

A Visualization Tool for Real-Time Dynamic Contingency Screening and Remedial Actions

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Abstract—This paper proposes a real-time visual interactive transient stability screening and remedial action tool that uses an approach based on Lyapunov functions to enable the selection of appropriate remedial actions that stabilize power systems due to large disturbances and cascading failures. At present, there is no effective tool that enables making a well-informed choice from amongst a profusion of remedial action alternatives. Conventionally, transient stability analysis of power system is performed off-line to assess the capability of the power system to withstand specific disturbances and to investigate the dynamic response of the power system as the network is restored to normal operation. In this work, post-fault stable and controlling unstable equilibrium points are determined using a homotopy-based approach. Subsequently, stability assessment of the system and the corresponding potential remedial actions are determined from the equilibrium points of the system dynamical model. The real-time transient stability analysis and remedial action algorithm are incorporated with the visualization tool to facilitate interactive decision making in real-time. The transient stability analysis and remedial action algorithm, and the visualization tool are demonstrated on several test systems including the equivalent Western Electricity Coordinating Council system and the simplified New England 39 bus test system.

Index Terms—Remedial actions, transient stability screening, visualization.

NOMENCLATURE

P_{mi}	Mechanical input power of machine i .
P_{ei}	Electrical output power output of machine i .
M_i	Inertia constant of machine i .
E_i	Internal voltage magnitude of machine i .
δ_i	Power angle of machine i .
ω_i	Angular frequency variation of machine i .
λ_d	A uniform damping constant.
G_{ij}	Conductance of the bus admittance matrix.
B_{ij}	Susceptance of the bus admittance matrix.
EP	Exit point.
MGP	Minimum gradient point.
X_{co}	Controlling unstable equilibrium point (UEP).
$A(X_s)$	Region of attraction (stability) of the post-stable equilibrium point (X_s).
$\partial A(X_s)$	Boundary of the region of attraction.
$R(X_{co})$	Region of convergence of a controlling UEP under Newton method.

$W^s(X_{co})$	Stable manifold of a controlling UEP.
X_s^{pre}	Pre-fault stable equilibrium point.
λ_h	Homotopy mapping factor.
ΔV	Energy margin.
ΔV_{KE}	Change in system kinetic energy.
ΔP_{PE}	Change in system potential energy.

I. INTRODUCTION

CONTROL paradigms of modern power grids have been augmented with sophisticated communication and computation technologies that enable real-time monitoring and control of possible contingencies. However, the increasing pace of integrating variable energy resources has driven power grids to operate at lower security margins due to the low inertia or lack of inertia of these resources. Consequently, transient instability has become a major concern in modern power system security despite the advances in the communication and computation technologies. In other words, power grids will grow more vulnerable to transient instability and cascading failures if real-time transient stability screening and remedial action tools are not integrated with the communication and computation technologies. Traditional on-line contingency analyses have only evaluated static contingencies; dynamic contingencies were deemed too computationally intensive to solve in real-time. Stability scenarios were evaluated off-line, safe operating zones were determined and documented, and operators were required to be familiar with these scenarios and remedial actions. Therefore, the need for better situational awareness has become evident, and triggered several ongoing efforts to develop improved methods of determining remedial action alternatives including special protection schemes, emergency action, and on-line contingency analyses.

More recently, there have been theoretical advances that can potentially enable determination of security margins and perform remedial action screening in real time. These methods are predominantly based on “direct” methods, such as Lyapunov or energy function methods. They utilize the advantages of the conservativeness of direct methods to recursively classify the designated set of contingencies into *stable*, *potentially unstable* and *undetermined* subsets. After using direct methods to screen out a large number of stable contingencies, time-domain simulations are performed to check those potentially unstable contingencies. Direct methods have proved to be very effective in reducing the number of contingencies that need further evaluation using time-domain simulations, and thereby made it possible to screen and compute dynamic contingencies in real time.

In addition to enabling decision-making in real time to stabilize power systems for large disturbances, rapid transient

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stability analysis and remedial actions can vastly enhance the reliability of power systems. As today's power systems increasingly operate at lower security margins, due to reduced regulation capability resulting from increased variable generation [1], some utilities and independent system operators (ISOs) are integrating dynamic contingency evaluation and expert systems for special protection schemes into their control center practices. This motivates the development of methods for real-time or faster-than-real-time transient stability analysis, dynamic contingency screening and remedial action, as well as appropriate visualization and operator interaction tools.

Several methods and strategies have been proposed in the area of the on-line transient stability assessment. These methods can be classified into artificial intelligence approaches [2]–[12] and direct methods [13]–[18]. Due to the open-access operation of power system networks, off-line analyses may not be fully correlated to the on-line data; therefore, the results of the artificial intelligence approaches may become invalid [15]. On the other hand, transient stability screening tools based on direct methods suffer from conservativeness of the results. However, such tools have the advantage of being able to screen out a large number of non-severe contingencies so that detailed simulations are applied only on severe or undetermined contingencies to reach the requirements of on-line applications. An on-line screening tool based on three levels of filtering using direct methods has been proposed in [13], [14]. Each level has two time frames, inertial transient filters and post-inertial transient filters. The filters screen the contingencies along the solution trajectory toward the controlling unstable equilibrium point (controlling UEP). Another on-line dynamic contingency screening tool based on the BCU method (boundary of stability region based controlling unstable equilibrium point method) has been proposed in [15]. This tool uses six classifiers to screen out a small number of critical contingencies for detailed simulations. Improvements for the screening tool of [15] have been proposed in [16]. In the improved screening tool, another level of classification, which is the detection of the islanding mode and improvements in the six classifiers of [15], has been added.

This paper presents a visualization tool for real-time transient stability screening and remedial action. A direct method is used for screening and evaluating system stability and developing remedial actions. Transient stability screening is performed based on the energy margin of contingencies and remedial actions are developed based on the sensitivity of the energy margin to the change in control parameters. In combination with developments in telemetry and communication technologies, the proposed visual interactive real-time transient stability screening and remedial action tool helps in improving the security and resilience of modern power systems [19].

The rest of the paper is organized as follows. Section II describes the approach to developing the proposed tool. Section III describes direct methods of transient stability analysis. Section IV shows the application of remedial actions. Section V presents the proposed visualization tool and its functionality. Section VI shows the demonstration of the proposed tool. Section VII provides concluding remarks.

