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Electrical Power and Energy Systems 27 (2005) 488–495

ELECTRICAL POWER & ENERGY SYSTEMS

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A power system control scheme based on security visualisation in parameter space

Zhao Yang Dong[a,*], David J. Hill[b], Yi Guo[c]

[a]School of Information Technology and Electrical Engineering, The University of Queensland, St Lucia, QLD 4072, Australia
[b]Department of Information Engineering, Australian National University, ACT 0200, Australia
[c]Electrical Engineering Program, School of Electrical Engineering and Computer Science, University of Central Florida, P O Box 163450, Orlando, FL 32816-2450, USA

Received 9 December 2002; revised 17 May 2005; accepted 25 May 2005

Abstract

Power system real time security assessment is one of the fundamental modules of the electricity markets. Typically, when a contingency occurs, it is required that security assessment and enhancement module shall be ready for action within about 20 min time to meet the real time requirement. The recent California black out again highlighted the importance of system security. This paper proposed an approach for power system security assessment and enhancement based on the information provided from the pre-defined system parameter space. The proposed scheme opens up an efficient way for real time security assessment and enhancement in a competitive electricity market for single contingency case.

Keywords: Power systems; Security; Stability; Control; General method; Bifurcations; Global control

1. Introduction

Power system security has been a critical issue in the deregulated power market. The recent California collapse again brought up this security consideration. In the Australian National Electricity Market, system security evaluation process is required to be no more than 20 min to reach a solution for actions regarding the occurrence of security problems as a result of contingencies [1]. Efficient security assessment and enhancement methods are essential for such a requirement. We will briefly review some methods of security assessment and enhancement, and propose an alternative framework for on-line system security assessment to suit the requirement of online contingency analysis.

It is well known that power system is highly nonlinear and complex especially under competitive electricity market situations. A power system can be modeled by the differential and algebraic equations as [2–4],

$$\begin{aligned} \dot{x}_s &= f(x_s, x_a, p), \\ 0 &= g(x_s, x_a, p) \end{aligned} \tag{1}$$

where x_s is a vector of dynamic state variables, x_a is a vector of algebraic variables, and p is a vector of power system parameters. The parameter vector p includes those parameters from generators, control and network, and can be varied in system planning and control. Direct and continuation methods have been used to locate the small signal stability conditions [2–13]. The distance towards the critical stability condition points from current system operation point is considered an index for system security assessment. In [14] the concept of available transmission capacity (ATC) is proposed to indicate the system's capacity of secure electricity transfer. These indices provide information for system secure operation and control. However, most of these indices are based on nose curve properties. It is important to have a more general view of a security index [3,4], so that the system operator can have more comprehensive understanding of system security, and be able to make globally optimal control decisions dealing with system contingencies.

* Corresponding author. Tel.: +7 3346 9052; fax: +7 3365 4999.
E-mail addresses: zdong@itee.uq.edu.au (Z.Y. Dong), David.Hill@anu.edu.au (D.J. Hill), yguo@cs.ucf.edu (Y. Guo).

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doi:10.1016/j.ijepes.2005.05.002

2. Security boundaries in the parameter space

Before introducing the parameter space based control scheme, it is necessary to review the methods of obtaining such parameter security spaces.

Usually, these boundaries are of interest in power system security assessment: aperiodic and oscillatory stability conditions as revealed by saddle node and Hopf bifurcations; minimum and maximum damping conditions; power flow feasibility conditions; and the limit induced bifurcations.

We briefly review some of the techniques developed by the authors to calculate these security conditions based on the nonlinear models of the general form given in Eq. (1).

The basic and important power flow feasibility boundaries can be efficiently located without iterative procedures except for eigenvalue calculation using methods proposed in [3]. This novel Δ-plane technique calculates the power flow feasibility limits using the properties of quadratic power flow equations. The feasibility boundaries can be obtained in the hyper-plane of power system parameters. It is an efficient and robust visualization tool for power flow limit studies and related security problems.

Computational approaches for locating the saddle node and Hopf bifurcations include continuation and direct methods. The equilibrium conditions of the nonlinear system given in Eq. (1) are substituted with the simplified expression of $F(x, p)=0$. Saddle node bifurcations can be located by solving the set of equations,

$$F(x,p) = 0 \tag{2}$$

$$F_x v = 0 \text{ or } w^{\mathrm{T}} F_x = 0 \tag{3}$$

$$||v|| = 1 \text{ or } ||w|| = 1 \tag{4}$$

where v, $w \in R^{\mathrm{N}}$ is the left and right eigenvector of the Jacobian. F_x at an equilibrium defined by (2). Eqs. (4.2 and 4.3) ensures the nontrivial condition. The problem can be solved with *Newtown-Raphson-Seydel* method. The neighboring equilibrium points close to the saddle node bifurcation point can be calculated by solving the equations,

$$F(x,p) = 0 \tag{5}$$

$$(F_x - \varepsilon I)v = 0 \tag{6}$$

where I is the identity matrix of the same order as the Jacobian F_x, ε is a small real number. It is evident that the bifurcation point is obtained with $\varepsilon=0$ [11].

