DEFENSE SCHEMES AGAINST POWER SYSTEM BLACKOUTS IN CHINA WITH HIGH LOAD GROWTH

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Abstract: This paper describes the experiences, new requirements and prospects of security defense schemes for power systems in China. Adaptive optimal control schemes have served well for 2-3 years to periodically refresh the decision table for preventive control and emergency control to track operating conditions. These schemes are supported by EEAC that is a quantitative method for stability analysis, novel optimization algorithms and case-based parallel processing. After thoroughly investigating recent blackouts around the world, a wide-area measurement based defense scheme, named as Wide ARea Monitoring Analysis Protection-control (WARMAP) is proposed to against cascading blackouts. Its essentials are: (1) acquisition and integration of wide area measurements from RTUs, PMUs, fault recorders and protection systems; (2) trajectory-based data mining and security analysis; (3) adaptive optimization of preventive control, emergency control and restoration control; (4) coordination among various stability controls. Based on relevant research achievements, such a scheme is well on the way to building in East China Power Grid.

Keywords: defense schemes; PMU; trajectory-based analysis; stability control; optimization; coordination; extended equal area criterion (EEAC)

1 INTRODUCTION

To maintain system security, it's necessary to quickly evaluate system stability under contingencies likely to happen, to identify problematical areas, to find operating limits and select the best control actions if needed [1-3].

The three-defense-lines criteria have been a security standard for power system planning and operation in China [4]. The first defense-line consists of preventive control (PC), grid strengthening, namely a long-term PC, and protection relays to assure system stability without load interruption under a "plain" contingency. The second one is armed with regional emergency control (regional EC, or REC) for "severe" contingencies. The third one is equipped with local emergency control (LEC), such as out-of-step protection and load shedding for "extremely severe" contingencies.

Although having successfully avoided system-wide blackouts in the relatively weak Chinese grids, the defense-lines are facing great challenges in rapid growth of loads, national-wide interconnection, ultra high voltage transmission and power market development.

Almost all the defense-lines nowadays are based on qualitative off-line analyses for typical scenarios. This "off-line pre-decision and real-time matching" fashion of stability control needs extremely heavy computation; reasonable matching of the measured condition with a pre-assigned one is not always possible. Moreover, most of blackouts resulted from cascading events, which are hard to foresee. Risks in blackout are not negligible.

A much better way is to track on-line information and refresh the pre-decision tables. Only the actual operating point (OP) and pre-assigned contingencies need investigating, thus the look-up table can be refreshed periodically or 1-3 minutes just after a change in topology or injection power. In this way, the control system not only can be standardized, but also is adaptable to both power systems and measurements.

A scheme was implemented to automatically refresh the decision table in a quasi-real-time fashion for both PC and REC by using EEAC that is a quantitative method for stability analysis [5], a novel optimization algorithm [6], and case-based distributed parallel processing [7].

Operational experiences of on-line dynamic security assessments, adaptive PC and adaptive REC in China are reviewed briefly in this paper.

One of the causes of the recent blackouts around the world is the lack of well-designed defense schemes and their coordination, reliable information acquisition and the adaptability to cascading events [8].

To further improve the defense-lines and build a coordination scheme against cascading blackouts, a wide-area measurements based defense scheme has been proposed and is being built for East China Power Grid.

This framework lays a foundation for further coordinating the PC in a continuous space with contingency-specified REC and LEC in a discrete space.

2 THREE-DEFENSE-LINES CRITERIA

2.1 Defense-lines VS Stability Controls

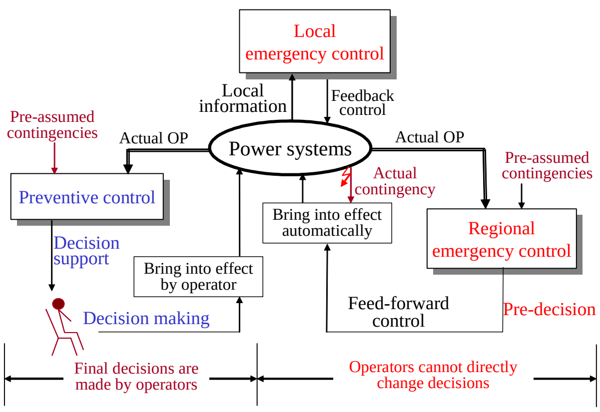

Figure 1: Three kinds of stability controls

PC actions in the first defense-line are issued by the operator; REC in the second line is feed-forward control; LEC in the third line is feedback control (Figure 1).