II. THEORETICAL APPROACH

Following a potentially destabilizing event, the grid can evolve along any of numerous possible trajectories, which may be exacerbated by subsequent events or ameliorated by operator action. One of the key revelations that emerged from studies of recent blackouts was that grid operators needed increased situational awareness and improved understanding of remedial action alternatives available to them. However, transient stability contingency studies have been limited to the system design or upgrade phase to yield stable and disturbance-rejecting power network design and limited to operator training exercises in order to help with robust power system operations [20]–[24]. Until recently, complexities and computation overhead associated with time domain analyses of transient stability problems have kept them from being run in real time to support decision making at the time of a disturbance. If a transient stability program could run in real-time or faster-than-real-time then power system control-room operators could be provided with a detailed view of the scope of cascading failures. Such a view of the unfolding situation can assist an operator in comprehending the gravity of the emergent problem and its ramifications so that proactive counter measures could be adopted to limit the extent of the incident.

We propose a visual interactive real-time screening and remedial action tool that uses an approach based on Lyapunov functions to enable, without time-domain simulation, the selection of appropriate remedial actions that are most likely to result in stabilizing trajectories. The interactive visualization tool that incorporates the screening and remedial action tool is developed for operator interface and to update system status in real time.

In developing the proposed real-time transient stability and remedial action screening tool, several technical challenges had to be solved, particularly: (1) using the tools available today such as time-domain simulation, it is impossible to evaluate or screen every trajectory the system could assume within the time available to an operator and (2) problems that are associated with precise determination of the post-fault stable equilibrium points (SEPs) and controlling UEPs. The problem relating to the first challenge was tackled using Lyapunov function based methods of transient stability analysis that can be solved at real-time speed (or faster than real-time) without the use of massively parallel computation resources. The second challenge arises because the accuracy of Lyapunov function based methods strongly relies on the determination of the controlling UEP. However, the presence of fractal shapes of the convergence region of the controlling UEP is the main reason of failure of many numerical methods in finding the correct controlling UEP. To find the correct controlling UEP, the initial guess, in using Newton methods for example, has to be within a certain neighborhood of the desired solution. This requirement makes it difficult to find the best guess and is computationally expensive. In this work, a method that is based on homotopy approaches, which was developed by the authors in [24], [25], is used to compute the controlling UEP. Homotopy methods, being globally convergent, was developed

to overcome the local convergence issues related to Newton methods. In other words, homotopy methods are guaranteed to converge to a solution regardless of an initial starting point provided that there are no singularities, bifurcation points, or turning points in its path. In cases where there are multiple equilibrium points, homotopy methods have the ability to find those solutions. As we describe later, an algorithm is developed to determine the exact controlling UEP.

III. TRANSIENT STABILITY ANALYSIS

Transient stability methods are known to be computationally intensive, and in recent times several efforts have been directed toward developing methods that execute close to real-time speeds. Using the tools available today, it is impossible to evaluate or screen every trajectory the system could assume—the computational challenge of performing time-domain simulation of every, or even a selected set of probable trajectories, within the time available to an operator, is simply unassailable. Direct methods have proved to be very effective in reducing the number of contingencies that need further evaluation using time-domain simulations, and thereby made it possible to screen and compute dynamic contingencies in real-time. Thus, one saves significant computation time without compromising accuracy. If the initial condition does not belong to any basin of attraction or belongs to the basin of attraction of an unstable solution or belongs to the basin of attraction of an unrealizable equilibrium (e.g. solution in complex domain), then time-domain simulation will be required to determine the system trajectory. However, even under such a circumstance it is noted that the initial condition search space, which is a subset of the total search space, may be significantly reduced. Further, if the evolving system state moves into one of the attractors for an equilibrium solution, then, further time-domain projection of dynamical path is not required for reasons explained above. Hence, the volume of time-domain simulation may not be significant, thereby saving the computational overhead and need for concurrent processing.

The work reported in this paper was developed by the authors under a contract from the U.S. Department of Energy. This Lyapunov function-based Remedial Action Screening tool (LRAS) utilizes a homotopy method [24], [25] to classify a designated set of contingencies into stable and unstable subsets using transient stability direct methods. This method utilizes the advantages of the conservativeness of the direct methods to initially classify the designated set of contingencies into stable, potentially unstable and undetermined subsets. The potentially unstable subset is further divided into stable, potentially unstable and undetermined subsets along the solution trajectory toward the controlling UEP. The scheme utilized in this paper, which we found to be effective, is to check the stability of different points by direct (Lyapunov) methods to screen out a large number of stable contingencies, and then apply time-domain simulation to check the potentially unstable contingencies. The need for time-domain simulations is considerably reduced and sometimes eliminated by applying the proposed homotopy-based approach to screen out a large number of contingencies.

A. System Model and Energy Function

This section presents the dynamical model of power systems and the associated energy function for transient stability analysis.

1) *The Dynamical Model:* Given an n -generator system and assuming a uniform damping, the dynamical model of the equations of motion of the generators with respect to the center of inertia (COI) can be described as follows [26].

$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i, \quad (1)$$

$$\dot{\tilde{\omega}}_i = \frac{1}{M_i} (P_{mi} - P_{ei}) - \frac{1}{M_T} P_{COI} - \lambda_d \tilde{\omega}_i, \quad (2)$$

where $\tilde{\delta}_i = \delta_i - \delta_o$, $\tilde{\omega}_i = \omega_i - \omega_o$, $\delta_o = \frac{1}{M_T} \sum_{i=1}^n M_i \delta_i$, $\omega_o = \frac{1}{M_T} \sum_{i=1}^n M_i \omega_i$, and $M_T = \sum_{i=1}^n M_i$.

