Operational Defense of Cascading Sequences

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Abstract—**This paper presents a new operational scheme to defend against power system cascading sequences of events, based on the observation that such sequences are often characterized by slow successive component tripping. This paper introduces the Dynamic Event Tree and describes its construction and how a system operator may use it. A prototype implementation on a 21-bus test system is provided.**

Index Terms—**power system, transmission, dynamic event tree, contingency, cascading sequence, event tree, linear programming, long term time domain simulation.**

I. TERMINOLOGY

We define terminology to clarify our use of it in the paper.

- *Component*: A line, transformer, or generator.
- *Network configuration*: A specification of the power system in terms of the in-service status of all components (unit commitment and branch topology).
- *Operating conditions*: A specification of the power system in terms of load levels, generator MW output, generator voltage set points, and transformer taps.
- *State*: A specification of the power system in terms of the network configuration and operating conditions.
- *Event*: A significant change in the power system state, i.e., a state transition. An event may be unexpected (faults, breaker failures) or expected (proper breaker action). An event may be due to a discrete change such as a network switching (a change in network configuration) or to an accumulation of continuous changes as in the case of a load increase or transformer tap changer movement (a change in operating conditions). Two or more events may be independent, dependent, or common mode.
- *Contingency*: A specified set of events occurring within a short duration where the first is unexpected, e.g., a fault followed by breaker action and subsequent line removal.
- *N-1 contingency*: A contingency resulting in loss of one component.
- *N-k contingency*: A contingency resulting in loss of k components where it is implicit that $k>1$.
- *Cascading sequence*: A chronological sequence of dependent events.
- *Initiating contingency*: A contingency that initiates a cascading sequence.
- *Successive events*: Those events following the initiating contingency in a cascading sequence.
- *Actions*: Events initiated to avoid failure conditions caused by a cascading sequence, e.g., to avoid a blackout.
- *Blackout*: A power system state in which a significant portion of the load has been interrupted.

II. INTRODUCTION

Major blackouts are usually caused by low probability, high consequence contingencies. Their causes are various. System conditions are typically characterized by heavy load, reactive power deficit, weakened transmission system, or unfavorable network flow patterns, when either an *N-1* or *N-k* contingency occurs. Table I lists some representative blackouts since 1965.

TABLE I
Summary of Some Large Blackouts around the World

Location	Date	Scale in term of MW or Population	Collapse time
US-NE[1]	10-11/9/65	20GW, 30M people	13 mins
New York[2]	7/13/77	6GW, 9M people	1 hour
France[3]	1978	29GW	26 mins
Japan[4]	1987	8.2GW	20mins
US-West[5]	1/17/94	7.5GW	1 min
US-West[5]	12/14/94	9.3GW	
US-West[5]	7/2/96	11.7GW	36 seconds
US-West[5]	7/3/96	1.2GW	> 1 min
US-West[5]	8/10/96	30.5GW	> 6 mins
Brazil[6]	3/11/99	25GW	30 secs
US-NE[7]	8/14/03	62GW, 50M people	> 1 hour
London[8]	8/28/03	724 MW, 476K people	8 secs
Denmark & Sweden [9][10]	9/23/03	4.85M people	7mins
Italy[11]	9/28/03	27.7GW, 57M people	27mins

Analysis of different reports on these blackouts indicates that they may be roughly classified as either fast (less than 3 minutes) or slow, and if slow, they always involve a cascading sequence. It is the slow types that we have targeted in the work reported in this paper. There are four typical stages of such cascading sequences.

1. Initiating contingency.
2. Steady-state progression (slow succession);
   a. System becomes stressed with heavy loading on lines, transformers, and generator;
   b. Successive events occur, typically the trip of other components with fairly large inter-event time intervals.
3. Transient progression (fast succession);
   a. System goes under-frequency and/or under-voltage;
   b. Large number of components begin tripping quickly.
4. Uncontrolled islanding and blackout.