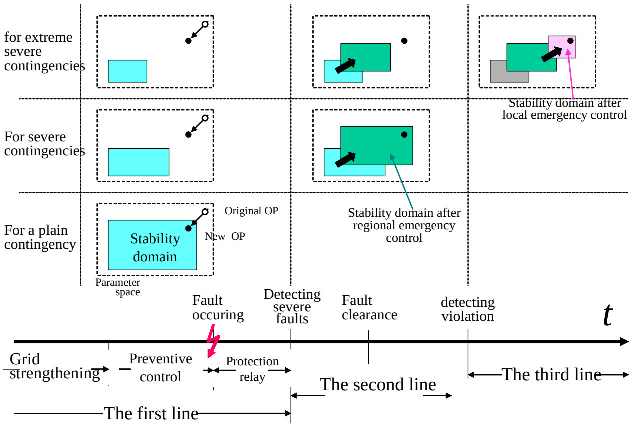

Figure 2: Different defense-lines with different mechanisms

The stability criteria in China are classified into 3 levels according to the contingency severity (Figure 2).

For a plain contingency such as a single-phase short-circuit, all loads should be kept by applying only the first defense-line. PC reschedules the generations and shifts the OP into the stability domain (SD).

For a severe contingency such as a three-phase short-circuit, the system integrality should be kept with REC.

For an extremely severe contingency, such as multi short-circuits occurring concurrently, system-wide blackout should be avoided by activating LEC.

2.2 Comparisons among Various Stability Controls

PC usually employs continuous actions, such as power rescheduling; EC actions are usually discrete, such as generator tripping, load shedding and out-of-step protection. Their decision spaces are different.

PC influences normal OP, thus improves stability at a price of reducing transmission power, which may be infeasible in some circumstances. EC allows the OP staying outside SD before the fault occurrence and avoids the instability by correcting the SD immediately after the fault occurs. This raises the transmission limits.

While improving system stability for a contingency, a control action may hurt system stability for others. PC actions are activated before any contingency occurrence; these negative effects should be considered carefully. EC actions are activated after the relevant contingency occurrence; the negative effects won't be in operation.

PC affects the dynamics from the very beginning of a fault; EC actions miss a valuable time period to act.

PC needs to pay daily cost, which is usually low, whether faults occur or not. If faults actually occur, EC actions usually cost dearly. Obviously, the coordination of PC with EC is significant for cost saving.

Based on regional measurements, REC is activated just after detecting certain contingencies. Being feedback control, LEC usually uses only local information and is activated after certain physical violation being detected.

2.3 Current Status

The whole dynamic security problem has been studied separately on synchronism, motor slip, voltage and frequency. For instance, voltage stability is discussed without considering the effects of angle swing. This is certainly unfavorable for understanding the problem.

Dynamic security assessment has to be performed with off-line calculations for each credible contingency under typical OPs. In real operations, the actual OP may not match any typical one. Thus, operational guidelines have to be very conservative and there will be no any guideline for almost all cascading events.

The common techniques for stability analyses and stability control can only answer "yes or no" questions and support off-line pre-decision without considering optimization, adaptability and coordination.

Instead of designating one of the three defense-lines to a certain type of contingencies, it is more reasonable to optimize the three defense-lines in a whole.

2.4 Facing Great Challenges

By the end of 2004, the total installed generation capacity in China is 440 GW, the annual increase rate is 12.5%, and meanwhile the load demand increases 17%. In 2020, the total power sending from west to east via North, Central and South routes is estimated as 150 GW.