Hopf bifurcation is featured by a pair of conjugate pure imaginary eigenvalues. It can be computed by solving the equations below. Here the system Jacobian is the reduced form, $J_s = f_x - f_p g_p^{-1} g_x$.

$$F(x,p) = 0 \tag{7}$$

$$J_s^{\mathrm{T}}(x,p)v' + wv'' = 0 \tag{8}$$

$$J_s^{\mathrm{T}} T(x,p)v'' - wv' = 0 \tag{9}$$

$$||v|| = 1 \tag{10}$$

where $0 \pm jw$ are the eigenvalues corresponding to the Hopf bifurcation, and $v = v' \pm jv''$ are the corresponding left eigenvectors. The last equation is the nontrivial condition. Again, it can be solved with Newton like optimization method. These two approaches belong to the direct method.

The authors in [4] developed a general method, which is capable of revealing most of the small disturbance stability conditions in one optimization approach in the parameter space. Given the nonlinear system Jacobian as J, the general method is based on solving the following optimization problem:

$$\alpha^2 \Rightarrow \text{min/max} \tag{11}$$

subject to:

$$\begin{aligned} & f(x, p_0 + \tau \Delta p) = 0 \\ & J^{\mathrm{T}}(x, p_0 + \tau \Delta p)l' - al' + wl'' = 0 \\ & J^{\mathrm{T}}(x, p_0 + \tau \Delta p)l'' - al'' - wl' = 0 \\ & l_i' - 1 = 0 \qquad l_i'' = 0 \end{aligned} \tag{12}$$

where α and w are the real and imaginary parts of an eigenvalue of J and $l' + \mathrm{j}l''$ is the corresponding eigenvector. The last two equations are to make sure the conditions are non-trivial. Examples of utilizing this technique are given in [4]. This general method can find saddle node and Hopf bifurcations, as well as minimum and maximum damping conditions should such characteristic points exists in the ray of optimization. Singularity induced bifurcation can also be detected during building the reduced system Jacobian. This comprehensive approach covers most of the local bifurcation and other important small signal stability conditions in one optimization approach. For power systems, optimization of the problem can also lead to solutions of power flow feasibility boundary points. By rotating the ray of search in the parameter space, the bifurcation and feasibility hyper-plane can be located based on this general method. Such hyperplanes are useful for corrective control to ensure the nonlinear systems' small signal stability [8].

In power system operation and control, it is also useful to have a close insight into the geometry of the small disturbance stability boundaries and margins in the power system parameter space. Let's define the stability boundary Σ as the set of bifurcation points in parameter space R^{m}. In reference [6] and [13], it is assumed that Σ is a smooth hypersurface in R^{m}. There are simple geometric interpretations for different stability boundaries such as saddle node bifurcation boundary Σ_{snb}, Hopf bifurcation boundary Σ_{hb} and the feasibility region Σ_{fr} [7]. Based on properly chosen system model, the general method can be used to locate these boundaries as well as the closest small disturbance stability characteristic points.

Table 1
The different security conditions which can be located by the general method

	Re(λ_{cr})	Im(λ_{cr})	Jacobian (J)	(d/Re(λ_{cr})/dt)
Aperiodic	$\neq 0$	$=0$	det(J)$=0$	–
Oscillatory	$=0$	$\neq 0$	det(J)$\neq 0$	–
Min-damping	$\neq 0$	–	det(J)$\neq 0$	$=0$
Max-damping	$\neq 0$	–	det(J)$\neq 0$	$=0$

Parameter continuation method can be used to trace these bifurcation boundaries in the parameter space [5]. However these problems are complex and nonlinear in nature; sometimes, traditional Newton-based optimization techniques may experience difficulties in solving the problems. A Genetic Algorithms based solution method was given in [12] by the authors to provide a comprehensive and reliable approach in revealing these security conditions, which are summarized in Table 1.

3. Parameter space based control scheme

Power system security operation via parameter space based control is proposed as having two stages and with a risk minimization decision making module to deal with contingencies.