The electrical output power of machine i is given as follows.

$$P_{ei} = \sum_{j=1}^n E_i E_j \left[G_{ij} \cos(\tilde{\delta}_i - \tilde{\delta}_j) + B_{ij} \sin(\tilde{\delta}_i - \tilde{\delta}_j) \right]. \quad (3)$$

The P_{COI} is computed as follows.

$$P_{COI} = \sum_{i=1}^n P_{mi} - \sum_{i=1}^n \sum_{j=1}^n E_i E_j \left[G_{ij} \cos(\tilde{\delta}_i - \tilde{\delta}_j) + B_{ij} \sin(\tilde{\delta}_i - \tilde{\delta}_j) \right]. \quad (4)$$

The compact form of the system of (1) and (2) can be expressed as follows.

$$\dot{x} = F(x). \quad (5)$$

2) *The Energy Function:* The energy function is used in transient stability analysis for fast screening and to compute the exit point to generate a sequence of steps to calculate the controlling UEP. The energy function associated with the model of (5) is given in (6) where the first term represents the kinetic energy and the last two terms represent the potential energy [27], [28].

$$V = \frac{1}{2} \sum_{i=1}^n M_i \tilde{\omega}_i^2 - \sum_{i=1}^n P_i (\tilde{\delta}_i - \tilde{\delta}_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^n \left[C_{ij} (\cos \tilde{\delta}_{ij} - \cos \tilde{\delta}_{ij}^s) - I_{ij} \right], \quad (6)$$

where the superscript s denotes the pre-fault stable equilibrium point (SEP), $C_{ij} = E_i E_j B_{ij}$, and $P_i = P_{mi} - E_i^2 G_{ii}$.

The term I_{ij} is the energy dissipated in the network transfer conductances, and it can be expressed as follows.

$$I_{ij} = \int_{\tilde{\delta}_i^s + \tilde{\delta}_j^s}^{\tilde{\delta}_i + \tilde{\delta}_j} D_{ij} \cos \tilde{\delta}_{ij} d(\tilde{\delta}_i + \tilde{\delta}_j), \quad (7)$$

where $D_{ij} = E_i E_j G_{ij}$.

The term presented in (7) is path dependent and can be calculated only if the system trajectory is known. However, the system trajectory is not known in advance. Several methods

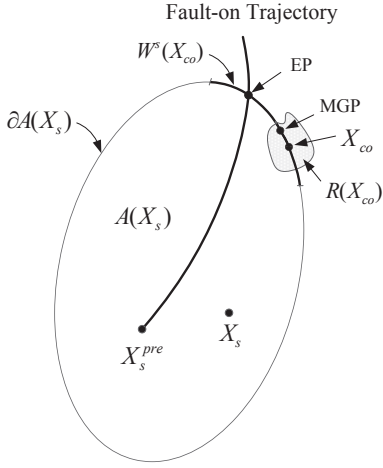


Fig. 1. Region of convergence of controlling UEPs under the use of Newton methods [29].

have been suggested in the literature to approximate this term. In this paper we have used the method suggested by [27] which can be expressed as,

$$I_{ij} = D_{ij} \frac{\tilde{\delta}_i + \tilde{\delta}_j - \tilde{\delta}_i^s - \tilde{\delta}_j^s}{\tilde{\delta}_i - \tilde{\delta}_j - \tilde{\delta}_i^s + \tilde{\delta}_j^s} \left[\sin \tilde{\delta}_{ij} - \sin \tilde{\delta}_{ij}^s \right]. \quad (8)$$

Since the energy function is used in determining exit points, the approximation in the path dependent term I_{ij} may cause difficulties in finding accurate exit points. However, in the method proposed in this paper, accurate exit points are not necessary in finding the controlling UEPs. Therefore, this approximation will not cause problems in calculating the controlling UEPs.

B. Calculation of the Controlling UEPs

Computing the controlling UEPs is crucial because the energy at a controlling UEP is used in computing the critical energy to assess the stability of the system. A state vector x is called an equilibrium point x^* of the system represented in (5) if $F(x^*) = 0$. A controlling UEP is one of the unstable equilibrium points, but it is not an easy task to determine and distinguish it from the other unstable equilibrium points. Mathematically, a controlling UEP is an unstable equilibrium point whose stable manifold, $W^s(X_{co})$, contains the exit point of the fault-on (sustained fault) trajectory $(\delta(t), \omega(t))$ [27], [29]–[31] as shown in Fig. 1.

The region of convergence of an equilibrium point can be defined as follows: starting from an initial guess, a numerical method succeeds in finding the desired solution if the starting point lies inside the region of convergence of the solution and it fails if the initial guess lies outside the region of convergence. The size and shape of the region of convergence of a controlling UEP can be very fractal and different for different numerical methods [29]. Therefore, if the initial guess is not in the region of convergence of the controlling UEP, numerical methods such as Newton methods fail to find the correct controlling UEP. In other words, to find the correct controlling UEP, the initial guess has to be sufficiently close to the controlling UEP.

A popular method to compute controlling UEPs is to use time-domain simulations to simulate the projected fault-on trajectory to obtain the exit point and the MGP, and then use the MGP as an initial guess to generate a sequence of solution steps toward the controlling UEP [30]–[36]. The exit point is the point at which the projected fault-on trajectory exits the stability boundary of the post-fault SEP. Computationally, the exit point is characterized by the first local maximum of the potential energy (the last two terms of (6)) of the post-fault network along the projected fault-on trajectory. Another method to detect the exit point is detecting the change in the sign of the dot product of the post-fault power mismatch vector and the fault-on speed vector [29]. The MGP is numerically characterized by the first local minimum value of the norm of the vector field of the post-fault trajectory of (1) and (2) [29].

The robustness of finding the controlling UEP depends strongly on the quality of the calculated MGP [30], [32], [33], [36], [37]. However, an inaccuracy in detecting the exit point may cause a difficulty in computing the MGP. Also, detecting an accurate exit point is computationally involved and sometimes it requires the use of interpolation methods after bounding the exit point in a certain range. Therefore, a numerical inaccuracy in computing the exit point will probably cause failure of numerical methods to calculate the controlling UEP.

Most of the methods described in the literature integrate the fault-on trajectory with large time step until the algorithm locates the exit point between two time points. The algorithm then bounds these points and starts searching for the exit point using some tools, such as the golden section, and linear or quadratic interpolation. Once a more accurate exit point is discovered, the algorithm uses this point as an initial point to compute the MGP and then the controlling UEP. Therefore, we can see that it requires significant efforts to compute the exit point.