Nation-wide interconnection results in very complex dynamics, such as low frequency (0.1Hz) oscillation, voltage instability, chaos behaviors, etc.

Ultra high voltage transmission shortens electrical distances, but not the geographical ones. This makes the information system more complicated and crucial.

With the development towards an open market, the operating condition of transmission systems will be more uncertain, and power flows will be harder to control.

All these factors drive the system to operate closer and closer to its physical limits and increase the complexity of assessing and controlling the security.

2.5 New Requirements to Stability Technology [9-11]

In order to stop blackout evolvement in time, a firm defense framework should consist of well-designed PC to deter slow cascading tripping, adaptive REC to stop fast cascading tripping, and adaptive LEC to mitigate the impacts of power cut.

New requirements are: (1) quantifiability of angle stability, voltage security and frequency security; (2) optimization; (3) on-line analysis and decision-making; (4) adaptability; (5) coordination not only within one defense-line, but also among different defense-lines; (6) assessment and prevention of cascading contingencies.

3 ON-LINE PRE-DECISION

3.1 Breakthrough Needed

Both stability margins for disturbed trajectories and SD in parameter spaces are in demand for synchronism stability, voltage stability and frequency stability. Quantitative stability assessment methods are the basis for optimization and coordination.

In order to track cascading events and adapt the decisions to both system topology and parameters, on-line security analyses and pre-decision are essential. On-line pre-decision assesses only the OP encountered in quasi-real-time, thereby reducing the uncertainty that exists in off-line analyses. If n-1 criterion decision-making can be finalized within a quasi-real-time scale, say 2min, (n-m) security criterion can be managed [12].

3.2 Trajectory-based Stability-Preserving and Dimension-Reduction (TSPTR) methodology

Instead of stereograph, orthographic projection views are widely used to describe 3-demensional objects for machine building, architecture, etc. All outline features of the object (or curves) are rigorously preserved in the 3 views. This is a good enlightenment for extracting stability information from multimachine swing curves.

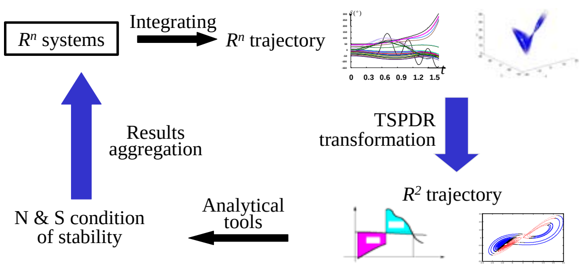

Figure 3: The principle of TSPDR

TSPDR [13] is a methodology for mining various stability information from time response curves (Figure 3). After numerical integration on full models, accurate time responses curves and phase portraits are obtained. In stead of extracting stability information and defining a rigorous index directly in R^n, TSPDR maps the curves from R^n to n orthographic planes of R^2 by using a full-rank linear transformation. Then assessment can be performed to the set of curves of R^2, which is much easier than data mining in the multidimensional space.

The results in R^2 are aggregated to get the rigorous answer to the R^n system.

However, proper selection of the transformation is another key to exhibiting clearly the desired information. The transformation matrix is problem dependent.

3.3 Extended Equal–Area Criterion (EEAC)

EEAC is an application of TSPDR methodology to the synchronous stability analysis of power systems. Its rigorous proofs can be found in Ref. [5,14,15].

EEAC performs numerical integration to the full models in R^n, and then maps the resultant trajectory into a set of time-varying one-machine infinite-bus (OMIB) planes. Thanks to the analytical form of the stability margin on an OMIB plane, the stability analysis can be quantitatively performed for the image OMIB systems of time-varying parameters. The most critical image among the all decides the critical mode and stability limit.

The key ideas are to assess the actual trajectory, which is just the same as the traditional method for stability analysis, and extract the stability index in the set of image spaces (Figure 4).