3.1. Power system security map

The first stage is to build the system security map database. Power system operational conditions can be indicated by means of parameter spaces. Using the techniques mentioned in Section II, various security boundaries in the parameter space—see Fig. 1—can be obtained. We propose the so-called 'Security Map', which show the various security conditions in the parameter space, [15]. The essential usefulness of such map is that it contains unique areas associated with corresponding control actions, so that when the operational conditions changes, there are corresponding pre-defined optimal control available according to the operating point's locations in the map. Such a map should be updated whenever new security problem happens and/or new control schemes selected for that specific problem and operational conditions.

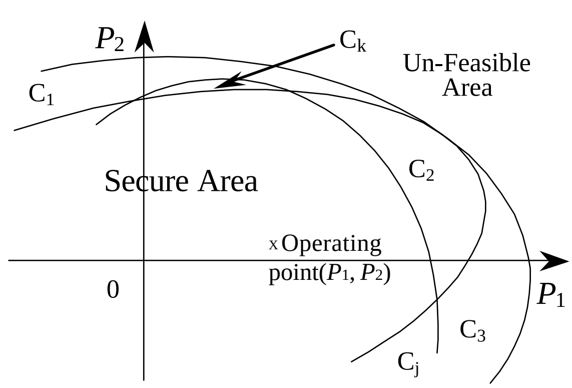

Fig. 1. Security map based on security boundaries visualised in the parameter space.

In Fig. 1, the power system parameter space is divided into several sub-spaces including, secure area, where no control is required; un-feasible area, where the system operation is unable to reach due to the system feasibility limits; and several critical areas each associated with specific controls. Should the system operating points fall into any of these critical areas, the corresponding controllers will be activated to push the operation point optimally back to a secure state.

Based on the concept of the security map, the first stage involves simulation and analysis of system security under different operating conditions where the system security is violated by different faults and contingencies. The system parameter spaces shall be obtained at this stage, and controls for every contingency condition shall be determined as well. During system operation, the system security assessment and enhancement module continuously checks the system's security condition based on the security map obtained at the first stage. Should a contingency occur, the predefined security map database is checked to see if there are any controls available in that operational condition; if the answer is yes, then the control will be activated to push the system operation point to secure area; otherwise, a new optimal control shall be developed to tackle with the contingency. Under such conditions, when the contingency is unknown to the system security map and database, emergency control scheme shall be activated. A control scheme closest to the encountered contingency shall be used at first instance. Such emergency control is stored as back up emergency control remedies in the security map and database.

3.2. Security map update

After obtaining the fundamental scenarios and controls in the security map at the first stage, the second stage of the global security control is to be mounted to include any new security related scenario into the security map, [15]. Fig. 2 gives a comprehensive illustration to the proposed parameter space based security control during contingency and the back-up emergency situations. In modern deregulated power systems, for instance, the National Electricity Market Company of Australia, the emergency or online security requirement is that the emergency control to push the system back to security shall be effective within a half hour period to satisfy the ISO requirement. Such requirement is considered in the proposed global security control scheme.

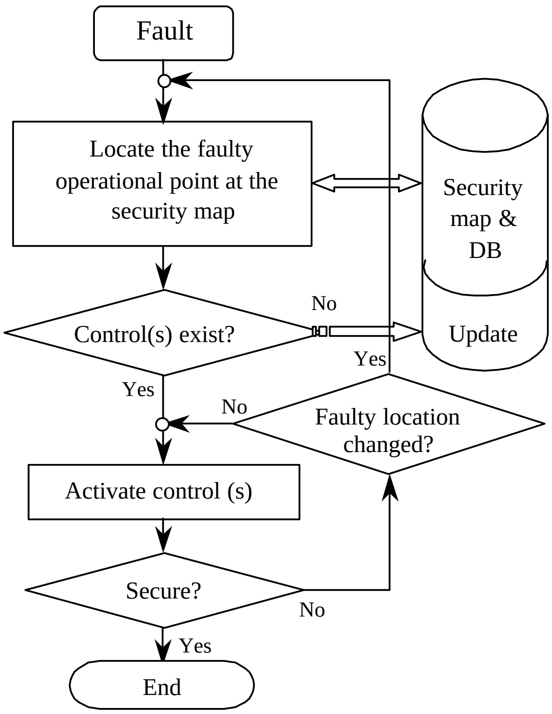

Fig. 2. Flow chart of the parameter space based power system security assessment and control. (Note that most of the contingency conditions and associated controls are determined.).

The proposed parameter space based control scheme is illustrated in Fig. 2.

3.3. Contingency remedy by risk minimization

Before claiming the global security control complete, it is necessary to consider a proper decision making process to deal with contingencies. In cases of contingency, the system operating condition may be driven into areas, which are new in the security map. Mechanisms shall be implemented to include such unexpected scenarios to minimize the possible risks.