An important attribute of the events in stage 2 is that they are almost always dependent events in that their occurrence

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depends on the occurrence of one or more earlier events; it is the case that the probability of occurrence of successive events increases dramatically following occurrence of a contingency. The time interval between an initiating event and successive events varies greatly. For example, the time between a fault and an inadvertent relay trip can be less than a second. However, if a fault followed by line clearing causes line overload and/or generator over-excitation, subsequent tripping may follow minutes or even hours later. The time interval may be long enough for an operator to initiate actions to mitigate the undesirable trend.

A primary goal of power system engineers is to reduce the frequency and mitigate the severity of blackouts. Accomplishing this requires innovations in planning, maintenance, and operations. The focus of this paper is to address cascading events from an operating perspective. Operating approaches include relieving the system via generation redispatch or load curtailment in a preventive mode, adapting the protection and control as a function of the operating conditions before occurrence of an event, or responding rapidly just after a potential cascading begins to unfold. We find the third approach most attractive, as it requires no action, and therefore no cost, unless and until it is needed. In addition, it represents the last line of defense; if rapid response actions are not available or if they are not properly chosen or if they fail to occur, then the cascading and its consequences proceed without interruption or mitigation. We give this approach the name *rapid response to unfolding events* (RRUE), and identify it is a generalization of today's system protection scheme (SPS). The difference is in terms of flexibility and action initiation. SPS utilize pre-set fixed logic, responding to a limited set of conditions with a limited number of possible actions, while RRUE utilizes a high level of logic intelligence and, ideally, is capable of responding to all conditions with a wide range of possible actions. The action of SPS is initiated automatically by hardware, but the actions of RRUE may also be initiated by an operator. Yet, a major challenge for implementing RRUE is speed; it must recognize the possible existence of an unfolding event, analyze it, identify possible actions, select one, and communicate the actuation commands to the appropriate equipment, all within a time frame of minutes, an information-intensive decision problem requiring fast computation. We describe an approach to facilitate this in Section III. Section IV illustrates the approach, and Section V concludes.

III. THE DYNAMIC DECISION EVENT TREE

We desire to enable identification and implementation of actions following the initiating contingency. The philosophy behind our approach is to prepare and revise. This philosophy manifests itself in technology that we call a dynamic event tree (DET), an extension of the more familiar "event tree" to be found in the reliability literature. Event trees are horizontally built treelike structures that model initiating events as the roots. Each path from root to end nodes of an event tree represents a sequence or scenario with associated consequence. The DET idea is in part inspired from the work reported in [12] where the authors provide results of applying long-term simulation for verifying the effectiveness of different decisions under islanding conditions. The DET is extended from ideas [13][14] in the probabilistic risk assessment (PRA) community, which largely emanates from the nuclear power industry. It is similar to the event tree, except for two fundamental differences. First, it includes decision nodes where it is effective and possible to take actions that avoid or mitigate event consequences. Second, it is dynamic; it grows according to a set of branching rules, and the tree structure, branch probabilities, consequence values, and decisions are updated as necessary to reflect changes in the physical network. This means that the growth and updating processes occur continuously with as much computing power as is available. In addition, trees can be stored. Therefore, when an *N-k* contingency begins to unfold, the amount of available information can be large, and the speed with which the action is taken is limited only by the efficiency of the search necessary to find the appropriate tree and the location on the tree corresponding to the particular situation at hand.

Fig. 1 illustrates the idea, where the system avoids a collapse after two timely actions are taken. The sequence of events comprising the Fig. 1 simulation is captured using the simple DET of Fig. 2. The DET edges represent events, including initiating and successive events of cascading sequences, power system behaviors, and actions necessary to mitigate undesirable consequences and avoid blackouts. For example, the initiating event in Fig. 2 is a fault with stuck breaker resulting in loss of three components. This event is represented in Fig. 2 by Branch C1. Branch B2 represents a fast voltage collapse, and Branch B3 represents the actions of under-load tap changing transformers in the network. B1 is a null event, which means no action is taken. Branch A1 is an action taken to arrest the fast voltage collapse, and Branch A2 is an action taken to block the transformer tap changes and avoid the slow voltage collapse.

