing the consistency of the messages.

8. SUMMARY

Two of the most significant issues facing power system operators are dealing with de-regulation and the graying and disappearing workforce. Possibly due to it small size and the rapid pace of change New Zealand has had to confront these issues sooner than many larger nations, Transpower has dealt with this successfully, the average age in the control room is under 40 and while the experience levels are perhaps not yet optimum the effort placed into training, people management, contingency planning and software systems mean we will maintain a professional and sustainable operations team while the experience develops. The effort into these three key areas of people, process and tools is seen as co-dependant in that for example good people will not stay in a role where they are not valued or where tools and process prevent them from being successful in their role, likewise investment in software without good process and training will not produce the required benefit.

9 BIOGRAPHIES

John Clarke (M'2000) was born in New Zealand on 13 August 1960. He was awarded the B.E. Degree etc in 1982 from the University of Canterbury. His employment experiences include distribution utilities, heavy power engineering consulting as well as 9 years in power system operation at Transpower. His special fields of interest include power system operation, development of technical codes and standards for industry governance in power system operation.

Kevin Small (non-member) was born in New Zealand on 11 September 1964. He has an NZCE from Auckland University of Technology. His employment experience includes the construction industry as well as 14 years in Transpower in the operations and markets areas. Kevin sits on a government advisory panel developing and implementing policy on security of supply. His special fields of interest include power system operations, electricity markets and human resource management.

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6. A Blackout in Hainan Island Power System: Causes and Restoration Procedure

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***Abstract*—**The blackout has become a problem of worldwide concern. We focus on the aspects of causes and restoration. In this paper, we review the blackout in the Hainan Island power system and analyze the causes and restoration procedure. Some experience is summarized. Finally, we put forward to some exposed problem and gave some suggestion.
***Index terms*—**blackout, black start, protection, typhoon, restoration, planning, construction, lone island, reliability

1. INTRODUCTION

On September 26th 2005,the blackout in Hainan Island power system was caused by the typhoon named "DaWi" .The typhoon destroyed the power grids and led to many faults. Especially in the east of Hainan Island, the typhoon reached level 12, and its velocity reached 55 meter per second. It lasted for 48 hours from the morning of Sept.25 th to the evening of Step. 26 th. The typhoon covered all the area of the island. Its center went though the island from the east to the west. The radius of the level 10 typhoon went beyond 100 kilometers. The blackout would have a great effect on the society [1-4]. The loss of the whole province exceeded 11,600,000,000¥.

Hainan Island power system is a separate system that doesn't join the power system of mainland. In 2005, the gross installed generating capacity of Hainan power system was 1651.6 MW, of which hydroelectricity capacity was 19.38% and steam plant capacity was 80.6%. The highest voltage level is 220kV. The grid of 220kV is a ring system that includes ten substations. There are 14 transformers and 20 lines. The total capacity of the transformers is 2000MVA and the total length of lines is 1195.2km. The 110 kV power grid covered all the area in Hainan. The sum of 110kV substation is 65 and the sum of 35kV substation of is 130. The load of Haikou city is 35%~40% in all the load of Hainan. Danzhou and Sanya are in the next place. In 2004, the maximum load was 1113.3 MW and the difference between the peak and the trough was 542.6 MW.

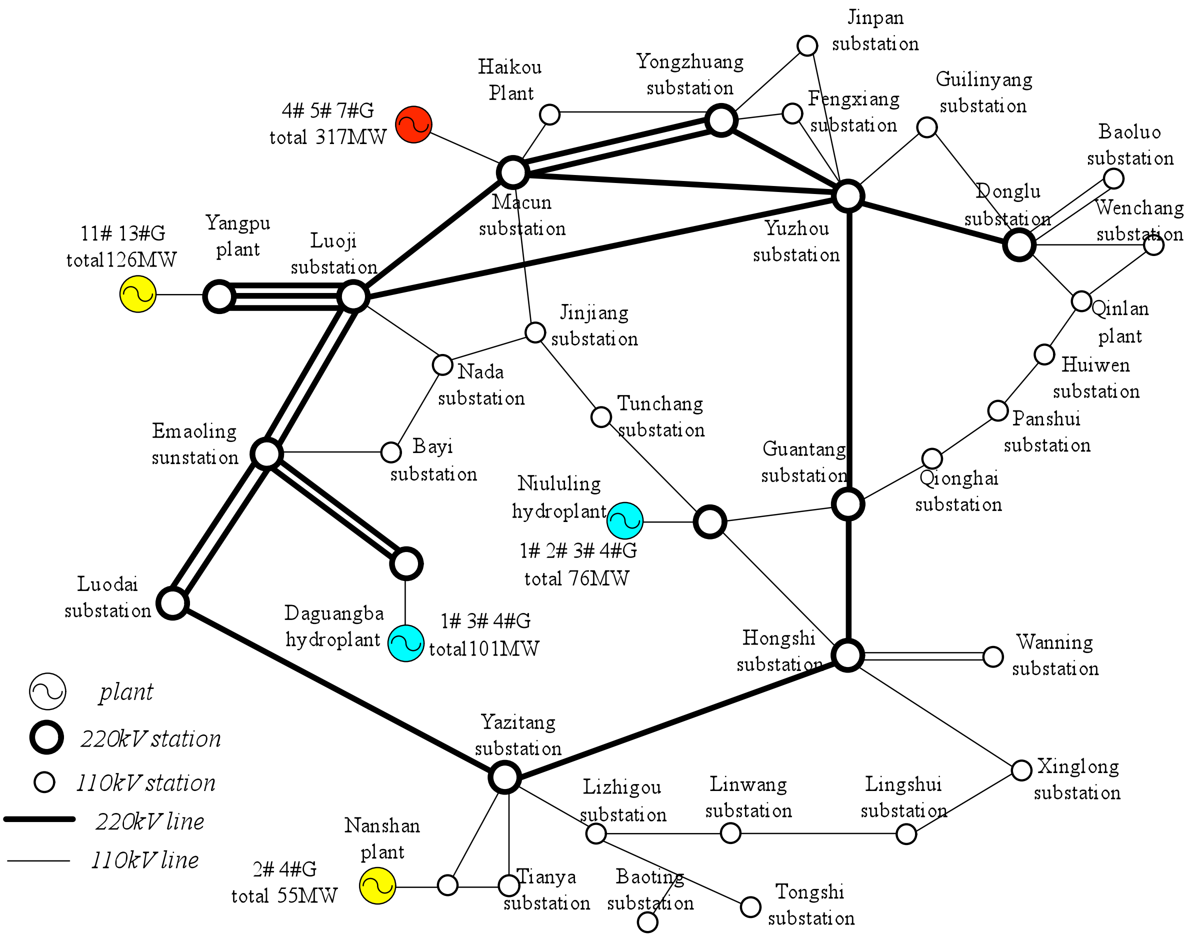

Fig.1 The frame of 220kV power grid in Hainan Island

This paper will introduce the blackout in Hainan Island power system, and the process of the startup and analyzing cause of the faults. Subsequently the procedure of the startup will be discussed. The experiences will be summarized and some suggestion will be offered.

2. THE PROCESS OF THE BLACKOUT

2.1 Mode of operation before the faults

Hainan island power system was operating normally before Sept.25 th. All the plants and substation were operating normally. The generators #4, #5 and #7 ran synchronously in the Haikou plant. The total output of the three generators is 317 MW. Generators #11 and #13 ran synchronously in the Yangpu plant. The total output of the two generators is 126 MW. Generators #2 and #4 ran synchronously in the Nanshan plant. The total output of the two generators is 55 MW. Generators #1, #3 and #4 ran synchronously in the Daguangba plant. The total output of the three generators is 101 MW. Generators #1, #2, #3 and #4 ran synchronously in the Niululing plant. The total output of the four generators is 76 MW. A generator was spare in the Qinglan plant. The generators ran alone with the load of the plant in the Jinhaijiang plant. The total generating load dispatched directly was 675MW. The supply load of Haikou city is 269.3 MW and the supply load of Sanya city is 113.8 MW.

2.2 Process of interruption of power supply

At 20:00 hrs on September 25 th, the level 10 typhoon began to arrive on the island. From 20:00hrs on September 25 th to 1:20 hrs on September 26 th, many lines protection tripped and a lot of loads were lost in the Hainan Island power system. Five 220 kV lines tripped. The Yongyu line dropped out. Twenty-six 110 kV lines dropped out. The Qionghai, Panshui, and Tunchang substation were in the no-voltage state because of holding faults. The Niululing hydro-plant disconnected from the power system because of holding faults. An isolated island came into being in the Tongshi and Baoting regions. The island with 4.3 MW load was maintained by hydro-plants.

Altogether the many holding faults led to a lot of load loss and blackout in a large area. The load of all of the power system decreased from 675MW to 253MW. The load in Haikou city decreased from 269.3 MW to 50 MW and the load in Sanya city decreased from 113.8MW to 68.9 MW.

2.3 Process of blackout in Hainan Island

At 1:20 on the 26th generators #5 and #7 were connected to the grid synchronously and supplied the load with 146 MW power in the Haikou plant. Generators #11 and #13 were connected to the grid and supplied the load with 78 MW power in the Yangpu plant. Generator #1B was connected to the grid and supplied 21 MW power for the load in the Nanshan plant. Generators #1 and #4 were connected to the grid and supplied 8.1 MW power for the load in the Daguangba plant.