To overcome the difficulty of finding an initial point inside the region of convergence, we propose the use of a homotopy-based approach in computing the controlling UEP. Homotopy-based approaches are known to be reliable in finding the solutions and they are globally convergent [38]–[41]. In this paper, a homotopy-based approach is used to eliminate the requirement of computing the MGPs and accurate exit points. The work in this paper shows that a controlling UEP can be obtained by using the homotopy-based approach with an approximate exit point as an initial guess. The next two sections present the proposed homotopy-based approach and the well known BCU method [15], [29] for the sake of comparison.

C. Homotopy Method

Traditional methods of solving (5) include the use of Newton methods. Newton methods, although computationally sound, will only converge to a solution if the initial guess is within the neighborhood of the convergence region of the desired solution. Homotopy methods have been developed to overcome the local convergence of Newton methods since they are globally convergent [38]–[41]. That is, these methods

are guaranteed to converge to a solution regardless of an initial starting point provided that there are no singularities, bifurcation points, or turning points in its path. In the case where there may be multiple equilibrium points, the homotopy method has the ability to find those solutions. However, when multiple solutions exist, a better initial condition can help to obtain the solution of interest first. The logic behind these methods in computing the controlling UEP is that with an exit point as the initial guess, the homotopy-based approach can find the controlling UEP first since its location is the closest to the exit point in terms of the energy value.

1) *Calculating Controlling UEPs:* Homotopy is a numerical method that is used to solve and find the roots of non-linear systems ($F(x^*) = 0$). The homotopy method traces the solution trajectory by a predictor-corrector algorithm to get a solution of the original equation. The basic concept of the homotopy-based methods is that they find the solutions by path continuation, starting at a known solution x^0 that satisfies $G(x^0) = 0$ as shown in (9). The most widely used homotopy function is expressed as follows.

$$H(x, \lambda_h) = \lambda_h F(x) + (1 - \lambda_h)G(x) = 0, \quad (9)$$

where λ_h changes from 0 to 1 with an incremental step-size through the mapping process, i.e., $H(x, 0) = G(x)$ and $H(x, 1) = F(x)$.

$G(x)$ can be chosen arbitrary as long as it has a known solution. However, the most widely used homotopy function is Newton Homotopy which can be expressed as follows.

$$G(x) = F(x) - F(x^0), \quad (10)$$

where x^0 can be any starting point. Therefore, the homotopy function becomes

$$H(x, \lambda_h) = F(x) - (1 - \lambda_h)F(x^0) = 0. \quad (11)$$

In this work, we used Newton homotopy to successfully compute the controlling UEPs of the tested systems. The $F(x)$ function represents the dynamical model of the system as given in (5) and x^0 is the exit point which is the first maximum point of the potential energy along system trajectory.

2) *Filtering Using Homotopy Method:* Screening and classification processes require sophisticated programs that can meet the requirements of on-line applications. The existing on-line transient stability analysis tools based on transient stability direct methods have introduced several system dependent thresholds for classifications. These thresholds are used to classify a set of contingencies into stable, unstable or undetermined subsets. The undetermined contingencies are the contingencies that have numerical convergence problems such as failure to calculate controlling UEPs. In order for these thresholds not to fail in classifying the contingencies, off-line transient stability analyses are usually required. Also, for the unstable or undetermined contingencies, detailed time-domain simulations are performed. Therefore, these methods require off-line transient stability assessments and may excessively use time-domain simulations.

Several criteria and requirements are suggested in the literature for any on-line transient stability screening candidate.

In [15], five requirements were suggested for any on-line transient stability screening tool. These requirements are: reliability measure, efficiency measure, on-line computation, speed measure, and performance measure [15].

The proposed transient stability screening tool checks stability by sequentially calculating the exit point and the controlling UEP for each contingency. Several methods can be used to increase the speed of computation such as using some indicators and thresholds to drop off, at the early stages of screening, mild contingencies, i.e. highly stable contingencies.

D. BCU Based Approach

The BCU method is a systematic method that uses the concept of reduced-state model for computing the controlling UEP [15], [29]. This method defines an artificial model that can be solved to find all the equilibrium points of the original model. For each power system stability model there is a corresponding reduced-state model such that static and dynamic properties of the original model are captured to compute the controlling UEP on the stability boundary of the original model. Computing the controlling UEP using the BCU method on the reduced-state model is easier than computing the controlling UEP of the original model [29]. For example, consider the following generic model [29]:

$$T\dot{x} = -\frac{\partial U}{\partial x}(x, y) + g_1(x, y), \quad (12)$$

$$\dot{y} = z, \quad (13)$$

$$M\dot{z} = -Dz - \frac{\partial U}{\partial y}(x, y) + g_2(x, y), \quad (14)$$

where x , y , and z are state variables, T is a positive definite matrix, M and D are diagonal positive definite matrices, U is the function of system dynamics, and $g_1(x, y)$ and $g_2(x, y)$ represent the transfer conductances.

The associated artificial, reduced-state model is given as follows [29]:

$$T\dot{x} = -\frac{\partial U}{\partial x}(x, y) + g_1(x, y), \quad (15)$$

$$\dot{y} = -\frac{\partial U}{\partial y}(x, y) + g_2(x, y). \quad (16)$$

The general procedure of finding the controlling UEP using the BCU method is summarized as follows [31] where the definitions are referred to Fig. 1.

- 1) From the fault-on trajectory, determine the EP.
- 2) Use the EP as an initial point and integrate the post-fault reduced-state model to find the MGP.
- 3) Use the MGP as an initial point to calculate the controlling UEP of the reduced-state model.
- 4) Determine the controlling UEP of the original system.

In implementing the above procedure, it is important to be aware of several potential numerical issues [29]. For example, an inaccuracy in calculating the EP may cause an inaccuracy in computing the MGP. If the computed MGP is not sufficiently close to the controlling UEP, the iterative method may diverge or converge to another equilibrium point.