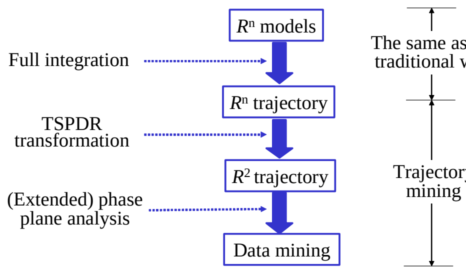

Figure 4: The steps of EEAC

EEAC is applicable to stability analyses on any detailed models, complex scenarios and multi-swing, while keeping much less computational burden. It can offer SD in the injection space and various kinds of sensitivity information. It can also identify the most dangerous loading patterns and the safest reloading ones.

Being quantitative and very informative as well as fast, EEAC can identify unstable mode (UM) and sub-critical modes, decide both searching direction and step for optimizing control, EEAC has been serving widely at home and abroad for power system planning, analysis, on-line operation, as well as for PC and EC.

3.4 Stability Margin and Security Margin

Margin value changes with the stability degree monotonously; a zero-valued margin coincides with the N&S condition for stability rigorously.

Transient stability index of induction motors and transient voltage dip acceptability index are also based on TSPDR concept.

Optimizations need the concepts of margin and contour map of a performance index in control spaces.

3.5 Unstable Mode (UM)

UM is a very important concept to characterize the system separation. In the procedure of margin calculation, UM is concurrently identified.

When a certain action helps the stability of a UM, it may have harmful effects on other UMs. Therefore, it is essential to compromise among various UMs.

3.6 SDs in Parameter Space

According to time scales, power system stability can be divided into transient, medium-term and long-term ones. Corresponding to the amplitude, frequency and relative phase, dynamic security can be classified as voltage, frequency or synchronous ones. Voltage (or frequency) security has two aspects, namely stability and dip/rises acceptability [16].

The global SD is the intersection of the domain for angle (transient, low frequency oscillation), that for voltage (transient, medium-term and long-term, static, dip acceptability) and that for frequency.

3.7 Decision Supporting Systems with On-line Pre-decision

The on-line pre-decision decision supporting systems implement EEAC on a case-oriented parallel processing platform. Tracking the current OP of the power system, EEAC quantitatively assesses system stability for a specified set of events. For insecure cases, the optimal countermeasures are searched with a non-convex nonlinear programming based on sensitivity analysis. The decision tables stored in the control devices are refreshed periodically and adaptive to successive outages as well as reformation of the grid [17].

4 APPLICATIONS OF ADAPTIVE OPTIMIZATION TO DEFENSE LINES IN CHINA

4.1 Adaptive Optimization of the 1st Defense Line

PC shifts some generation power from the critical machines to the non-critical ones according to the objective UM [18]. The smaller the excursion from the original OP, the lower the additional operating cost.

Advanced on-line transient stability assessment functions in Guangxi Grid's EMS and Henan Grid's EMS have been put into normal operation service to support PC since Sept. 2003 and July 2004 respectively.

The Guangxi Grid model contains 1876 buses and 248 generators. Under normal conditions, 3 Dell 2650 servers assess transient stability and another one assesses voltage stability. It can complete the entire assessment cycle of 100 contingencies within 5 minutes. The failover capability ensures the continuous satisfactory operation of the PC functions when any server fails.

Planned enhancements include exchanging data with neighboring utilities to improve the on-line model, and integrating with REC. Due to the recent incidents of the low frequency oscillations in the southern China Grid, small signal stability analysis functions may be also considered.

4.2 Adaptive Optimization of the 2nd Defense-line

An adaptive REC scheme was proposed to automatically refresh the decision table in a quasi-real-time fashion [19]. The decision-making is a problem of non-convex nonlinear integer-programming; an effective algorithm was proposed [6]. The relevant software has been implemented in optimal REC systems for engineering services in Shandong grid since Nov. 2002 and in Guangdong grid since Dec. 2002.

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

4.3 Adaptive Optimization of the 3rd Defense-line

The optimization of low voltage (frequency) load shedding includes placement, set points and activation. The set points optimization has been successfully applied to Liaoning Grid, Northwest Grid, Sichuan Grid, etc. Research projects on placement optimization and activation optimization and intelligent out-of-step protection are going on [20].