At 1:22:31.074, a short fault between b phase and c phase occurred intermittently in the Guantang side of the Yuguan line. The faults lasted for 2794ms, 4145ms and 9553.4 ms respectively. The intermittent span among the faults was 966ms and 748ms. The relay tripped rightly in the Guantang side. The relay didn’t work in the Yuzhou side.

- At 1:22:45.212, the circuit protection tripped in the Macun side of the Mayu line.
- At 1:22:45, the negative-order current protection of the #13 and #11 generators tripped in the Yangpu plant. The plant lost 78MW load.
- At 1:22:46, the voltage and over current protection of the #7 generator tripped in the Haikou plant. The plant lost 79 MW load.
- At 1:22:47, the voltage and over current protection of the #5 generator tripped in the Haikou plant. The plant lost 79 MW load.
- At 1:22:47, the stability and control equipment work, and cut the load of 20.5 MW.
- At 1:22:58, the low frequency generator protection of the #1B generator in the Nanshan plant tripped when the frequency is lower than 47 Hz. The plant lost 21MW load.
- At 1:25:30, the low frequency protection of the exciter of the #2 generator tripped.
- At 1:26:0, the frequency decreased to 31hz. The field failure protection of the #4 generator tripped in the Daguangba plant.
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The power system broke down.

3. THE BLACK START AND RESTORATION IN HAINAN ISLAND

After the blackout, emergency started-up was initiated by the Hainan grid corporation . The multiple electrical sources were organized. The important cities such as Haikou, Sanya, Danzhou, and Dongfang were supplied with electrical power as soon as possible.

At 1:35 on 26th. the generators in Nanfeng hydro-plant were dispatched to start up. At 2:00, generator #1 started up successfully. At 2:27, electrical power was transmitted through the 110kV Nanan line. At 2:40, important load in Danzhou city was supplied with the electrical power. Electrical power was transmitted from Nada substation to Haikou plant at 2:50. The relay of Najin line tripped at 4:10. The electrical power was transmitted to Haikou plant again at 4:27.

At 2;50, the Qushou plant started up by diesel engine and supplied the Daguangba plant with electrical power. At 2:54, generator #2 in the Daguangba plant started up successfully and at

3:35 the over-voltage protection of generator #2 r tripped. At 3:39, generator #2 started up again. Electrical power was transmitted from the Daguangba plant to Haikou city at 3:39. Important load in the Dongfang city was supplied with electrical power at 6:35.

At 5:03, most substations in Haikou city were supplied with electrical power.

At 1:30, the black-start procedure was implemented in the Yangpu plant. Diesel generator #12 started up successfully at 5:10. At 7:00, generator #12 was connected to the power grids synchronously. At 7:59, important load in Haikou city was all supplied with electrical power. Generator #4 in the Haikou plant was connected to the power grids.

At 1:33, the dispatch center of Sanya city was commanded to execute the black-start procedure. From 1:40 to 5:15, the Xiangshui hydro-plant and Youyi hydro-plant started up in order to supply the Nanshan plant with electrical power. But the scheme failed. At 10:28, generator #2A was started up by the generation car.

The subsystem built by Daguangba plant and Nanfeng plant connected synchronously the subsystem built by Yanpu plant and Jinhaijiang plant. The total load reached 92 MW. From 11:26 to 11:55, separation happened again. At 16:30, the system came back into the pre-state.

At 24:00 hrs on the 26 th, electrical power was transmitted to eleven counties among 18 counties. At 17:46 on the 27 th, all the 110kV substations started up. At 19:07 on the 28 th, the 220kV power system restored to a ring system. At 18:00 on 29th, the main frame of the power grid was supplied by electrical power in the Hainan Island. At 18:12 on September 30 th, the 110kV lines were electrified. The dispatched load reached 828MW. On October 1st., electrical power was transmitted to all the 35kV substations. The dispatched load reached 846.5 MW.

On October 9 th, the black start succeeded completely.

4. ANALYSIS OF THE BLACKOUT

The speed of the typhoon exceeded that used in planning the lines. The distributed lines tripped which couldn’t experience this violent typhoon. These faults led to the blackout in the Hainan Island power system. On the basis of the related standard, the planned wind speed of the 35kV lines is 35 meter per second. the planning wind speed of some 10kV lines is 30 meter per second and the planned wind speed of other 10kV lines is 25 meter per second. The holding faults happened in the six lines among twenty 220kV lines. And the holding faults happened in the 24 lines among ninety-nine 220kV lines. One hundred and twenty three 35kV lines were destroyed. one thousand nine hundred and fifty seven 10 kV lines were destroyed in the whole power system. The typhoon led to great loss of power.

The width of the line corridors and the safe distance were not sufficient. There are many trees in Hainan Island that are tall and have strong vitality. The residents use the trees as the means of anti-wind and pocketbook. It is too difficult to clean up the corridors for the electric power corp. The trees are broken by the typhoon on the two sides of the corridors and which led to a lot of faults.

Fig.2 The short fault on b phase to c phase of the coupling capacitor.

The typhoon led to a short fault on the Yuguan line and led to the DC source not working in the Yuzhou substation. The line protection didn’t trip, which led the power system to be outaged. The B phase to C phase short fault happened on the coupling capacitor on the side of Guantang substation. The breaker didn’t trip, which brought on backup protections of the Muyu line, Yuluo line, Haikou plant and the Yangpu plant tripped successively.

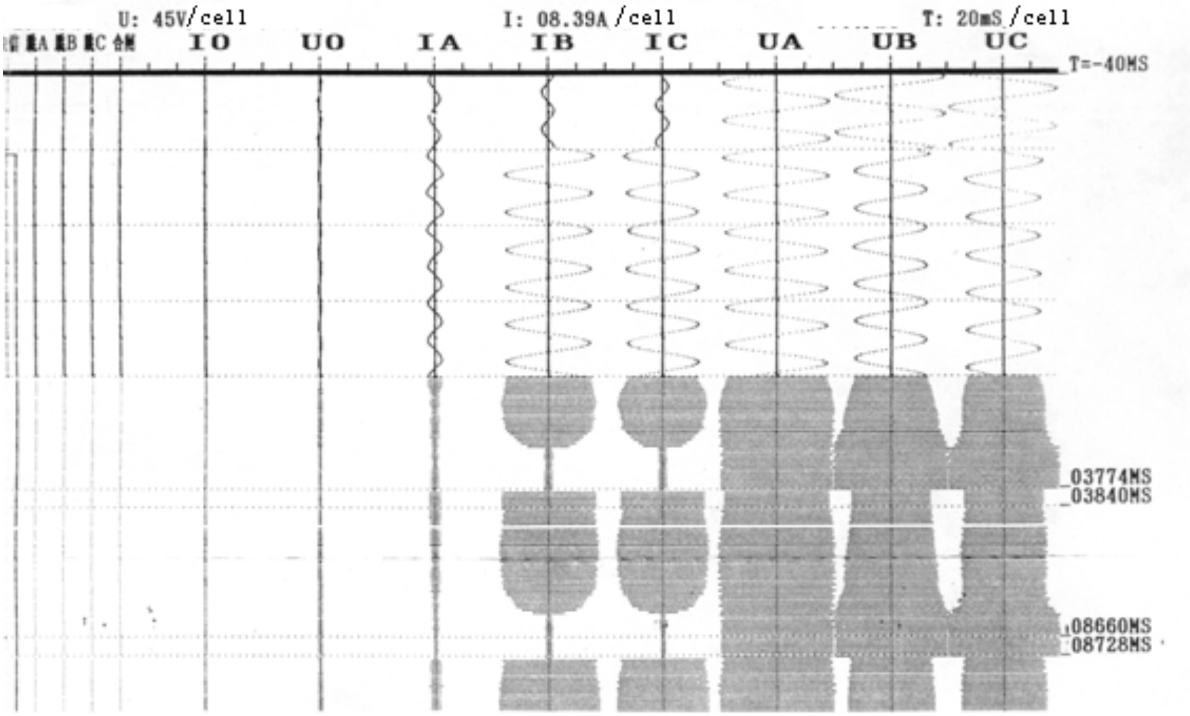

Fig. 3 the wave of the bus in the Haikou plant when Mayu line relay tripped.

After generators #5 and #7 in the Haikou plant and generators #11 and #13 in the Yangpu plant disconnected from the power system, the power supply transmitted to the system decreased to 12%. The active power could be balanced with the active load. The frequency of the system decreased fast so that the generators in the Nanshan plant and Daguangba hydro plant tripped. The main system broke down.