IV. REMEDIAL ACTIONS

There are two types of remedial actions, namely, corrective actions and preventive actions. Corrective actions can be performed locally or globally depending on the available measurements and means. On the other hand, preventive actions are performed globally. Global corrective actions could be generation tripping, load shedding, line tripping, and local corrective actions could be control of excitation and output power. The preventive actions could be generation rescheduling and load shedding. The ability to distinguish between these actions depends upon the initial conditions of the system and the triggering events. The preventive screening and the corresponding remedial actions can be triggered either periodically or upon operator request. The preventive action tool starts with screening a full list of possible contingencies assuming the system resides in a healthy state. On the other hand, the corrective screening and the corresponding remedial actions are triggered immediately after an occurrence of an event. Here, instead of screening the entire set of possible contingencies, only the “related” contingencies and the possible contingencies on some critical lines are screened. When a fault occurs at some location in the grid, the neighboring lines will be exposed to overload and/or false tripping due to hidden failures in the protection equipments [42]. Also, some critical lines that carry a large amount of power, transient stability-limited lines, and the inter-ties between areas may be affected by faults in non-neighboring lines. The process of performing remedial action control is shown in Fig. 2.

After screening, contingencies are divided into two main sets: stable and unstable sets. For the stable set, no control actions are needed. On the other hand, for the unstable contingencies, control measures are required to prevent unacceptable impacts on system stability (preventive actions) or to immediately respond to the occurring disturbance in order to maintain system operation in balance (corrective action).

A. Energy Margin and Sensitivity Analysis-based Remedial Action Control

The energy margin (ΔV) is defined as the difference between the value of the energy function V at the instant of clearing the fault, V^{cl} , and at the controlling UEP, V^u , to determine the critical value (the critical value of the energy margin is calculated at the controlling UEP). This condition is mathematically expressed by the following equation [26]:

$$\Delta V = V^u - V^{cl}. \quad (17)$$

If the difference is larger than zero, the system is deemed stable; otherwise, it is deemed unstable. The energy margin is calculated as follows [26].

$$\begin{aligned} \Delta V = & -\frac{1}{2} M_{eq} (\tilde{\omega}_{eq}^{cl})^2 - \sum_{i=1}^n P_i (\tilde{\delta}_i^u - \tilde{\delta}_i^{cl}) - \sum_{i=1}^{n-1} \sum_{j=i+1}^n [C_{ij} \\ & (\cos \tilde{\delta}_{ij}^u - \cos \tilde{\delta}_{ij}^{cl}) - D_{ij} \frac{\tilde{\delta}_i^u + \tilde{\delta}_j^u - \tilde{\delta}_i^{cl} - \tilde{\delta}_j^{cl}}{\tilde{\delta}_{ij}^u - \tilde{\delta}_{ij}^{cl}} (\sin \tilde{\delta}_{ij}^u \\ & - \sin \tilde{\delta}_{ij}^{cl})], \end{aligned} \quad (18)$$

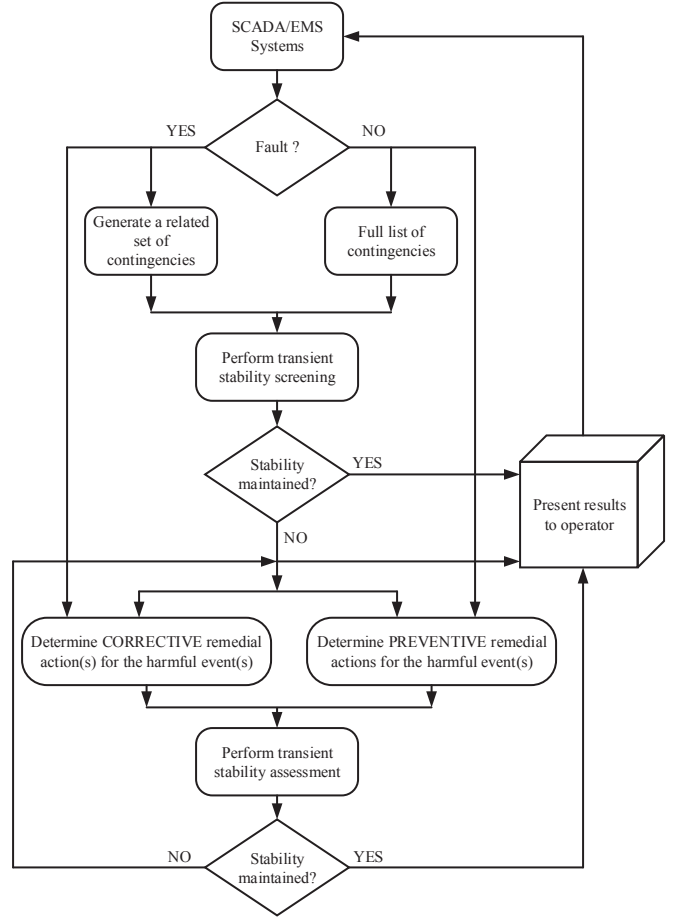


Fig. 2. Flowchart of the corrective and preventive remedial actions scheme.

where

$$M_{eq} = \frac{M_{cr} M_{sys}}{M_{cr} + M_{sys}},$$

$$\tilde{\omega}_{eq}^{cl} = \tilde{\omega}_{cr}^{cl} - \tilde{\omega}_{sys}^{cl},$$

and M_{cr} and M_{sys} are the total inertia of advanced rotor angle machines and total inertia of the rest of machines at the calculated controlling UEP, respectively; $\tilde{\omega}_{cr}^{cl}$ and $\tilde{\omega}_{sys}^{cl}$ are the change in the angular frequency of advanced rotor angle machines and the rest of machines referred to the COI reference frame at the clearing of the disturbance, respectively.

B. Sensitivity Concept

As can be seen from equation (18), the energy margin is a multi-variable function and can be expressed as follows.

$$\Delta V = f(P_m, \tilde{\delta}^u, \tilde{\delta}^{cl}, \dot{\tilde{\delta}}^{cl}, E, G_{ij}, B_{ij}). \quad (19)$$

When shifting the scheduled power among generators, changes in clearing speeds, clearing angles, controlling UEP, and the generators internal voltages are significant. However, changes in G_{ij} and B_{ij} are neglected because of their small values unless there is a change in system configuration. Due to the small size of generation changes, it is assumed that the high order terms in the sensitivity equation are neglected and the mode of disturbance is unchanged by generation shifting.