Researches are also being conducted to introduce some remote measurements and multi-agent techniques into LEC to improve the adaption and efficiency.

4.4 Adaptive Optimization of the 4th Defense-line

Some time restoration control is named as the 4th defense-line in China. Besides speeding up the whole restore procedure, restoration control should prevent new risk due to the restoration actions themselves.

5 EVOLVEMENT OF CASCADING BLACKOUTS

Extensive investigations on blackouts around the world suggest that a global blackout evolved with cascading contingencies can be decoupled into the following five stages (Figure.5, where the time intervals are taken from the 8.14 case). (1) A slow cascading stage, which allows operators to implement PC before the occurrence of the next event. (2) A fast cascading stage, in which REC is feasible, but not PC. (3) An oscillation stage. (4) A collapse stage. In the above two stages, LEC can be activated to restrain the blackout zones from broadening. (5) A restoration stage, in which interrupted loads should be energized quickly as well as efficiently. Blackouts without undergoing slow cascading stage or oscillation stage can be considered as some special cases.

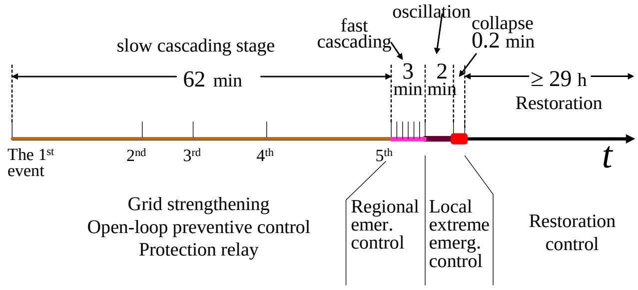

Figure 5: Typical evolvement of cascading blackouts

There were opportunities to hold out the disaster in various stages of the blackout evolvement, such as preventive actions during the stage with slow cascading tripping, REC for the stage of fast cascading tripping, LEC for the stage of system oscillation and collapse, black-start or restoration decisions for blackout stage.

6 DEFENSE SCHEMES AGAINST CASCADING BLACKOUTS

6.1 Lessons on Cascading Blackouts

The biggest blackout in history occurred in one of the strongest grids with the highest techniques in the world. It may be impossible for a single contingency to directly destroy a strong system; however the contingency may introduce a new event. If there is no countermeasure to stop the cascading, system-wide blackout may occur. Obviously, a well-designed defense scheme against cascading blackouts is helpful.

6.2 A Project in East China Power Grid

Studies on three-defense-lines have been isolated with each other so far, though they are interacted tightly. Both over-control and insufficient-control are harmful, thus a global defense scheme is preferred.

It is also significant to introduce concepts on probabilistic stability evaluation and risk management.

NARI and East China Power Grid are developing and implementing a holistic defense scheme, namely Wide ARea Monitoring Analysis Protection-control scheme (WARMAP), to avoid cascading blackouts and give optimal attention to both economics and security.

6.3 The Essentials of WARMAP

The essentials of WARMAP are: (1) acquisition and integration of wide area measurements from not only RTUs, but also PMUs, fault recorders and protection management systems; (2) trajectory-based data mining and security analysis; (3) adaptive optimization of PC, REC, LEC, and restoration control; (4) coordination among different defense-lines; integration of existed EMS and various stability controllers (Figure 6).

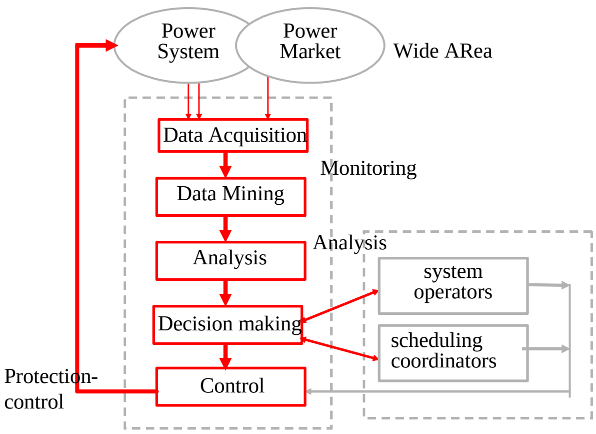

Figure 6: Main functions of the scheme: monitoring, analyses and control

6.4 Dynamic SCADA System

The sufficiency and security of information are the basis for monitoring, analysis, protection and control. A new data platform integrates various data resources, such as PMU, RTU, traditional SCADA systems, and data from simulators. PMUs provide continuous and time-synchronized data [21].