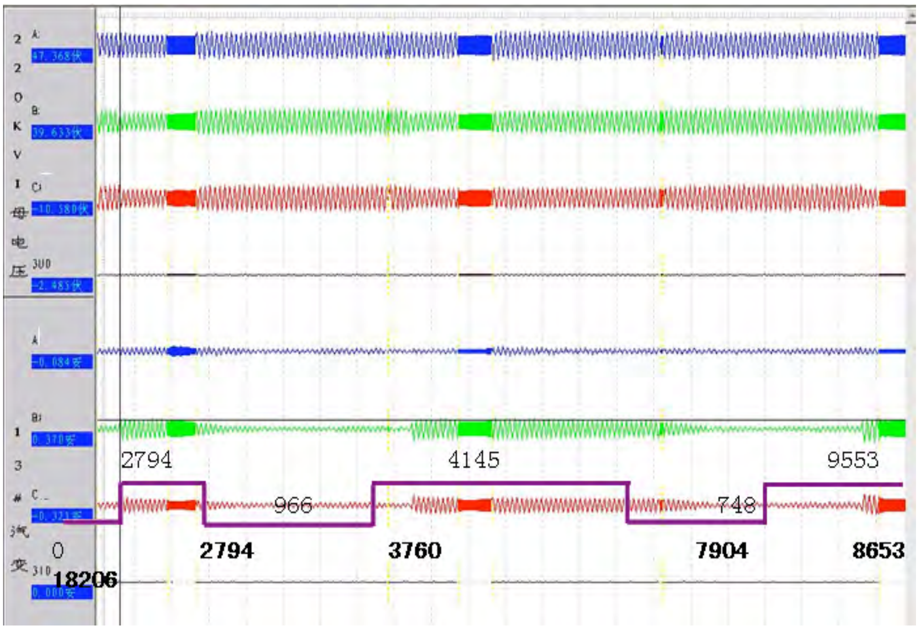

Fig.4. The voltage and current waveform when the fault happened in the Yangpu plant.

5. SOME EXPERIENCE

The emergency electrical source must be prepared. The communication equipment and the automation equipment must work surely. Before the typhoon came, the electrical power corporation prepared backup electrical source, diesel engine and enough diesel. The automation equipment was working effectively all the time when the black-start scheme was implemented. It is important to keep the communication system straightway that the dispatcher knew the state of system and dealt with the accident surely.

When the black start scheme was implemented, multiple electrical sources, multiple directions and multiple subsystems could improve the efficiency greatly. The dispatch center organized multiple electrical sources through multiple routes to start up the system. The idea that Haikou plant first started up and supplied power to the Haikou city ensured that the black start succeeded and the island restored regeneration fast.

Ensuring the house load and the ability for self-triggering of the generators is the key measure for the success of the black-start. Enough preparations were made in the Nanfeng hydro-plant. Generator #1 in the Nanfeng hydro-plant started up successfully in half an hour and supplied the Haikou plant with power through the Nanan line, Najin line, Jinma line, which laid a foundation for the black-start. Generator #2 in the Daguangba plant disconnected from the power system and operated on house load.

It is an important allow for black-start to ensure the equipment starts safety in the main plant.

To improve the speed of black-start, it is necessary that careful preparation is made, the detailed scheme is established and the operation is implemented. Before the typhoon came, the electrical power corporation had made a detailed preparation. After the blackout, the plants strictly implemented the dispatching command. The China Southern power grid corporation organized a repairing contingent of 355 people for rushing to repair to Hainan Island. 80% load was supplied with power the next day. Power were transmitted all the over the province.

6. THE EXPOSED PROBLEM

The Hainan Island power system is separated from the main land. It is a protruding problem that the large generating capacities don't match to the small power grid. Stability is on a low level. The Hainan power grid structure is weak; the reliability of the key cities grid is poor. Reliability of the secondary equipments is poor; few secondary circuits were designed unreasonably. The research of the black-start scheme, training and management needs to be strengthened. The main power plants that have no secure configuration are lacking of self-starting capability. There are few operating staff and they lack experience of dealing with unexpected incidents. The backup protection settings of the generator units in the main plant is questionable.

7. SUGGESTION

Combined with the problems exposed with Hainan's economic development strategy, the following measures and recommendations are put forward. The construction of Hainan networking should be speed up. The power should be balanced with the load of each division by adjusting planning ideas and planning for power points rationally. In accordance with the requirement of stability guidelines, the generating capacity of single generators should be planned reasonably. The building of the main grid, secondary system planning and reactive power planning should be strengthened.

The related issues of power grid construction should be researched again. It is important for the stations to improve the shielding resilience. Closely relying on the government and social support, the electrical power corporation should protect the line corridors and facilities. Accelerating technological upgrade of the power equipment is necessary.

At the same time a number of subsystems are launched, which is an effective way of rapid restoration of power grid operation. The launching path of the black-start should be set according to voltage levels and the principle of multi-path. To ensure normal operation of the dispatching system is essential. The building and management of house power should be strengthened. Perfecting the operation mode of the isolated island is important. Strengthening staff training and drills is necessary.

Taking effective measures should enhance the reliability of power supply in the key cities. The important users must be set with double power supply.

Adhering to unified dispatch and strengthening the technical supervision of the equipment will be essential.

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7. Complex Emergency Control System against Blackouts in Russia

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Abstract— Emergency control is an inherent part of operating control of electric power systems. The paper describes the experience gained by the Unified Energy System (UES) of Russia, its emergency control arrangements and components. The UES control system represents a hierarchical structure of dispatch centers with a clear separation of the all-system and local normal and emergency grid control responsibilities. In the UES emergency control system, there are several "lines of defense" starting from the preventive arrangements and operating procedures, ending by local automatic protection devices. Some elements this system may not be widely known in western countries. Meanwhile, over the many years Russia developed set of advanced solutions to address power grid problems similar to the ones that appears now in western countries.

Index Terms— Electric power system, Emergency control, Automatic protection devices**.**

1. Introduction

An important trend in electric power industry is towards integration of electric power systems (EPSs) and formation of regional, state and interstate interconnections on this basis. Interconnection of EPSs results in system effects owing to maneuvering the energy resources, generation capacities and power flows. The integration of power systems is primarily intended to provide consumers with power and power services of high quality on the whole territory of the interconnection. Thus the electric power industry becomes to a larger extent an infrastructures sector of the economy.

Russia's electric power industry has passed a long way from construction of the first large power plants interconnected by electric networks (envisaged in the plan of "GOELRO") to formation of the Unified Energy System of Russia – the world largest centrally controlled power interconnection. As Russia's UES expanded, the problems of control became more and more complicated due to very extended electric networks, unevenly distributed energy resources and production forces on the territory of the country, complex structure of generation capacities and configuration of main electric networks

[1].

Emergency control that provides reliability and survivability of the interconnection plays an important part in controlling the operating conditions of Russia's UES. Emergency control is performed by the technological (dispatching and automatic) control systems that include the automatic systems of voltage, frequency and capacity regulation, basic automatic systems of EPSs elements, relay protection and automatic line control, system emergency control [2, 3].

Liberalization of electric power industry has led to a dramatic change in the UES organizational structure that is no longer coinciding with its technological and control structures. Market developments resulted in higher power exchanges (with short-term commercial

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objectives), and of course were not taken into account in the original system design. All this led the system to operate closer and closer to its limits according to current security criteria and made the UES operation insecure. Therefore, blackout prevention became a key task in developing the emergency control.

2. Emergency Control Systems in Russia: General Considerations

The power object called “Unified Energy System of Russia” is a power interconnection, where seven Interconnected Power Systems (IPSs) are combined by weak ties. Under the emergency conditions the UES of Russia as a power interconnection is able to disintegrate into autonomously operating self-balanced IPSs without grave consequences.

At the same time disintegration of any of the mentioned seven IPSs is far from smooth. Because of large power flows in the ties, practically any disintegration creates parts with power lack and power surplus. As a result, load and generator disconnections are quite possible and can acquire a cascade character, i.e. turn into system crash fault. For this reason at the IPS level the generator and load disconnections by special system emergency devices (in order to unload cutsets and to maintain admissible values of operation parameters) are of course more preferable than cascade disconnection by protection devices (after these parameters go beyond the fixed limits). Just this principle is basic for arranging the emergency control in Russian EPSs [2, 3].

The emergency control system in Russia’s IPSs includes the following components:

A) Dispatching emergency control: to provide admissible loading of the electric network ties according to the Guidelines on power system stability.

B) Automatic emergency control:

- *in pre-emergency conditions* – to maintain necessary transfer capabilities of ties by efficiently controlling them through the use of PSS; synchronous machines; control systems of reactive power sources, DC links, etc.
- *in emergency conditions* –
  - The above automatic controllers and control systems – to maintain the voltage levels and damp the oscillations in EPS;
  - Automatic stability control of EPS;
  - Automatic frequency load shedding; automatic voltage deviation limiting, automatic isolation of power plants with maintaining the auxiliary power supply, etc.

C) Restoration of EPS after large emergencies.

The main principles of emergency control system operation in Russia’s IPS are:

- Observation of standard transfer capabilities margins in electric ties in pre-emergency and post-emergency operating conditions;
- Echelonized system of automatic emergency control whose actions are coordinated in order, depending on type, time and severity of emergency; the system is aimed at interrupting the emergency process development at its earliest stage;
- Prevention of development and interruption of severe system emergency is an exclusive prerogative of the automatic emergency control system due to a fast development of the process and, therefore, impossibility for dispatcher to act adequately; after a large emergency EPS is mainly restored by dispatching personnel through the use of some automatic systems.

3. STRUCTURE OF CONTROL CENTERS AND PRINCIPLES OF REAL-TIME DISPATCH – S[ST] LINE OF DEFENSE [4]

3.1 Principles of operation of the grid control centers

The main principles of the Russian hierarchical dispatch system are as follow [3]:

- Separation and independence from the administrative and economic management functions.
- Hierarchical structure with the direct subordination of the lower-level dispatchers to the higher-level dispatchers.
- Independence of the dispatchers at each level when intervention from the high-level dispatchers is not needed.
- Clear definition of the dispatch personnel responsibilities at each level at normal and emergency conditions, and
- Strictest dispatch discipline.