The sensitivity equation of the energy margin, ΔV , caused by generation shifting can be approximated as follows [26].

$$\Delta(\Delta V) \approx \sum_{k=1}^n \frac{\partial(\Delta V)}{\partial P_{mk}} \Delta P_{mk}, \quad (20)$$

where ΔP_{mk} is the change of mechanical power input at machine k and n is the number of machines at which generator outputs are adjusted. Once the output power of machine k is shifted, the sensitivity of the energy margin is calculated by the partial derivative of ΔV with respect to P_{mk} [43]. This concludes the description of the LRAS engine.

V. INTERACTIVE VISUALIZATION TOOL

We designed and built an interactive real-time visualization tool that enables the selection of appropriate remedial actions that stabilize power systems following large disturbances. We emulated the Supervisory Control and Data Acquisition (SCADA) system in the grid that receives data from phasor measurement units (PMUs) and conventional meters and runs state estimation and real-time contingency analysis programs so that the operator can monitor bus angle, frequency, and voltage as well as power flows on a single line diagram. System status is updated on both the visualization tool and the transient stability screening and remedial action tool. The recommended remedial actions also are displayed on the visualization tool so that the users can decide which action should be initiated. The layout of the real-time interactive visualization tool that we implemented is shown in Fig. 3.

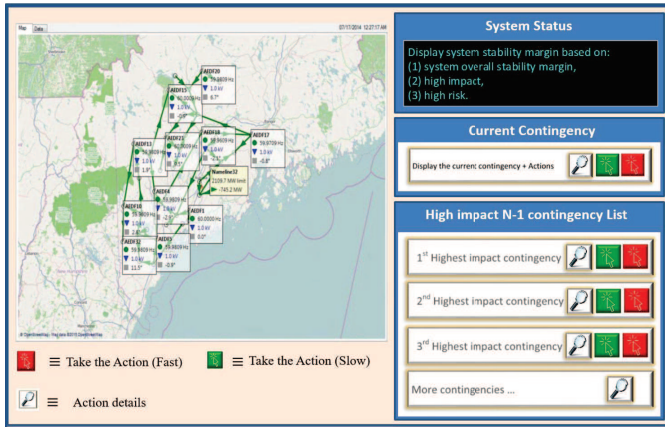


Fig. 3. The layout of the visualization tool.

A. Tool Functions

The tool receives data, displays data and suggested remedial action, and initiates actions. The function of the interactive visualization tool can be summarized as follows: (1) receives measurements, fault conditions, and suggested remedial action, (2) displays the status of the system along with the suggested action, (3) initiates actions for the faulted cases or for the preventive action, and (4) sends control signals back to the system to perform the action.

In addition to displaying the appropriate data, the tool displays the suggested remedial actions and enables initiating

control actions. These actions can be classified according to the time frame as follows: (1) *fast* actions which include (i) line tripping, (ii) load shedding, and (iii) generation tripping, (2) *slow* action which include (i) generation rescheduling, (ii) voltage control, (iii) reactive power control. If the time available to execute the fast actions is too short, these actions are disabled.

Several methods can be used to represent the stability status of the system. Two types of outcomes are displayed on the screen. These types are summarized as follows: (1) ranking according to the severity which is achieved by displaying the most severe $N-1$ contingencies with the stability margins and the recommended action and (2) providing a “stability index” for the current status of the system.

B. Remedial Actions

Along with each suggested action, which could be one or more of the following: line tripping, load shedding, and generation rescheduling, the action ID and a flag with value 0 are sent to the visualization tool. If an action is initiated, the action ID with a flag value of 1 is sent back from the visualization tool to the LRAS engine. The flag will remain 0 if no action is initiated. The ranking and list of contingencies are updated with a constant frequency.

While the sample rate of updating system status for preventive actions does not have to be high, the sample rate of updating system status for corrective actions should be while the contingency is evolving. For preventive actions, the sample rate is around 5 minutes and for corrective actions ranges from 30 to 60 samples per second.

C. Tool Description

The visualization tool provides a visual interface to monitor the status of the electrical network. It enables the user to constantly analyze the system status through monitoring bus angle, frequency, and voltage as well as power flow on the lines on a single line diagram. A visualization of a system is shown in Figure 4.

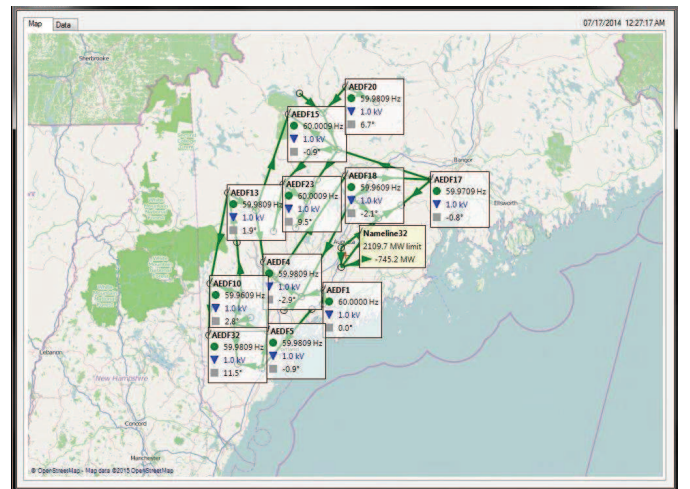


Fig. 4. Network visualization in the LRAS system.

The screen is divided into four parts: (1) the map showing the measurements, (2) a window shows system status, (3) a window shows the current contingencies if there is any, and (4) a window shows the a list possible future contingencies that are ranked according to their impact for preventive actions.

For the current and possible contingencies, there are three buttons: one to show the details (with a magnifier sign), one to take slow action (green arrow) and one to take fast actions (red arrow). For the current contingencies window, if there is no contingency, these buttons will be disabled. However, if there is a contingency, the detail button will be active and the slow and fast action buttons will be active only if it causes instability. For the possible contingencies list, all of the three buttons will be active.

VI. CASE STUDIES

The LRAS system described above was tested on several systems, including a real system, the Southern California Edison (SCE) system. The SCE system data being confidential, results are reported here for the equivalent WECC (Western Electricity Coordinating Council) system and the simplified New England 39 bus system (NE 39), which are widely used in transient stability analyses. For both systems, real-time system simulation was performed and measurements are streamed to the transient stability assessment and remedial action tool. As measurements are being streamed, system status is updated and transient stability screening and remedial actions are performed on a list of all possible contingencies. The remedial actions are classified into corrective actions and preventive actions. Corrective actions are generated for evolving contingencies whereas preventive actions are generated for all possible future $N - 1$ contingencies.