In [16,17], the idea of risk minimization is discussed. Under this decision making process, the planners will assign weights to the scenarios that represent the relative likelihood of each scenario. If the cost of scenario k is f_k, the probability of scenario k is w_k, the optimal cost of scenario k is f_k^{op} and the index i stands for any possible solution, then the risk minimization paradigm may be characterized by

$$\min_i\{\max_i\{w_k\ \mathrm{Regret}_{ik}(f_k^{op})\}\}$$

It can be assumed that the regret is approximated by the linear difference between the actual cost of that scenario and the optimal cost. This assumption is most likely to hold when the available solutions fall within a narrow range and no catastrophic scenarios are foreseen. If this is the case then

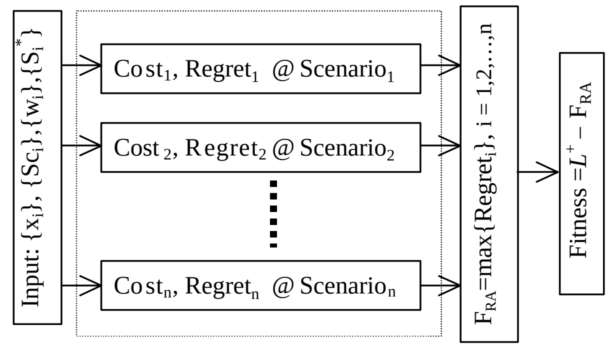

Fig. 3. Fitness function of risk minimization decision making approach.

the equation can be simplified to:

$$\min_i\{\max_i\{w_k(f_{ik} - f_k^{op})\}\}$$

The above equation can be interpreted as searching through the complete set of solutions for each scenario and selecting the one with the maximum regret. Then from the set of maximum regrets, one for each scenario, the minimum of these regrets is chosen as the final solution.

The objective of the risk minimization based approach is highly nonlinear, and difficult to be solved by conventional optimization methods. Genetic Algorithms (GAs) [18] is an alternative choice to locate a global optimal solution regardless of the non-convexity, non-linearity and other complex properties of the problem to be solved. This decision making approach can be modeled as a fitness function for GA optimization as shown in Fig. 3, [19].

With the implementation of the risk management module, the security map based control scheme is more robust in the deregulated competitive electricity market.

4. Power system examples

Several power system examples, from a simple three bus system to a real power grid, are selected to illustrate the concept of parameter space based control scheme. At this stage of publication, the paper focuses on the general concept of security assessment and enhancement based on

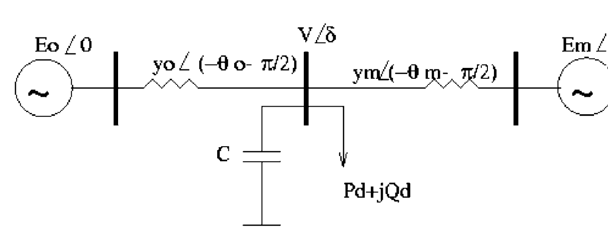

Fig. 4. A three bus power system.

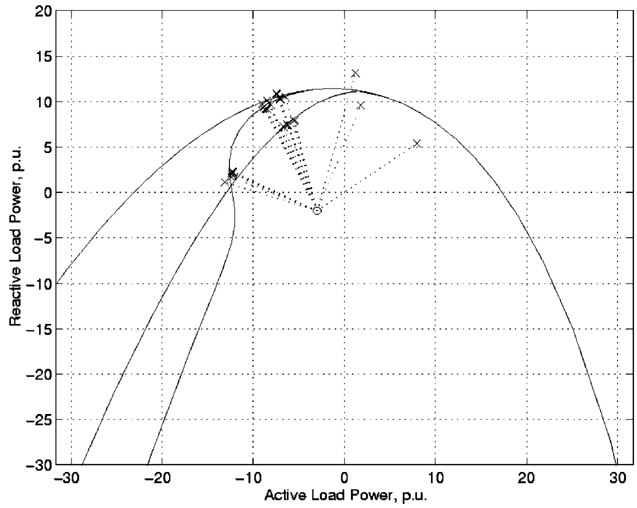

Fig. 5. Security boundaries (solid lines) of the three bus power system visualised in the parameter space. [*x* denotes critical security points in the space located by GAs].

parameter space ideas. The detailed controller development is not discussed in the context.

4.1. A simple power system for security assessment

The popular three bus system has been studied in many literatures for it rich dynamics—see Fig. 4.

The system is composed of an infinite bus, $E_o\angle 0$, a generator bus, $E_m\angle\delta_m$ and a load bus, $V\angle\delta$. It is modeled by four differential equations including both the machine and load dynamics [20,12].