The basis of the Russian dispatch system is formed by the centralized Automated Dispatch System (ADS). The ADS structure is shown in Fig. 1 [3].

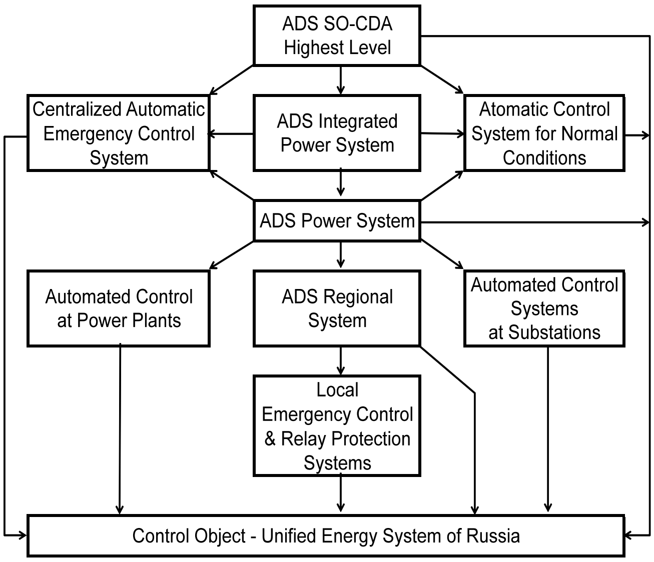

Fig. 1. Russian centralized automated dispatch system [3]: “System Operator – Central Dispatch Administration” (SO-CDA) is the highest level of the Russia’s Unified System dispatch hierarchy.

3.2 Hierarchical state estimation – "Wide area" approach

Availability of the actual power flow model provided by the state estimation algorithms is considered in Russia as a necessary condition for the adequate decision-making by real-time dispatchers[4]. Periodic state estimation is conducted automatically and simultaneously on the upper and lover levels of the dispatch control hierarchy. The lower level results are sent to the upper levels where they are processed and combined together to form a wider-area state estimation model. State estimation results are presented on the “visual walls”. Visual walls form a friendly interface to the dispatchers where the state estimation results form a comprehensive, easy-to-understand, changing image that helps a the real-time dispatcher to quickly apprehend and understand the situation.

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[4] One of the main reasons of the US-Canada blackout on August 14th, 2003, was the lack of “wide area” visibility of the system state and processes in the neighboring Control Areas [4, 5].

3.3 Interconnection frequency control

Significant and/or sustained deviations of the interconnection frequency can cause the under- or over-frequency relaying and force some loads and generators out. Under unfavorable conditions, this may result in a cascading failure and system collapse (that is pictorially called in Russia "an avalanche of frequency"). Under the steady-state conditions, frequency is a uniform parameter in an AC interconnection, and it appears to be logical and most efficient to control it from one designated center. The fundamental difference between the existing frequency control approaches used in the USA and Russia may be briefly categorized as de-centralized approach vs. the centralized approach[5].

Frequency control in Russia is based on the combination of:

- *centralized frequency control,*
- *manual operating procedures,*
- *coordinated automatic actions,*
- *under- and over-frequency relaying,*
- *mandatory reliability requirements.*

The Russian frequency standards limit frequency deviations at normal operating conditions by ±0.1 Hz. Short-term deviations are limited by ±0.2 Hz [6]. Manual Operating Procedures [3, 4, 7]:

- *Sudden Frequency Decrease by 0.1-0.2 Hz*. The SO-CDA dispatchers determine the reasons of the decrease and issue mandatory instructions to the dispatchers of the IPS to increase generation by using a specified amount of the spinning reserves. The instructions must not cause violations of the operational transfer capability on the interties connecting regional systems.
- *Subsequent Frequency Reduction by 0.5 Hz and Lower*. The SO-CDA and IPS dispatchers issue mandatory instructions to the plants to fully engage their spinning reserves and to start up non-spinning hydro generators, to move the units operating in the synchronous condenser mode to the generation regime, and to increase generation on the thermal power plants. All transmission constraints must be satisfied.
- *Further Frequency Reduction Regardless Under-Frequency Relays Actions; Frequency Decrease Remains 1 Hz or Lower for 3-5 Minutes*. The SO-CDA and lower level dispatchers issue mandatory instructions to curtail the load; this must not cause transmission violations. Lower level dispatchers obey SO-CDA instructions, but they also make their own decisions; if their area is separated from the system or frequency reduction reaches 1.5 Hz, they act completely independently shedding the load (after 3-5 minute delay needed to engage all generation available reserves).

Similar procedures are developed to cope with the frequency increases. Frequency excursions of such a magnitude can only happen when some parts of IPS separate from the rest of the grid with significant load/supply imbalances inside them. Nevertheless, the corresponding procedures are enforced, and the dispatch personnel if trained to follow them.

3.4 Real-time emergency dispatch procedures in Russia **[3]**

[5] The decentralized approach concerns the *secondary* frequency control loop only: local *primary* frequency controls (such as speed governor and load frequency responses) remain local controls.

The system failure development process is usually too fast to allow real-time dispatchers to intervene. The power grid under these conditions is controlled by the emergency control systems and relay protection schemes.

In the most number of cases, the real time dispatchers start to act at the post-fault stages. Their task is to restore power supply of interrupted loads return the operating conditions to normal as quickly as possible. The emergency dispatcher control is performed by coordinated actions of real-time dispatchers at different levels of the dispatch hierarchy.

The main condition of a successful emergency control is considered to be *an optimal separation and definition of the higher and lower level dispatch functions*. The core idea is to provide maximum degree of independence of the lower-level dispatchers addressing their regional emergency situations. The upper level dispatchers intervene only when the problem becomes their level problem. Thus, the SO-CDA dispatchers lead the emergency control in situations where the problem becomes system wide, such as faults on the interties connecting IPSs, system separation, frequency reduction, etc. The entire process is instructed by very clear operating procedures[6].

Moreover, the Russian standards establish detailed guidelines for periodic mandatory training of the dispatch personnel including extensive training to cope with the emergency conditions.

The restoration process in Russia is similar to the process in USA[7], but a higher-level dispatcher in the dispatch hierarchy leads the procedure. The procedure includes the following steps [2, 3]:

- *Recovery of the Generation Capacity*. The first priority of the dispatchers is to prevent damages or long-term capacity loss on the steam turbine units and nuclear plants that remain operational under the no load condition. The recovery process begins with starting the hydro and combustion turbine units. The supply from these units is then used to feed auxiliary loads and start non-spinning steam turbines. As a black-start measure, at the dangerous excursions of the system frequency or voltage, some generators are separated from the grid and are kept spinning to use them later in the restoration process.
- *Resuming Normal Operations on Substations*. The key concern is maintaining a sufficient air pressure to provide conditions for close air breakers. Another important concern is preventing dangerous voltage surges and frequency declines; it is prescribed to lower voltage before connecting lines with large capacitance; connect additional loads on intermediate substations of long-distance transmission lines; temporarily deactivate automatic protection devices such as automatic re-closing of circuit breakers, under-frequency relays, on load tap changers, etc. Manual restoration of system loads during a frequency recovering process is allowed by permission of the SO-CDA dispatcher to prevent secondary frequency declines.

4. AUTOMATIC CENTRALIZED EMERGENCY CONTROL SYSTEMS – S[ND] LINE OF DEFENSE [4]

Emergency control system in Russia's EPSs operates under the principle of hierarchy, i.e. combines different levels of related and subordinated systems and devices (Fig. 2).

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[6] These procedures address deep reductions of the frequency and voltages, sudden reductions of the frequency and voltages, overloads on the transmission lines, asynchronous operation, system separation, etc.

[7] Except that the interchange schedule is not a concern since the Russia's Unified System does not have a multi-area structure based on controllable interchanges.

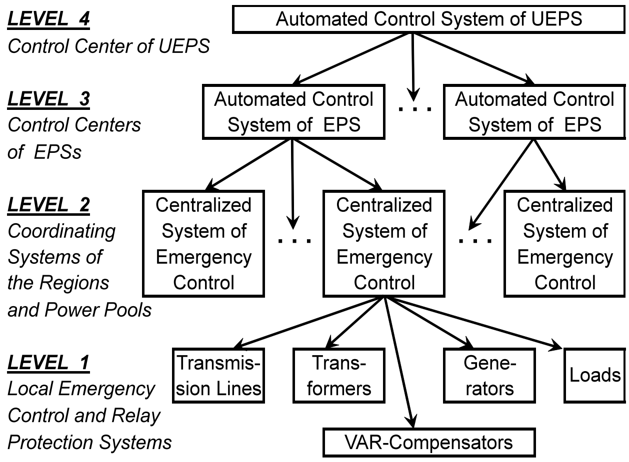

Fig. 2. Hierarchical system of emergency control.

Automated centralized emergency control systems (CECS) are installed in several EPSs and intended for taking the coordinated control actions aimed at prevention of the system emergency development, maintenance of the steady-state and transient stability and keeping the main grid in operation. There are 10 CECS systems, which control large regions of the UPS under emergency conditions [4, 10]. These include Ural and Middle Volga IPSs, Taymyr&Norilsk and West Siberia EPSs, Krasnoyarsk-Bratsk-Ust'-Ilimsk power pool, and others [3].

The main use of the CECS is providing system stability [8]. These systems collect and process information regarding the current state and disturbances in a large power system region or in the entire power system. The remedial actions may include a variety of geographically dispersed measures triggered by sophisticated algorithms.