Ref. [22] optimizes PMUs' placement based on coherency characteristics of both rotor angles and bus voltages. Ref. [23] presents the model of jointly utilizing SCADA and current phasor measurements. Ref. [24] proposes a method for coordinating PMU measurements with RTU measurements of different delay.

Before an action is actually carried out, the system trajectory can be known only by simulations, but not PMUs. Simulation is vital for reliable decision making.

The database should be of good compatibility for static/dynamic, real-time/historical/simulation data.

6.5 Data Mining on PMU Curves

The objectives of data mining on time responses acquired by PMU include fault locating, low frequency oscillation analysis [25], ancillary service monitoring, model recognition and stability margin calculation.

Ref. [26] proposed a method to assess directly the system stability margin along the swing trajectories. Based on EEAC, however, the method requires neither system models, nor system parameters.

6.6 The Framework of WARMAP

EMS, DTS, DMIS and other automation systems are integrated in the proposed framework (Figure 7), which extends EMS to dynamic EMS and lays a foundation for adaptive optimization of defense-lines and their coordination. WARMAP gives operators not only tactical supports but also strategical advices.

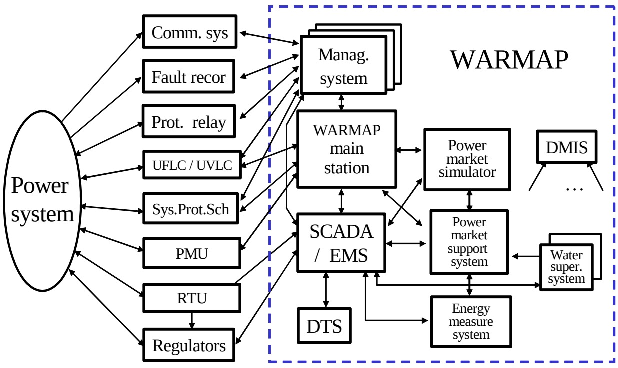

Figure 7: The framework of WARMAP

7 COORDINATION AMONG DEFENSE-LINES

7.1 Coordination of Controls

The synthetical framework coordinates PC actions to obstruct slow cascading tripping, REC to avoid fast cascading tripping and system oscillation, LEC to mitigate the impacts of power cut.

The coordination has many aspects: coordination within the same defense-line, coordination among different defense-lines, and coordination between defense-lines and SCADA/EMS systems.

7.2 Coordination between the 1st and 2nd Defense-lines

With relatively low cost, PC actions have to pay the daily cost whether the objective disturbances occur or not. In contrast, REC actions usually cost dearly if activated, and need restoration time after the execution. Obviously, the coordination between PC and REC is significant for cost saving.

If the original OP (X_o) is potentially unstable, PC may be activated to move the system to a target point (X_T) that may be still insecure for some contingencies. When an unstable contingency-i is detected, relevant EC_i is activated immediately (Figure 8).