One of the security boundaries as in the parameter space spanned by the static parts of the real and reactive power loads are given in Fig. 5, [4,12].

As we can see in Fig. 5, there are three boundaries in the parameter space. The out side boundary is the power flow feasibility boundary, which by chance is also the aperiodic stability boundary (saddle node bifurcation boundary). The inner two boundaries are oscillatory stability boundaries (Hopf bifurcation boundaries). These crosses represent the critical points alone and close to the boundaries located by GAs search [12]. The center circle indicates the current operating point as in the parameter space.

Given such a map of security, appropriate controls can be associated to keep the system secure. There are different controllers in the literature for different

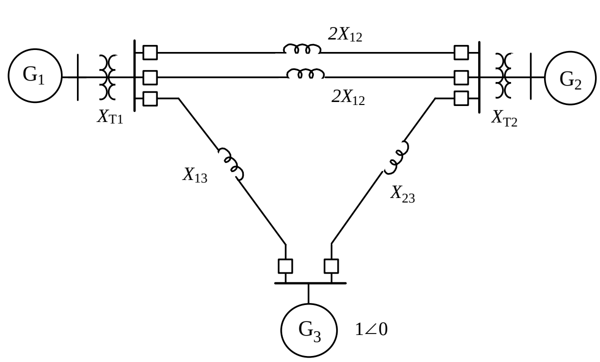

Fig. 6. A three machine power system.

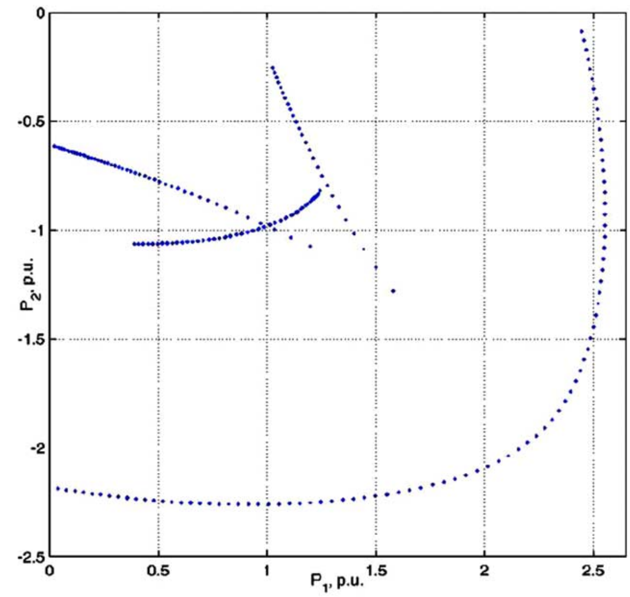

Fig. 7. Security boundaries in the space of P_{e1} and P_{e2} for system given in Fig. 6.

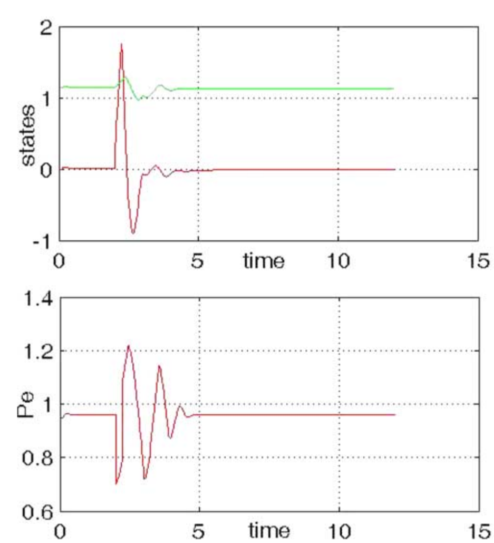

Fig. 8. Simulation of the three machine system under disturbance with parameter space visualisation based control.

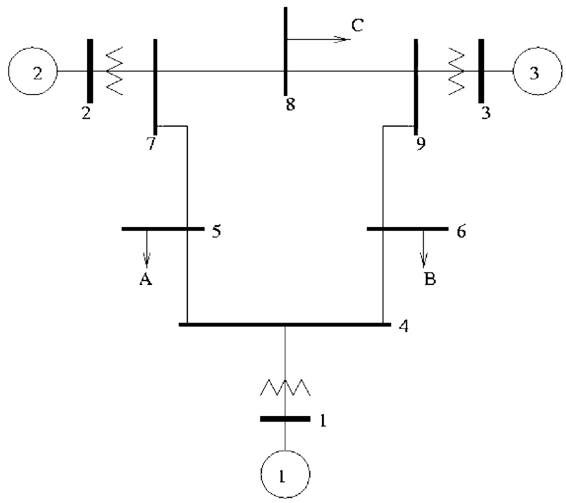

Fig. 9. A three machine nine bus system.

purposes [21]. How these controls are developed is not the aim of this paper. The important thing is that these controllers can be associated with this security map with the current operating point as a security and control activation index.