On the level of an individual EPS the CECS performs on-line the following functions:

- Tracking the EPS topology (from remote signals),
- Determination of load-flow conditions (from remote measurements),
- Assessment of EPS stability and detection of emergency contingencies, when the system is unstable,
- Identifying the danger of instability and decision-making whether remedial actions are necessary.
- Selecting of the most effective actions to prevent instability from the arsenal of available remedial actions.
- Determining the size of the corrective remedial actions.
- Formation of signals (in terms of disturbance parameters) for adjustment of local devices.

4.1 CECS: Structure and principles of operations [3, 4, 9]

A typical structure of a CECS is shown in Fig. 3. The data regarding the current state of the system, collected by sensors, are channeled (through a telemetry system) to the CECS Computer. This computer estimates the current state of the system, simulates emergencies, and determines remedial actions required to prevent instabilities for all specified contingencies. Selected remedial actions are stored in the memory devices. The CECS process is repeated automatically and periodically to follow changes in power flow conditions. The triggering devices are monitoring certain key parameters changes in the system used to detect specific emergency conditions. These parameters can be similar to the parameters used in the relay protection triggering mechanisms, or they can be some other parameters such as generator's acceleration, voltage dips, etc. If a specific disturbance is detected, a signal is generated by the corresponding triggering device and sent to the relevant memory devices. The memory devices, activated by the triggering signal, release pre-calculated emergency control signals to control devises, executing remedial actions.

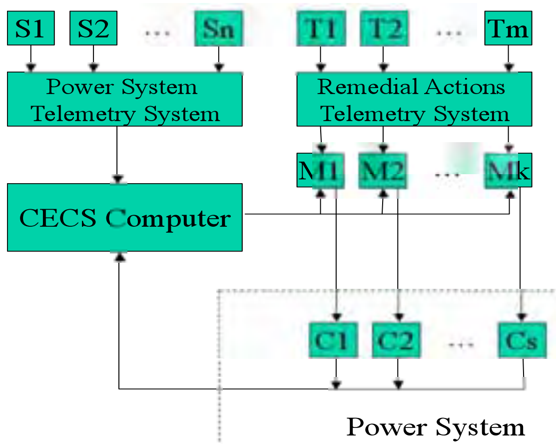

Fig. 3. CECS Structure:

- S1,…, Sn are sensors installed in the different parts of the system;
- M1,…, Mk are memory devices;
- T1,…,Tm are triggering devices;
- C1,…,Cs are control devises.

4.2 CECS: Brief description of the algorithms [3, 4, 8, 9]

The CECS system shown in Fig. 3 is an example of a system based on the remedial actions pre-calculated at normal operating conditions (BEFORE principle). There are also systems based on the AFTER principle where remedial actions are calculated in emergency conditions. The AFTER systems are mainly used in local emergency control systems described in the next Section. Among the BEFORE CECS algorithms, there are non-adaptive (I-BEFORE) and adaptive (II-BEFORE) algorithms.

I-BEFORE. The non-adaptive algorithms are based on the stability boundaries pre-calculated offline beyond the CECS cycle and usually approximated by polynomials in coordinates of controllable parameters. Remedial actions corresponding to particular emergency conditions are also pre-calculated and stored in a special table.

Within the CECS cycle, the CECS computer algorithms solve the following problems:

- State estimation of the current operating point.
- Positioning of the current operating point is against the approximated stability boundary.
- If the operating point is found outside the boundary, a pre-calculated remedial action is selected from the table to bring the operating point back inside the stability boundary.

The procedure is repeated for each simulated emergency.

II-BEFORE. In adaptive CECS, remedial actions are calculated directly within the cycle for each of the simulated emergencies. The procedure includes the following steps:

- Fast calculation of the post-emergency power flow.
- Fast calculation of the stability margin.
- Fast calculation of remedial actions when they are required.

To fit these calculations into the CECS cycle, simplified models are employed at each stage.

5. LOCAL EMERGENCY CONTROL AND PROTECTION DEVICES – V[RD] LINE OF DEFENSE [4]

Russia's protection an emergency control systems include multiple elements; some of them are not widely known or used in Western countries. These elements represent a common whole system distributed emergency control system that is structured, designed, tuned, prioritized and coordinated according to the system conditions, protection functions, selectivity, and reservation. Similar to the US grid, this system is triggered by local parameter variations and applies local remedial actions; at the same time, in some extent, it is designed to address more general tasks of coordinated protecting of the entire control area and even the entire Unified Power System and preventing secondary failures and wide-spread cascading developments. The Russia's coordinated emergency control system also provides a coordinated protection of key transmission and generation facilities as well as inter-area transmission lines. The high-level control centers are responsible, and has sufficient authority, to ensure adequate protection of key facilities in the grid and to make sure that the entire decentralized protection and emergency control system is coordinated and operates as a whole without conflicts between local area subsystems, "blind spots", and that the local failures are not propagating through the system.

5,1 Transmission lines relay protection [4, 10]

All main transmission lines in Russia are protected by high-speed relay protection (RP), mostly using carrier current phase comparison. On 750 and 1150 kV lines, a more sophisticated RP is used in which two methods of fault detection are combined: directional (used during symmetrical three-phase operation) and phase-difference (used in two-phase operating conditions during the cycle of one-phase automatic re-closing). Transformers and bus bars are equipped with the high-speed RP with the time of operation ≤ 20 ms.

The most difficult problem is fault clearing in the case of main RP or circuit breakers failures. The oldest type of the back up RP is the remote back-up design providing fault clearing in the cases mentioned above. Nowadays, the local back up RP is added – circuit breaker failure protection (CBFP), which results in lesser time for short circuit clearing and better sensitivity and selectivity. If a circuit breaker fails to open, CBFP gives commands to open all neighboring circuit breakers. CBFP is installed at all main substations and power plants. The CBFP time delay is ~0.3-0.4 s at 330-1150 kV substations and ~0.5 s at 110-220 kV substations.

5,2 Automatic flow limiters

The Automatic Flow Limiter (AFL) is a special protection system invented and widely used in Russia [4, 10]. Its purpose is to automatically prevent overloads on the transmission facilities under normal and contingency conditions. This system significantly increases grid reliability by preventing transmission lines trips caused by stability conditions or overloads. By doing so AFL helps to prevent further aggravation of system problems and cascading. AFL operates as a 'watchdog'. If the controlled power flow is found within the limits set for both directions, the Limiter does not operate. When the controlled flow exceeds the limits, the Automatic Flow Limiter starts to regulate the designated power plants on the both sides of the line maintaining the an overall power balance in the system. AFLs are fast acting emergency control systems with the time constant of about 15-30 s. The AFL operation is coordinated with the other control systems such as the Automatic Frequency and Flow Control[8]. Potential conflicts between these two systems are resolved by giving the higher priority to the Automatic Flow Limiters as an emergency control device.

5.3 Automatic system separation

Automatic system separation (AS) is used in Russia as an emergency control measure to prevent instability, eliminate asynchronous regimes or to preserve auxiliary load supply capability on power plants by isolating designated generation units [8]. AS is performed by tripping

[8] This system is similar to the Automatic Generation Control Systems (AGC) in the United States.

transmission lines connecting different parts of the system or by opening bus bar breakers at substations. Stability-oriented AS schemes are triggered by events (e.g. line tripping) or by some other criteria such as increasing power flows, voltage angle differences, etc. In the USA, this effective measure has recently become a subject of research work [11].

The automatic systems preventing asynchronous regimes are extremely important in preventing the blackouts and increasing the overall survivability of a power system. They analyze and compare currents and voltage phase differences on the controlled lines. The system separation signal is generated after 2-3 asynchronous swings. In cases where a real danger of a fast development of the asynchronous regimes (within 1-2 asynchronous swings) with multiple frequencies exists, the AS schemes are used that react to occurrences of significant angle differences on the controlled lines (usually in the range 90-180 degrees). The most difficult task is to determine the configuration of the regions that need to be separated.

The automatic isolation of designated black start units is triggered by deep reduction of the system frequency (up to 45-46 Hz). Obviously such reductions may only occur as a result of severe cascading failures. The main objective here is to keep some generation units running to start-up power plants later during the system restoration process.

5.4 "Strong action" PSS

The Power System Stabilizers (PSS) installed on many generators in Russia have a different structure, use additional input signals, and are thoroughly tuned to ensure their best performance in the system and coordinated operation with the other PSSs. They are called the “strong action” PSSs, which allow to significant increase the steady-state stability margin (by ~10%), effectively damp oscillation, and stabilize transient processes. They also help to prevent sudden reductions of nodal voltages.

Comparing to the PSSs used in other countries, the “strong action” PSS systems employ derivatives of the input parameters and use more significant gains in their stabilization channels. Regulators of this type are installed on all hydro and thermal generators rated 100-200 MW and more [10].

5.5 Voltage support from generators

The Russian reliability standards require all generators and synchronous condensers to be equipped with power system stabilizers and forced excitation systems [12]. It is also required to boost the excitation emf on generators to its maximum acceptable levels (not less than twice its nominal value) at significant voltage declines. At emergency conditions, a short-term overload on generators is permitted[9].