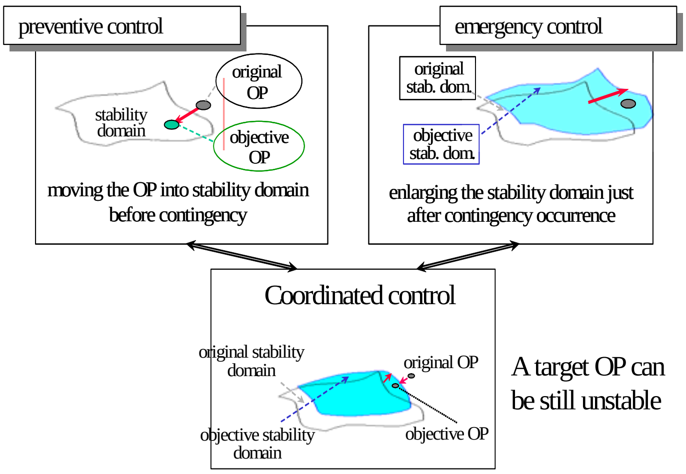

Figure 8: The coordination between PC and EC

Due to the complex mutual-influences between PC and EC, the globally optimal control is extremely complicated. Ref. [27] proposed a general optimization method for the coordination, where the task is formulated as a nonlinear hybrid-programming problem with both integer and continuous control variables. The objective function is the sum of the daily cost for PC and the possibility-weighted cost for EC.

Unstable contingencies are classified into subsets according to the UM. An action has the same qualitative effects on all the contingencies in the same subset.

The coordination is achieved by properly replacing some PC actions with contingency-specified EC actions. It is formulated as an economic dispatch model with additional costs due to the emergency actions.

Ref. [28] proposed an algorithm, which searches for the globally optimal solution straightforwardly, instead of iterations between EC and PC. It includes two steps: the first step is the local coordination for each subset respectively; the second one is the global coordination among the locally optimal schemes.

The insufficient EC schemes obtained during the optimization procedure for pure EC scheme are valuable candidates for the coordinated optimization. The optimal searching is started respectively from several candidates to avoid trapping in local minima. The good results can be explained with analogizing settlements for 0-1 knapsack problems using multi-points greedy algorithm.

7.3 Coordination between the 2nd and 3rd Defense-lines

Out-of-step protection can be activated as a feed-forward action in the 2nd defense-line, or as a feedback action in the 3rd defense-line. The former is more effective; the latter is more accurate.

Similarly, load shedding can be executed either as an action of the 2nd line or as an action of the 3rd line. There is room for compromising.

7.4 Restoration Control and Other Controls

PC actions don't require restoration procedure afterwards, however EC actions require. As a result, all four defense-lines should be taken as a whole.

8 FURTHER THEORETICAL RESEACH

Present achievement is still preliminary; more efforts should be devoted to improving our understanding of the coordination problem before practical applications can be expected.

Breakthroughs on nonlinear stability theory are needed in order to estimate the stability beyond the observation period and terminate the simulation as early as possible. Differing from the general concept of chaos concerning only bounded dynamics, new concepts are needed for unbounded chaos and pre-unbounded chaos.

It is also essential for practical applications of PMU to develop the trajectory-based data mining techniques, which are independent of the information on actual models and parameters of the power system.

9 CONCLUSIONS

The three defense-lines have successfully prevented system-wide blackouts in China. However, they are facing great challenges resulting from rapid growth of loads, interconnection and power market development.

Present dynamic security analyses cannot offer security indexes, SD and on-line pre-decision; present stability controllers are designed with little consideration on optimization, adaptability and coordination.

It is necessary to advance the existing SCADA/EMS to dynamic ones, namely DSCADA/DEMS. WARMAP is such a serious effort in China. This wide-area measurement based defense scheme integrates information acquired with RTU, PMU, fault recorder and protections and information resulting from model-based simulations. Then, data mining is performed to the time responses for quantizing stability, which is the basis for both adaptive optimization and coordination.

Optimization of PC, EC and restoration control is supported by EEAC and other quantitative algorithms.

Adaptability of these controllers is a result from on-line pre-decision algorithms, which are fast enough to refresh the decisions according to the actual operating conditions and the evolvement of cascading events.

Coordination among various stability controls is then possible with hybrid-programming.

There is still a long way to go with some risks before such a scheme can be put into daily service for East China Power Grid. However, it is even surer that there is no much time left before the existing defense schemes become helpless with cascading blackouts. Serious research and application are being conducted.

ACKNOWLEDGMENTS

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