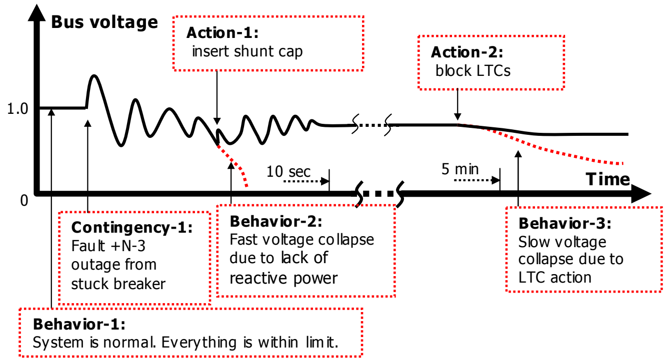

Fig. 1 A typical system emergency scenario

Fig. 2 A dynamic event tree illustration

These events do not necessarily happen at one time instant. Usually they are associated with a continuous time interval. For example, the voltage collapse event B2 in Fig. 2 is actually a continuous changing process rather than an abrupt occurrence; the contingency event C1 in Fig. 2 is not the fault/stuck tripping only, rather, it is the tripping plus the behavior of the system that defines the event C1. Thus, each branch in the DET corresponds to one or a sequence of events.

The nodes in an event tree correspond to system states represented by the large black dot *S1-7* in Fig. 2. As an event tree is a discrete structure whereas power system condition must be characterized by both discrete and continuous variables, we must discretize system states so that the number of nodes in an event tree is limited. We therefore introduce the concept *set of equivalent states* (SES). An SES is a set of system states that respond the same (equivalent) way to a specified event. Therefore, an SES may only be defined in relation to an event. So each node in DET is not a single power system state; rather it is an SES to the branches (events) that follow. We return to this topic in Section IV-B.

IV. DET CONSTRUCTION

Generating a DET occurs via the procedure illustrated in Fig. 3. We provide a brief description of each of the main elements illustrated in this figure.

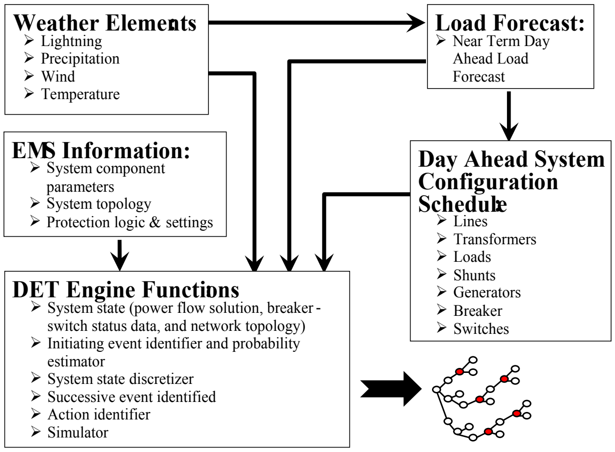

Fig. 3: A dynamic event tree generating scheme

A. Day-Ahead Forecasting System

The day-ahead forecasting system performs two functions: a) forecast next day component on/off status according to generation and maintenance schedule; b) forecast next day load/generation profile. These forecasts are made assuming that there are no unintended events. The function of this element is to predict the future status and levels of key variables affecting the physical performance of the power system. These variables may be discrete, as in the case of circuit or generator up or down status, or they may be continuous, as in the case of load and generation level.

One of the inputs to this functionality includes day-ahead weather forecast. Weather forecast information is also used to update contingency probability within the DET engine. For example, the tripping probability of a line may increase due to the expected presence of lightning.