5.6 Fast valving and turbine torque restriction **[8]**

The fast turbine valving is an automatic short-term measure is used to minimize the kinetic energy gained during the fault and the following pause before re-closing the circuit breaker. The valving is performed by temporary closing the valve that regulates the steam flow from the steam generator to the turbine. It is triggered by the fault. Due to the inertia of the steam mass, there is a ~0.2 s delay in the actual response. The resulting decrease of the mechanical torque helps to reduce acceleration of the generator’s rotor. The size, duration, and the shape of the control impulse are limited by the danger of an excessive deceleration of the rotor with the resulting instability at the second or subsequent swings. If the re-closing is not successful and the circuit breakers open again, the turbine torque restriction is usually applied. This measure restricts the mechanical torque during the post-fault condition. It is triggered by the fact of unsuccessful fault

[9] For instance, the stator current can be increased by 10% from its nominal value for 60 min, and by 50-100% for 1 s. The rotor current is allowed to be increased by 6% for 60 min, and by 100% for 20-30 s. These numbers depend on the type of the rotor and stator cooling systems.

clearing. It performed to a certain minimum turbine load level dictated by its technology, usually to 50-60% of the nominal load. If a further reduction is needed, the automatic generator tripping is executed as it is described below.

5.7 Dynamic breaking

To ensure stability at the first cycle of synchronous swings at significant disturbances such as three- and two-phase faults nearby a large power plant, it may be required to apply more significant stabilizing measures. One of them (used in Russia) is the dynamic breaking. Dynamic breaking automatically applies an additional electric load – parallel or sequentially connected breaking resistor. Switching is performed using fast thyristor-based systems.

5.8 Automatic generator tripping to provide stability [8]

This type of emergency control is used to prevent instability in contingencies related to the tripping of network components and the corresponding weakening of the transmission paths. Generator or unit breakers perform switching with the minimum possible delay following the disturbance. The switching is performed no later than 0.2-0.5 s after the disturbance. The stabilizing effect is provided due to the reduction of the power flow in the lines forming the stability limited cut set during the transient process and in the post-transient system state. Generator tripping helps to increase the decelerating energy by sudden reduction of the equivalent mechanical torque provided by the generators' prime movers. This positive effect could be mitigated due to the reduced electrical torque caused by voltage declines after the generation trip. In this situation, the "strong action" PSSs on the remaining generators help very much to support voltage level. Usually, the generators selected for the tripping are electrically located away from the critical cutsets.

5.9 Under frequency load shedding

This emergency automatic system is generally similar to the one used in the USA[10]. The objective of the Russian under frequency relaying system is to eliminate any possibility of frequency reductions below 45 Hz[11], limit frequency excursions below 47.5 Hz by 20 s, and below 48.5 Hz by 60 s.

Russia's under frequency relay system consists of two main and one optional stage with a well-developed selectivity of frequency settings and time delays [4, 6, 10]:

- *Stage I* is the fast response (t = 0.1-0.3 s) stage that operates in the range of 48.5-46.5 Hz. It prevents sudden frequency drops in the beginning of a large frequency disturbance. Within Stage I, where are different settings for different loads that differ by 0.1 Hz. The size of load curtailment for each setting is approximately the same.
- *Stage II* is designed to restore the normal frequency if it remains at a low level for a longer time. It is also activated in case of additional active power deficiencies that may arise during emergency spreading. The entire series of Stage II settings is set at a value equal to the upper setting of the Stage I or slightly higher, with the time delays between settings of 3 s in the

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[10] The difference is in:

- stronger coordination of these important systems,
- absence of geographical limits in selecting and prioritizing interruptible loads,
- unified and strictly enforced principles of operation,
- well developed staged, deeper, and timed sequence of operations.

As a result, the Russia's grid can withstand severe reductions of frequency and voltages while preserving the all-system reliability and the most important loads.

[11] An approximate evaluation of the minimum frequency at which the cascading failure called "the avalanche of frequency" begins.

interval from 5 to 90 s. Longer time settings of Stage II provide time for mobilizing the power system generation reserves.

- *Stage III* (for some deficient areas in the United System receiving power from the rest of the system) is a high-speed under frequency relaying with the highest setting of 49 Hz. It prevents overloads on the supplying tie lines. To restore the power system frequency more rapidly and to decrease the amount of load disconnected by Stage II, the operating reserve must be expeditiously activated by loading the rotating reserve units, fast start-up, connection to the network, loading the hydroelectric units as the frequency is decreased to 49.3 Hz. In this situation the rapid loading of the hydro and thermal units, which operate partly loaded, is effected. Since a long operation of electrical motors at a reduced frequency may cause a complete loss of thermal power plants, contingency procedures are enforced to separate auxiliary equipment from the network and to supply them with special generators. Schemes that isolate some thermal power plants (or some of their units) with approximately balanced load and generation are applied usually with two thresholds at 45-46 Hz and 0.5 s; 47 Hz and 30-40 s. After elimination of under frequency condition, power supply of disconnected loads will be restored automatically by automatic frequency re-closing schemes.

5.10 Under voltage relaying

Sometimes contingencies and extreme local imbalances of reactive power make it necessary to use special measures, which limit undesirable voltage deviations. When under voltage does occur, the automatic disconnection of shunt reactors on ultra-high-voltage grids may be used to raise the voltage. Also, the automatic boosting the excitation of generators and synchronous condensers, up to overload levels, which are permissible for short periods of time, plays an important role in preventing induced-induced fault spreading. For especially large shortages of reactive power, threatening the loss of steady-state stability ("voltage collapse" type of faults), the automatic voltage load shedding is used. These devices are equipped with two voltage relays having high reset factor with settings equal to 0.85 of the nominal voltage and time relays. There are typically two or three steps of the under voltage relay systems with various time settings in the range of 5-15 sec.

5.11 Over frequency protection

The automatic over frequency protection system prevents frequency increases above or equal to 55 Hz, that can cause further thermal units trips. This system also protects hydro units from the exposure to frequency increases of 60 Hz or more. The over frequency protection system decreases the frequency by tripping hydro units or by controllable network separation. Taking into account the dangers of the power system operation with high frequency, the system is implemented with two stages: the first one (main stage) that trips selected hydro units at 51.5 Hz, and the second one (back-up stage) that operates at 52-53.5 Hz. The second stage shares isolates selected thermal units in the regions with approximately balanced load and generation.

5.12 Over voltage protection

The automatic over voltage protection is provided at 330-1150 kV substations to prevent electric equipment damages in case of one-side transmission line disconnections. Possible dangerous over voltage may also occur due to electric resonance conditions. Surge arresters are the main devices that limit over voltages to a permissible level. For example, over voltages on the 500 kV network should not exceed 1.7 p.u. Over voltages of a lower level can be dangerous as well if they persist over a longer period[12]. The Russian over voltage protection relays address these differences. They consist of the following components: the initiating, selecting, and time

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[12] For instance, the 750 kV equipment is designed to withstand overvoltages of 1.1 p.u. for 1200 s, 1.3 p.u. for 20 s, 1.88 p.u. for 1 sec, and of 1.98 p.u. for only 0.1 sec.

delaying elements. The initiating element, containing three voltage relays measuring phase voltages, detects the fact of an inadmissible voltage increase. The selecting element determines the transmission line that caused the increase. The time delaying element provides the required operation delay. Usually, the over voltage protection system has two stages: the “sensitive” and “coarse” stages. In case of an inadmissible voltage increase, the system (at any stage) turns in the shunt reactor (if it has been disconnected); then, if the voltage does not decrease, trips the idle transmission line; and finally, if line’s circuit breaker fails to open, opens all circuit breakers connected to the failed one. Operating voltages for the “sensitive” stage are 15-1.25 p.u., and for the “coarse” stage they are 1.4-1.5 p.u.

6. CONCLUSION

In accordance with the today’s realities, for effective development of emergency control systems (and respectively for reasonable decreasing the probability of future blackouts) it is necessary[13]:

1) To develop:

- Wide-area coordinated approach to improve the overall security of power grids.
- Procedures regulating interactions and coordination between control centers in emergency conditions, preparedness of the dispatch personnel to act in situations where disturbances and violations are in different control areas.
- Automatic emergency control systems relieving overloads and preventing instabilities, under frequency and under voltage load shedding systems sufficient to prevent uncontrollable cascading, and to provide integrity of the automatic protection equipment.
- Controllable system separation schemes to prevent widespread system failures. This requires advanced measuring and control systems, in which information from several areas and system conditions is integrated.
- Protection systems able to detect voltage collapse in the entire system.
- Mandatory reliability standards.

2) To provide:

- Situation awareness tools for system operators (including real-time information on the forced outages, status of critical facilities, system topology, and system problems). This includes wide-area system visibility and state estimation (including information on the status of the neighboring control areas and dispatcher alarm systems).
- Look-ahead vision capabilities including automatic contingency analysis cycling periodically every 5-15 minutes.
- Clearly defined and robust interactions between informational, computer, and real-time dispatch services and personnel.
- Automation providing survivability of power plants at large power deficiencies in the system (power stations should disconnect from the grid earlier to go into house-load operation before a system collapse), and possibility of restoring voltage from these plants at system black starts.

As it can be seen from this paper, most of the above listed tasks are already solved (fully or partially) in Russia. The authors hope that some of the proven and field-tested technical solutions reported here (such as System Separation to prevent asynchronous regimes, “Strong Action” PSS, Centralized Emergency

[13] Recent blackouts in many countries of the world have stimulated the intensive examination of technical and organizational weakness of existing emergency control systems. Here we give only a brief summary of observations and recommendations made by blackout investigation teams, which analyzed the causes of blackouts in USA-Canada, London, Sweden-Denmark, Italy, and others. In more details these findings are presented in [4].