The analysis follows the procedure that are shown in Fig. 2. After updating system status, system post-fault SEPs and controlling UEPs are calculated using the homotopy based method. From the equilibrium points, system energy margin is calculated. If the energy margin is positive, the system is stable; otherwise, the system is unstable. For unstable contingencies, the sensitivity of the energy margin with respect to control variables such as generation rescheduling is calculated and remedial actions are determined. In addition to system status and measurements such as voltage, frequency, and generation output power, remedial actions are displayed on the visualization screen. The list of corrective and preventive actions as updated for each change in system status. The flow of the measurements and control actions between system components is shown in Fig. 5.

The homotopy-based method is used in computing the controlling UEPs and post-fault SEPs. The homotopy-based method was able to determining all controlling UEPs and post-fault SEPs—no convergence problems were encountered. Therefore, time-domain simulations were not executed because there was no undetermined contingencies. After determining the controlling UEPs and post-fault SEPs, the energy margin is calculated and remedial actions are generated for unstable contingencies.

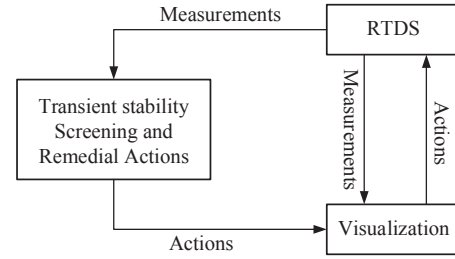


Fig. 5. Flow of the measurements and control actions between system components.

TABLE I
CONTINGENCIES AND CORRESPONDING EXIT POINTS

No.	Fault Near Bus	Line Trip		Exit point, (rad)		
		From	To	δ_1	δ_2	δ_3
1	4	4	5	-0.83157	2.05223	2.16748
2	5	4	5	-0.85604	2.24468	1.95048
3	4	4	6	-0.82573	2.00656	2.22575
4	6	4	6	-0.82663	2.00656	2.22575
5	5	5	7	-0.77351	2.07331	1.66662
6	7	5	7	-0.84828	2.68764	0.94769
7	6	6	9	-0.75797	1.83370	2.05405
8	9	6	9	-0.50293	0.51129	2.86278
9	7	7	8	-0.73581	2.28572	0.91888
10	8	7	8	-0.77159	1.74633	2.34681
11	8	8	9	-0.76930	1.74136	2.33940
12	9	8	9	-0.45872	0.48828	2.56452

A. WECC Test System

This system consists of three generators, nine buses and six transmission lines [44]. The exit points (section III-B) associated with the designated twelve contingencies (one at each end of a line) are shown in Table I.

The controlling UEPs of the twelve designated contingencies are shown in Table II. Starting from the exit points of Table I, the algorithm converged to these controlling UEPs. The controlling UEPs using the BCU method, which were taken from [29], are shown in Table III. It can be seen from Table II and Table III that the computed controlling UEPs using the homotopy-based approach are very close to the results provided in [29] for the same test system.

TABLE II
THE COMPUTED CONTROLLING UEPs USING HOMOTOPY METHOD

No.	Fault Near Bus	Line Trip		Controlling UEPs, (rad)		
		From	To	δ_1	δ_2	δ_3
1	4	4	5	-0.8323	2.0742	2.1447
2	5	4	5	-0.8323	2.0742	2.1447
3	4	4	6	-0.8266	2.0821	2.0540
4	6	4	6	-0.8266	2.0821	2.0540
5	5	5	7	-0.7598	1.9521	1.8071
6	7	5	7	-0.7598	1.9521	1.8071
7	6	6	9	-0.7586	1.8576	1.9979
8	9	6	9	-0.7586	1.8576	1.9979
9	7	7	8	-0.5430	2.1797	-0.3764
10	8	7	8	-0.3500	0.0738	2.5861
11	8	8	9	-0.2915	-0.1017	2.5004
12	9	8	9	-0.2915	-0.1017	2.5004

To test the performance of the proposed approach, less accurate exit points (by utilizing large step size in calculating the exit points), have been used in calculating the controlling

TABLE III
THE COMPUTED CONTROLLING UEPs USING BCU METHOD [29]

No.	Fault near Bus	Line Trip		Controlling UEPs, (rad)		
		From	To	δ_1	δ_2	δ_3
1	4	4	5	-0.8364	2.0797	2.1466
2	5	4	5	-0.8364	2.0797	2.1466
3	4	4	6	-0.8256	2.0830	2.0549
4	6	4	6	-0.8256	2.0830	2.0549
5	5	5	7	-0.7589	1.9528	1.8079
6	7	5	7	-0.7589	1.9528	1.8079
7	6	6	9	-0.7576	1.8583	1.9986
8	9	6	9	-0.7576	1.8583	1.9986
9	7	7	8	-0.5424	2.1802	-0.3755
10	8	7	8	-0.3495	0.0745	2.5864
11	8	8	9	-0.2910	-0.1011	2.5008
12	9	8	9	-0.2910	-0.1011	2.5008

UEPs. Less accurate exit points are easy to calculate but they are expected to cause numerical problems when attempting to use conventional iterative methods. The homotopy-based approach has succeeded in calculating all the controlling UEPs providing that the exit points are not very accurate.

B. NE 39 Bus Test System

The NE 39 bus test system consists of thirty nine buses, ten generators, twelve transformers, and thirty four transmission lines [44]. A sample of generation rescheduling as preventive actions for possible contingencies are given in Table IV. These control actions are determined based on the sensitivity analysis of the energy margins with respect to generation rescheduling. The rescheduled output power of the ten generating units are given for each contingency.