B. Discretization of System State

A change in network configuration due to, for example, loss of a component, results in a clearly defined new state and is therefore a precisely identified event and corresponding DET branch. Small changes in operating conditions normally need no special treatment, yet accumulation of small changes can build up until it is necessary to treat the change as an event or a state transition. In establishing a basis for doing this, we observe that an action that mitigates a cascading sequence initiated from one operating condition may also mitigate that cascading sequence initiated from a similar operating condition. Thus, we desire to lump all such operating conditions into a discrete state. The easiest way to discretize operating condition is to divide, for example, the next 24 hour period into equal intervals and assume that each operating condition within each time interval is an SES. Fig. 4 shows the hourly system load change in one typical winter weekday [15]. As we see from the figure, the load increase between 5:00am to 6:00am is almost 15 percent. Any contingency analysis results we obtain for the power system condition at the beginning of the hour (5:00am) would not be applicable at the end of that hour (6:00am). The solution to this problem is to use iso-variance time intervals, where the system experiences the same amount of total load variance for each time interval. Fig. 5 shows the results of discretizing operating condition by iso-variance for a typical weekday loading cycle.

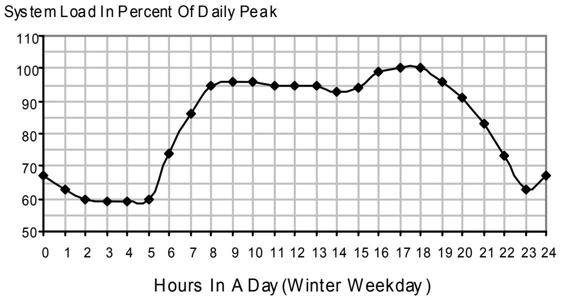

Fig. 4. Discretizing 24-hour load forecast by equal time interval

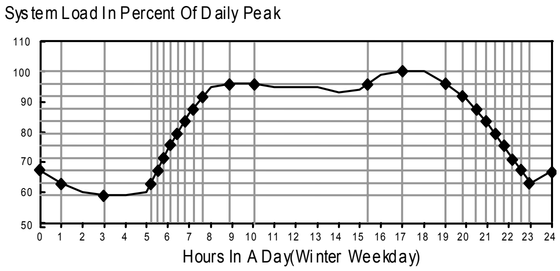

Fig. 5 Discretizing 24-hour load forecast by equal load change

C. Simulator

A time domain simulator is the preferred analysis tool for developing DETs. However, it must be specialized to quickly perform extended-term (several hours) of simulation. This means it must model both fast and slow dynamics and be capable of lengthening time steps when fast dynamics are inactive. In addition, it must have the necessary intelligence to recognize when failure conditions are encountered, retrieve earlier conditions, and determine appropriate actions; it must also have modeling capability for a wide range of protection devices. Finally, in order to combine it with contingency identification and apply it online, it should be able to seamlessly integrate with system real time topology information. We have developed a simulator with these characteristics, with appropriate models of generator excitation systems, speed-governing systems, and automatic generation control. The numerical integration method used is similar to that described in [16].

D. Initiating contingency selection and tree growth rules

The breadth and depth of a DET is guided via intelligent initiating contingency selection and tree growth rules. A set of initiating contingencies is selected based on the approach outlined in [17] resulting in a contingency list comprised of the *N-1* and *N-k* initiating contingencies having probabilities greater than a user-specified threshold. It is intended that the probability level is chosen so that the initiating contingency list is much larger than contingency lists used for security assessment in most control centers today. We have designed an algorithm to process switch-breaker data (as used in most EMS topology processing functions) to identify *N-k* contingencies, and their probabilities as a function of substation topology, protection failures, and common mode events [17]. These contingencies constitute the first tier of branches for the DET.