Control Systems, and others) would be helpful in developing the emergency control systems for the futur power grids.

At the same time, the Moscow 2005 blackout demonstrated that the Russian multi-layer power systen protection mechanisms also have certain deficiencies, and even with the Russia's long record of successfu blackout prevention, they need further improvements due to changed environment. First and foremost it i necessary to provide harmonization of emergency control and protection systems operation with th today's power transactions between the market participants.

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8. BIOGRAPHIES

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8. A New Generation of EMS Implemented in Chinese Electric Power Control Centers

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***Abstract* —** The energy management system (EMS) is the core of an electric power control center (EPCC) to manage and control the power system in a secure and economical way. Because the power system nowadays is large and interconnected (in the space dimension), the operational state is continuously varying (in the time dimension), and the control objectives are numerous (in the dimension of objectives), an EMS has to meet the various requirements in all these three dimensions for power system operation. A new generation of EMS (N-EMS) is developed for this purpose. This short paper introduces briefly how this newly developed N-EMS is used to prevent contingencies from evolving into a blackout. Special attention has been paid to the coordination in spatial, temporal and objective dimensions of the N-EMS. This N-EMS has been put into real practice in Chinese control centers and some results from the field are presented to show how the N-EMS is helpful in blackout prevention.

Index Terms — EMS; Control center; Blackout prevention; Contingency analysis; 3-dimensional coordination

1. INTRODUCTION

Energy management systems (EMS) have been proposed in concept for nearly 50 years [1] and widely used in electric power control centers (EPCC) all over the world. It is no doubt that the EMS has taken a crucial role in EPCC as the central nervous system to prevent contingencies and blackouts. But it is notable that no essential improvement on the conventional EMS (C-EMS) has been made since 1980s [2].

However, the power systems now in place have expanded fast and have been interconnected into a large and highly meshed network. The way to manage such a large power system should be changed correspondingly. From the investigation report about the August 14, 2003 blackout in US and Canada [3], it can be seen that there was more than one hour between the first key outage and the final blackout, but the EMS in MISO's EPCC did not function properly during that period and the dispatchers there did not take any proper actions to stop the evolution of the cascading contingencies.

Should we make some improvements to the C-EMS to make the EMS play a more powerful role in blackout prevention? The answer should be 'Yes'.

In this short paper, the conceptual design of a new generation of EMS (N-EMS) with coordination in three dimensions of space, time and objectives are briefly introduced. Some field operation results are reported to demonstrates how the N-EMS wakes up the dispatcher when the

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power system becomes frangible and what countermeasure can be taken by the dispatcher through the N-EMS.

2. CONCEPTUAL DESIGN OF N-EMS WITH 3-DIMENSIONAL COORDINATION

2.1 Concept

This N-EMS is designed based upon three dimensions of space, time and objectives. On-line global analysis, closed loop control, comprehensive early warning and computer-aided decision-making are all implemented in this N-EMS.

The operation mode of the N-EMS is an automatic, tracing, recursive, intelligent early warning type. The N-EMS continuously traces the variation process and the evolution trend of the power system operation state, to predict, to early warn and to prevent any potential contingency whenever it appears in the monitored power system.

2.2 Network remodeling (spatial)

All the local network models of the underlying systems as well as that of the superior system are automatically merged together to form a global power system model in the superior control center. Then, based on the global power system model, an external equivalent model for each underlying systems is produced automatically and transmitted to the underlying control centers through the wide area communication network [4]. Such a remodeling technology with coordination in the space dimension can ensure the correctness of the network analysis results in all these hierarchical control centers.

2.3 On-line Analysis and decision making (objective)

An early warning and security countermeasure (EWSC) system, which is a core function of the N-EMS, is developed for on-line security monitoring and decision making support [5].

The functions of the EWSC include steady state security analysis (SSA), voltage stability analysis (VSA), transient security analysis (TSA), and also the potential impact assessment of protective relay and auto-device misoperations on the power system. Then a comprehensive early warning mechanism with coordination in the objective dimension is proposed to estimate the overall security level. Furthermore, preventive control and emergent control strategies can be generated automatically for the power system according to the overall security level. Fig. 1 gives the functional configuration.

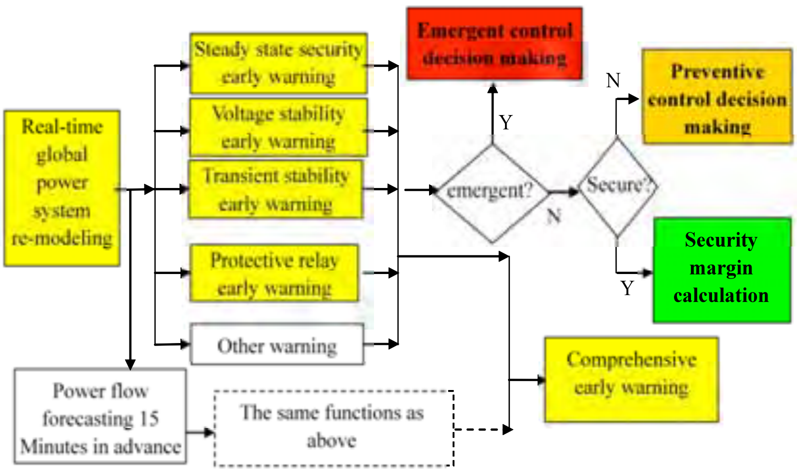

Fig.1 EWSC functional structure in the N-EMS

2.4 Closed loop controls for coordinated AVC and MW optimization (temporal)

If the current power system is in a normal state, the N-EMS executes a close-loop control to optimize MW and MVar flows based on real-time network analysis. A Three-level hierarchical AVC [6] and AGC technologies with coordination in temporal dimension is proposed and implemented.

2.5 Supporting platform —— based on MAS, PC clusters

To meet the needs for high-speed calculation for the N-EMS, a PC cluster is used. A task based online parallel processing platform is developed to balance each PC's loading and the Multi Agent System (MAS) technique is used to manipulate the software modules [7]

.

3. SOME RESULTS FROM FIELD OPERATION

3.1 Implementation of the N-EMS

The N-EMS has been fully developed and practically implemented in a real life provincial power system with 728 buses and average load demand of 6000MW in China. The following sections give some results of security assessment from field operation to illustrate the blackout prevention functions. The PC cluster used consists of 8 PCs, 6 among them are used for EWSC. The total time for all calculations in EWSC is less than 5 minutes from field experience that satisfies the need for online application.

3.2 Comprehensive security improvement

Not like C-EMS in which only static N-1 contingency analysis is executed, the N-EMS can give a comprehensive analysis and decision making including TSA and VSA while tracing on-line the variation of the power system state.

(1) Load margin for VSA

A daily curve of the load margin for the whole system is given in Fig 2. The load margin gets smaller (8:00-20:00) during the heavy loading period and larger in the middle of the night. The maximum margin is 2257.70MW at 2:08 at night and the minimum margin is 640.52MW at 13:20 in the afternoon. It can be seen that the load margin is tracing the variation of the system state. The dispatchers can be timely advised by this curve so as to take adequate measures for improving operation of the current power system. The load margin can also be calculated area by area.

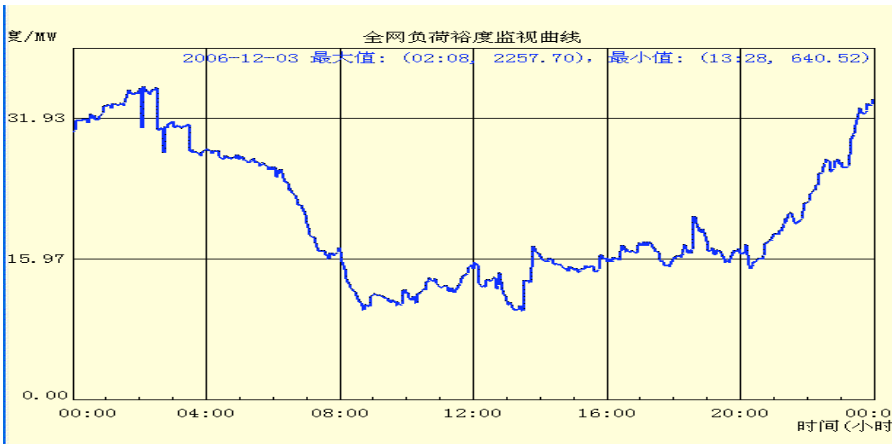

Fig. 2 A day curve of load margin for whole system (Dec. 3, 2006)

(2) Real time MW transmission capacity limit for TSA

MW transmission capacity limit for a given transmission corridor is a major concern of the dispatcher. The limit calculated off line and used today is very conservative. Fig 3 gives the MW transmission capacity limits calculated online for four corridors. In each sub-picture of Fig 3, the upper curve (red) is the calculated MW transmission capacity limit and the lower curve (blue) is the actual MW flow. The x-axis is time (0:00-24:00). This picture helps the dispatcher to monitor MW margins in these corridors in real time.