TABLE IV
GENERATION RESCHEDULING BASED ON THE SENSITIVITY OF ENERGY MARGINS TO THE OUTPUT POWER OF THE GENERATING UNITS

Tripped Line	From	To	ΔP_{m1}	ΔP_{m2}	ΔP_{m3}	ΔP_{m4}	ΔP_{m5}	ΔP_{m6}	ΔP_{m7}	ΔP_{m8}	ΔP_{m9}	ΔP_{m10}
			ΔP_{m6}	ΔP_{m7}	ΔP_{m8}	ΔP_{m9}	ΔP_{m10}					
1	2		-0.1781	-0.0121	0.0055	0.0195	0.0266					
			0.0259	0.0229	0.0282	0.0300	0.0315					
2	25		0.0536	-0.0025	0.0068	-0.0063	0.0084					
			-0.0627	0.0565	-0.0224	-0.0235	-0.0078					
2	25		0.0295	-0.0013	0.0108	-0.0059	0.0250					
			-0.0659	0.1034	-0.0394	-0.0417	-0.0144					
17	27		0.2361	0.0052	-0.0249	-0.0196	-0.0220					
			-0.0228	-0.0385	-0.0374	-0.0479	-0.0282					
25	26		-0.3185	0.0616	-0.1815	0.2281	0.2384					
			0.3711	-0.2601	-0.0940	-1.0979	0.4157					
26	27		0.1375	-0.0036	-0.0098	-0.0129	-0.0156					
			-0.0154	-0.0196	-0.0184	-0.0237	-0.0185					
26	28		0.6691	-0.0450	-0.0530	-0.0802	-0.0508					
			-0.0528	-0.0229	-0.0873	-0.1921	-0.0850					
26	28		0.0592	-0.0026	-0.0031	-0.0044	-0.0232					
			-0.0082	0.0004	-0.0047	-0.0088	-0.0047					
26	29		-0.3382	0.0250	0.0573	0.0399	0.0423					
			0.0449	0.0063	0.0410	0.0345	0.0471					
28	29		-0.0243	-0.0004	-0.0004	0.0003	0.0018					
			-0.0011	0.0305	-0.0017	-0.0032	-0.0013					
28	29		0.4545	-0.0275	-0.0360	-0.0799	0.0478					
			-0.1145	-0.0108	-0.0551	-0.1299	-0.0485					

A sample of possible corrective actions are shown in Table V. These actions consist of generation tripping and load shedding which are also determined based on the sensitivity of the energy margin to the control parameters.

TABLE V
CORRECTIVE ACTIONS BASED ON THE SENSITIVITY OF THE ENERGY MARGIN TO LOAD SHEDDING AND GENERATION TRIPPING

Faulted Bus	Tripped Line		Corrective action		
	From	To	Type	Bus	Value (p.u.)
2	1	2	Generation tripping	30	0.25
2	2	25	Load shedding	4	0.1
25	2	25	Load shedding	8	0.1
17	17	27	Load shedding	8	0.1
26	25	26	Generation tripping	39	1.8
26	26	28	Load shedding	20	0.1
26	26	29	Load shedding	16	0.1
28	28	29	Generation tripping	31	0.05
29	28	29	Generation tripping	31	0.05

C. The Visualization Tool

System diagram as well as system status are displayed on the screen of the visualization tool. While green represents normal conditions, other colors allow deviant conditions to be instantly recognized by the user. For frequency and angle, blue represents low values, while red represents high. For the branches, red means congested. The deviant frequencies and voltages are shown in Figure 6.

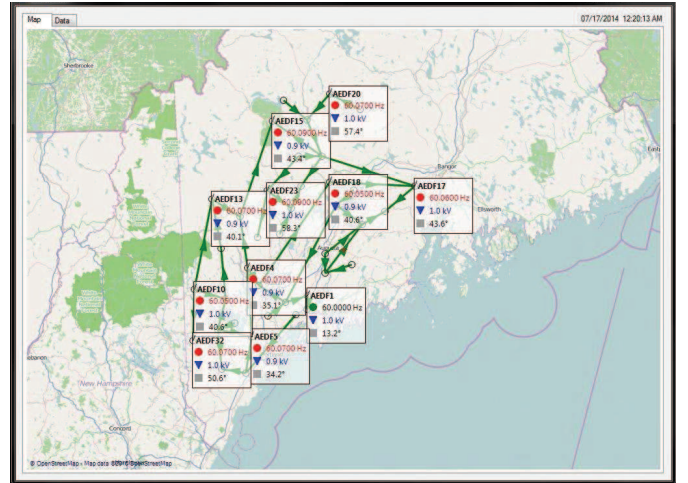


Fig. 6. Deviant of frequencies and voltages.

In addition, both bus and branch boxes can provide textual faults or warnings as provided in the data stream, as illustrated in Figure 7.

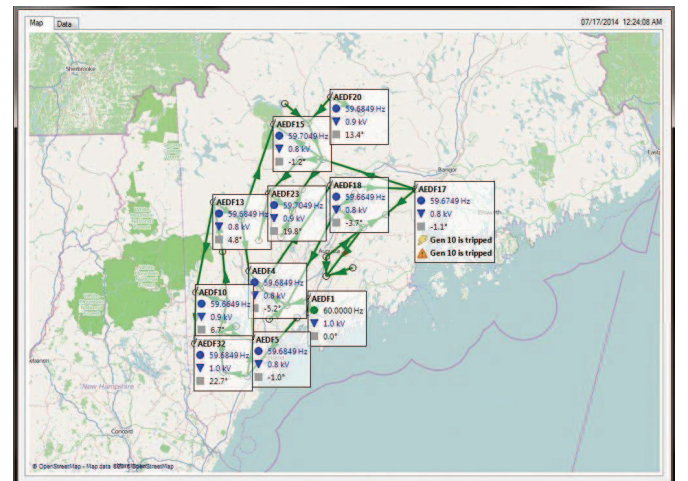


Fig. 7. Textual faults or warnings.

VII. CONCLUSION

This paper has presented a real-time dynamic contingency screening and remedial action tool, referred to here as the LRAS system. The system uses a Lyapunov function-based method for performing transient stability analysis and suggesting remedial actions. The LRAS framework included a visualization tool to display power system status in real time and enable interactive selection of appropriate remedial actions. The proposed tool was demonstrated on several systems, and results have been reported in this paper for the New England 39 bus test system and the equivalent WECC (Western Electricity Coordinating Council) system. It is possible to implement the LRAS tool to monitor and control modern power systems in real real-time, using modern communication and computing systems.

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