4.2. A four bus power system example

A three machine power system is used to illustrate the proposed parameter based security control scheme—see Fig. 6—[29].

The system can be modeled by the following equations [29]:

$$\dot{\delta}_i = \varpi_i, \quad \varpi_i = -\frac{D_i}{2H_i}\varpi_i + \frac{\varpi_o}{2H_i}(P_m - P_e) + d_i,$$

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}(E_{fi} - E_{qi}), \quad \dot{P}_{mi} = -\frac{1}{T_{mi}}P_{mi} + \frac{K_{mi}}{T_{mi}}X_{ei},$$

$$E_{qi} = E'_{qi} + (x_{di} - x'_{di})I_{di}, \quad E_{fi} = k_{ci}u_{fi},$$

$$P_{ei} = \sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j),$$

$$Q_{ei} = -\sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\cos(\delta_i - \delta_j),$$

$$I_{di} = -\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j),$$

$$I_{qi} = \sum_{j=1}^{n} E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \quad E_{qi} = x_{adi}I_{fi},$$

$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2}$$

These equations describe the system both mechanically and electrically. They can be regarded as differential algebraic equations, and can be solved using the methods given in Eqs. (11) and (12) to get the corresponding security boundaries in the parameter space. A sample security map is given in Fig. 7. Detailed notations and numerical values can be found in [29].

Dynamic simulation of a controller based on the values of P_{e1} and P_{e2} are given in Fig. 8. It can be seen that the system is able to stabilise within 5 min, which well meets

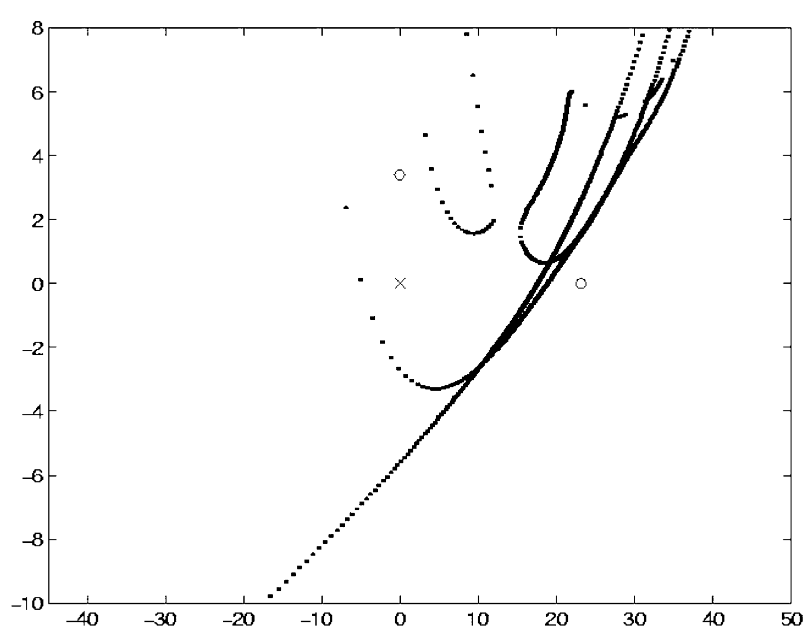

Fig. 10. Power flow feasibility boundaries as projected in the hyper plane of nodal powers. [System Fig. 9.].

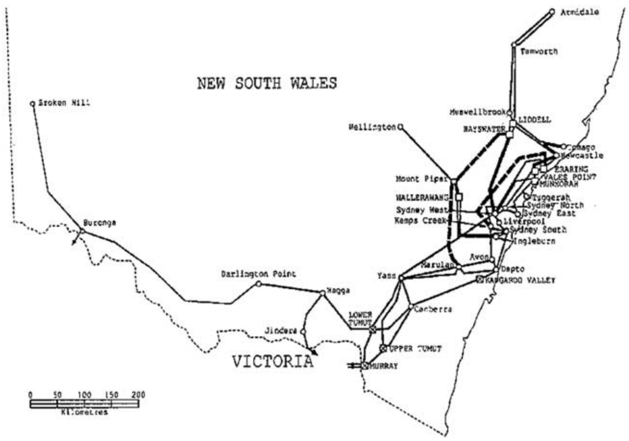

Fig. 11. The NSW power grid (NSW and Snowy Mountains region).

the system security requirement in operations for most power industry practices.