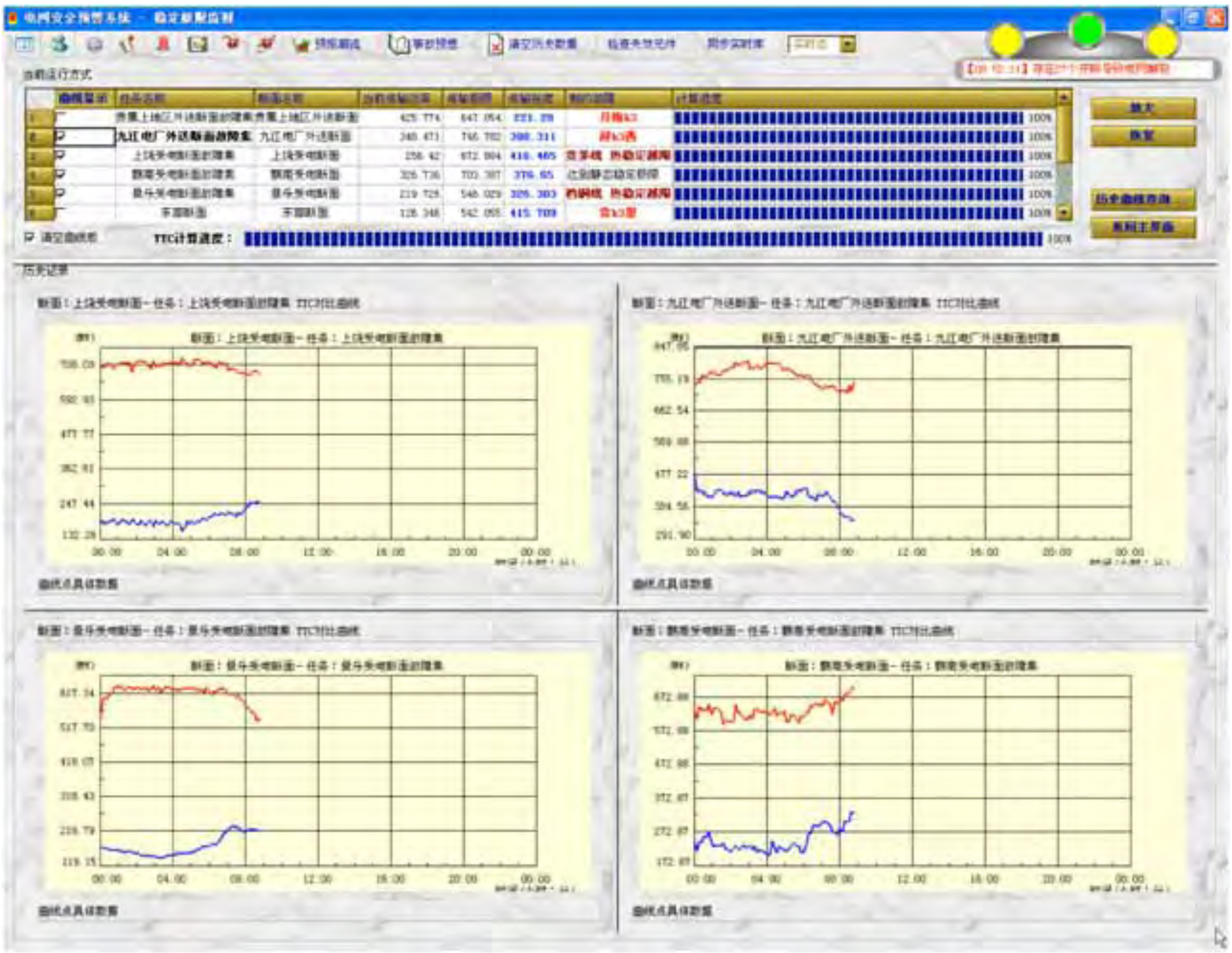

Fig. 3 MW limits and actual loadings for transmission corridors

(3) Preventive control strategy

The re-scheduling of the MW outputs of generators to improve transient stability of the power system is significant. Upon the basis of online TSA, the N-EMS can give a MW adjustment strategy for this purpose. Fig 4 gives the results from field operation.

The red bar (left) and blue bar (right) in the upper right part of Fig 4 indicates MW outputs of a generator before and after adjustment. This adjustment improves transient stability to some extent. The Table in the lower right part of Fig 4(re-tabled in Table 1) gives the result of the minimum CCT before and after adjustment. It can be seen from Table 1 that before adjustment, the minimum value of the min CCTs is 0.245933 for the Jing-Du line faulted 3-phase to ground. After adjustment, this min CCT is increased to 0.305415. Although the other min CCTs increase to some extent, they are still larger than this minimum value among min CCTs. So from a systematic point of view, the transient stability for the whole system has been improved by this MW adjustment.

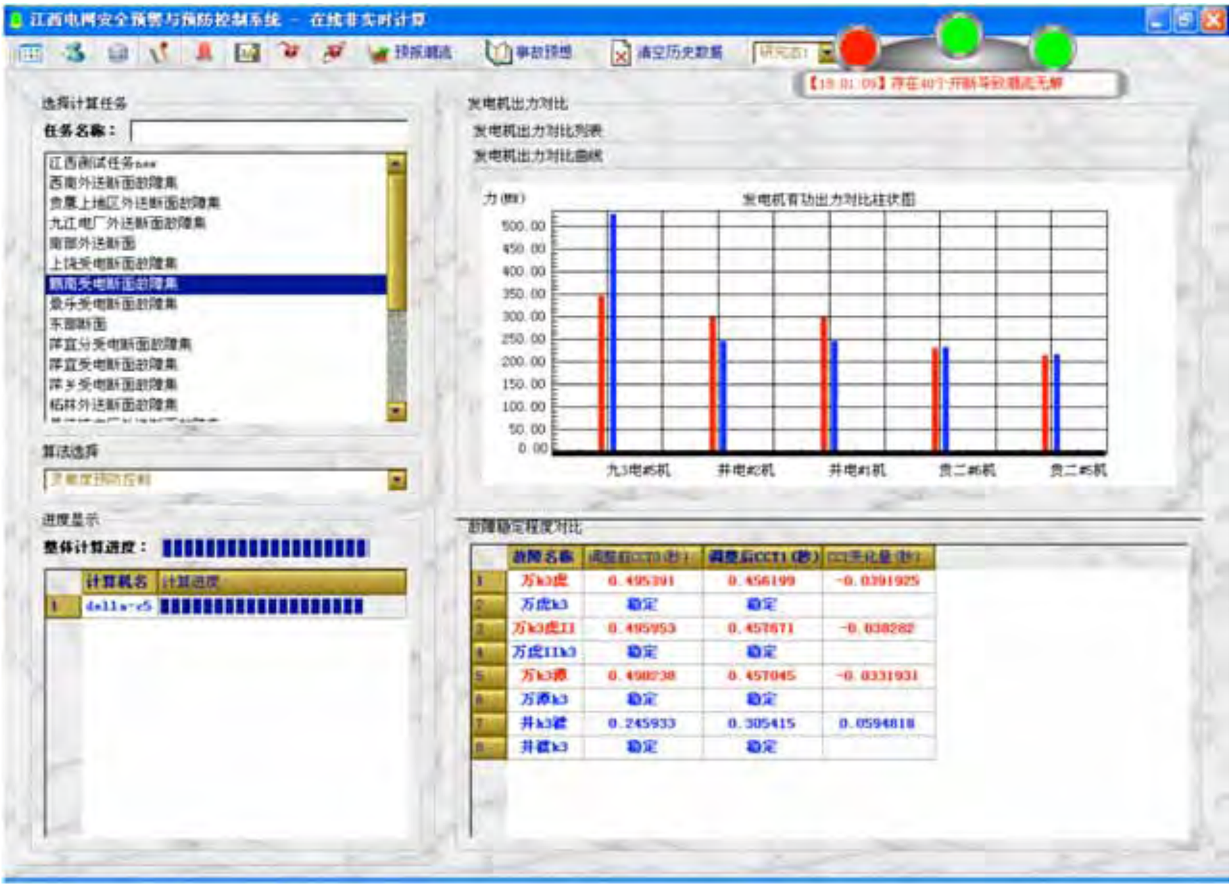

Fig. 4 MW re-schedules to improve transient stability

TABLE 1 TRANSIENT STABILITY IMPROVEMENT BY MW RE-SCHEDULE

Faulted line	Min CCT before adjust	Min CCT after adjust	ΔCCT
Wan-Hu	0.495391	0.456199	-0.0391925
Wan-Hu	0.495953	0.457671	-0.038282
Wan-Tan	0.490238	0.457045	-0.0331931
Jing-Du	0.245933	0.305415	0.0594818

In Fig 3 and Fig 4, we can see three pilot lamps (like traffic lights) with different colors in the upper right corner. This is an indicator to alert the dispatcher to the security grade of the current power system. The pilot lamps from left to right indicate the static state security, transient stability security and voltage stability security respectively.

4. CONCLUSION

The problem of power system operation becomes more and more complicated in three dimensions of space, time and objectives. So a N-EMS designed along these three dimensions is proposed and implemented. This is a systematic point of view, in which previously well-known functions and many new functions have been systematically organized to overcome many practical difficulties in the C-EMS implementation. For example, poor modeling of neighbor networks, a snapshot based TSA using an off-line program, static N-1 contingency analysis, etc are replaced and systematically organized in the N-EMS structure.

The N-EMS is the attempt to change such a situation. Operational results from the field show that the N-EMS is more powerful in security improvement and blackout prevention.

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