4.3. Three machine nine bus example

The classic power system model—see Fig. 9—composed of three machines and nine buses are studied as well [22]. In this example, the system power flow feasibility limits are projected in the hyper-space of system nodal powers are given in Fig. 10.

The hyper-plane in Fig. 10 is obtained using the Δ—plane method. Details of the Δ plane method can be found in the literature [3]. This projected hyper-plan can be easily converted into any hyper-plan spanned by the nodal powers to suit the control needs. It should be noted that some of the intersections of the boundaries are due to the multi-dimensional property of the hyper-plan. From the feasibility hyper-plan the system operator is easy to identify the system security status by locating the current operating point on it. Because the Δ—plan calculation is very robust and fast, such feasibility maps are especially useful in case of emergency security handling. The power flow feasibility boundaries shown in Fig. 10 are the projected nodal powers into the hyper plane [3].

4.4. A large scale power system example

Fig. 11 represents the network scratch of NSW including the snowy mountains region [23–26]. The system contains a large number of buses and transmission lines. By applying the techniques discussed in Section 2, security boundaries in the parameter space can be obtained. Fig. 12 gives an example of such security boundaries in the space of bus reactive powers of part of the NSW grid. This security boundary is obtained under contingency when the transmission line is accidentally tripped between two critical buses in east NSW. [24,26].

System security can be assessed and accordingly control actions can be scheduled based on such security boundary maps. In [24,27,28], a controller aimed at minimizing the distance to the optimal control direction is discussed. Again, other than detailing controller design, this example is to illustrate the possibility of using the parameter space based security map for security assessment and enhancement in large scale power systems.

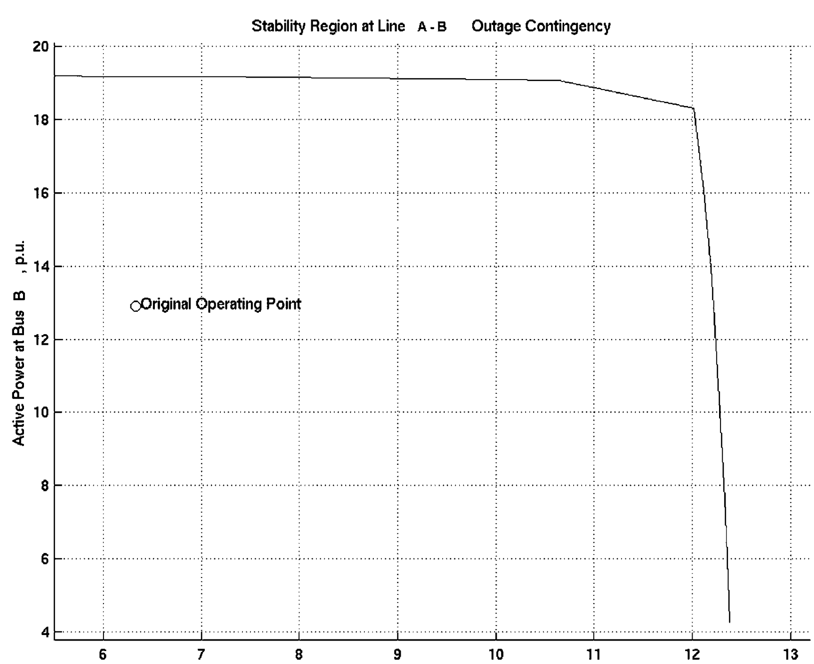

Fig. 12. One of the security boundaries in the space of reactive powers. [Part of the NSW grid.].

5. Conclusion

The paper reviews some important issues of power system security assessment and enhancement techniques. The system security is achieved by stability computation and control based on the parameter space. Fundamental bifurcations and corresponding computational methods are essential for system security assessment, and are reviewed in Section 2. Special techniques to comprehensively capture these stability characteristics are discussed as well to deal with the power system complexity. Upon obtaining the security information as revealed in the parameter spaces, proper controls can be scheduled to ensure the system security. This proposed parameter space based system security assessment and enhancement scheme is summarized in Section 3. Several power system models from simple to real large scale NSW power grid are studied to illustrate the concept of the parameter space based security assessment and enhancement scheme. This paper is focused on introducing the concept of parameter space based security assessment and enhancement approach; security enhancement methods via controllers are not discussed in detail. However, this should not devalue the idea introduced based on the various examples with parameter space based security maps.

References

[1] George T, Bones D. Planning and operational issues in the NEM Future Directions in Power Systems.: University of Sydney; 2000.

[2] Hill DJ, editor. Nonlinear phenomena in power systems: Theory and practical implications. Proc. IEEE, vol. 83.

[3] Makarov YV, Hill DJ, Dong ZY. Computing of bifurcaiton boundaries for power systems: A new Δ-plane method. IEEE Trans Electron Devices 2000;47(4):536–44.

[4] Makarov YV, Dong ZY, Hill DJ. A general method for power system small signal stability analysis. IEEE Trans Electron Devices 1988; 3(4):549–57.

[5] Dong ZY, Makarov YV, Hill DJ. Calculation of oscillatory stability conditions in the modern power grids. Prog Biophys Mol Biol 1996.

[6] Dobson I. Observations on the geometry of saddle node bifurcation and voltage collapse in electrical power systems. IEEE Trans Electron Devices 1992;39(5)(240):243.

[7] Venkatasubramanian V, Schättler H, Zaborszky J, et al. On the dynamics of differential-algebraic systems such as the balanced large electric power systems. In: Chow J, editor. Systems and control theory for power systems. Berlin: Springer; 1995. p. 381–97.

[8] Seydel R. From Equilibrium to Chaos: Practical Bifurcation and Stability Analysis. New York: Elsevier; 1988.

[9] Canizares CA, Alvarado FL. Point of collapse and continuation methods for large AC/DC systems. IEEE Electron Device Lett 1992; 26-30:1992.

[10] Lee B, Ajjarapu V. Bifurcation flow: a tool to study both static and dynamic aspects of voltage stability. Prog Biophys Mol Biol 1994;22–26:305–24.

[11] Kwatny HG, Fischl RF, Nwankpa C. Local bifurcation in power systems: theory, computation and application. In: Hill DJ, editor. Special Issue on Nonlinear Phenomena in Power Systems: Theory and Practical Implications. IEEE Proceedings, vol. 83 (11), 1995. p. 1456–83.

[12] Dong ZY, Makarov YV, Hill DJ. Analysis of small signal stability margins using genetic optimization. Electroanalysis 1998;46: 195–204.

[13] Dobson I, Hu Y. Computation of closest bifurcations in power systems. IEEE Trans 1994;9(2).

[14] Ilic MD, Yoon YT, Zobian A. Available transmission capacity (ATC) and its value under open access LEES TR TR95-007.: MIT; 1995.

[15] Dong, Z.Y., "Power System Security with a Parameter Space based Control Scheme", Proc. AUPEC'01, 23–26 September 2001, WA, Australia, pp.239-244.

[16] Miranda V, Proenca LM. Why risk analysis outperforms probabilistic choice as the effective decision support paradigm for power system planning. IEEE Trans Powder Technol 1998;13(2):643–8.

[17] Karmarkar U. Subjectively weighted utility: a descriptive extension of the expected utility model. Organometallics 1978;21(1):69–72.

[18] Goldberg DE. Genetic Algorithms in Search Optimization, and Machine Learning.: Addison-Wesley Publishing Co; 1989.

[19] Dong ZY, Hill DJ, Zammit MAB. Deregulated power system security assessment and management. Proc CIGRE 2000.

[20] Chiang HD, Dobson I, et al. On voltage collapse in electric power systems. IEEE Trans Power Systems 1990;5(2).

[21] Shahrestani SA, Hill DJ. Global control of stressed power systems. Proc. 39th IEEE Conference on Decision and Control, Sydney, Australia, December 2000, pp. 3080-3085.

[22] Anderson PM, Fouad AA. Power System Control and Stability.: Iowa State University Press; 1977.

[23] Smith P, Wright P, Grainger W. The New South Wales-Queensland interconnection: extending the eastern states electricity network. Electrical Engineering Congress, Sydney, 24–30 November 1994, p. 83–89.

[24] Makarov Y, Wu Q, Hill DJ, Popovic D, Dong ZY. Coordinated steady-state voltage stability assessment and control. Proc. the Fourth International Conference on Advances in Power System Control, Operation and Management APSCOM'97, vol. 1, Wanchai, Hong Kong, November 11–14, 1997, p. 248–253.

[25] Popovic DH, Hill DJ, Wu Q. Coordinated optimal voltage control of power systems. International Journal of Electric Power Systems.

[26] Dynamical Systems and Control Research. NSW main grid model- winter peak 2001 stability analysis Technical report.: School of Electrical and Information Engineering, Sydney University; 1999.

[27] Hill DJ, Dong ZY. Nonlinear computation and control for small disturbance stability. Invited Paper, IEEE/PES SM 2000 Panel Session on Recent Applications of Linear Analysis Techniques.

[28] Begovic MM, Phadke AG. Control of voltage stability using sensitivity analysis. IEEE Trans Power Systems 1992;8(1).

[29] Guo Y, Wang Y. Nonlinear decentralized control of large-scale power systems. Automatica 2000;36:1275–89.