Once a set of contingencies is selected, it is necessary to arrange their processing order according to one of three tree-growth rules. The probability-based rule orders the contingencies in decreasing probability. The severity-based rule orders the contingencies in decreasing severity. The risk-based rule orders the contingencies in decreasing risk, where risk is the product of event probability and event severity, a rule that attempts to find a balance between the probability- and severity-based rules. The risk-based rule is most attractive; however, it (and the severity-based rule) suffers from the fact that severity is unknown until the contingency is analyzed. Thus a preliminary severity estimation is needed for each contingency. The number of components outaged in the initiating contingency (*k* in "*N-k*") is such a measure. Although it is rough, it enjoys the benefit of being available with no additional simulation.

Successive event modeling is challenging. At one extreme, we could implement the initiating contingency procedure for each node in the DET, resulting in an event list for each of the nodes. Such an approach would require estimation of successive event probabilities as the computation proceeds. We have implemented the simplest form of this approach where we assume that, following (and excepting) the initiating event, all equipment operates as designed with probability 1.0, and events associated with unexpected operation (e.g., breaker inadvertent operation) have probability 0. Although this approach eliminates modeling of protection failures as successive events, it does not eliminate modeling of protection failures since they may be included in the initiating event.

E. Action identification

The decision set includes any operational procedures that are available, e.g., generator redispatch, load shedding, shunt capacitor insertion, generation rejection, HVDC ramping, etc. Of these, unit redispatch and/or load shedding are almost universally effective (although not always optimally so) in mitigating deteriorating conditions, and so we have elected to design into our simulator an algorithm for identifying these type of actions; we have not yet designed algorithms for identifying other types of actions. We use a linear programming formulation to find the action necessary to back off any line loading exceeding a specified threshold. The objective is to maximize load with a constraint that prevents loading from exceeding actual demand, so that the actions identified utilize unit redispatch first and then load interruption to accomplish what unit redispatch cannot.

Objective: $Max \sum_{i\in\{1,\ \dots\ N_D\}} \alpha_i \times P_{D_i}$

Constraints:

$P_{D_i}^{\max} \ge P_{D_i} \ge 0, \quad i \in \{1,\ \dots\ N_D\},$

The served load at bus i must be $\le$ *total demand* P^{max} *at bus i;*

$P_{G_i}^{\max} \ge P_{G_i} \ge 0, \quad i \in \{1,\ \dots\ N\}$,

Each generator generates between 0 to P_{max}*;*

$\gamma_i P_{B_i}^{\max} \ge P_{B_i} \ge -\gamma_i P_{B_i}^{\max}, \quad i \in \{1,\ \dots\ N_B\}$,

The power flow in each branch is limited by its emergency rating;

$B' \times \theta = P^{inject} = (P_G - P_D)$,

DC power flow equations;

$(D_B \times A) \times \theta - P_B = 0$,

Branch flow equations;

Here

N_D *is the total number of load buses;*
N_B *is the total number of branches;*
N_G *is the total number of generating buses;*
D_i *is the load demand at bus i;*
α_i *is the price factor to serve one MW load at bus i;*
L_i *is the total load (MW) served at bus i;*
P_{G_i} *is the real power generation at bus i*
$P_{G_i}^{\max}$ *is the maximum real power generation at bus i, it is the summation of rating of all generators connected to bus I;*
P_{B_i} *is the real power flow in branch i;*
$P_{B_i}^{\max}$ *is the short term MVA rating of branch i;*
γ_i *is the constant factor to account for the power factor of the power flow in branch i.* γ_i *range from 0 to 1;*
B' *is the N×N B-matrix used in DC power flow and N is the number of buses;*
A is the M×N adjacency (or incidence) matrix
D is the M×N diagonal matrix where the i^{th} *diagonal element is the admittance of the* i^{th} *branch;*
θ *is the N×1 vector representing the voltage angles in radius at each bus;*
P^{inject} *is the N×1 vector representing the net power injection for each bus and its element* P_i *can be calculated by* $P_i = P_g - L_i$

The linear programming problem is solved only when failure conditions are detected, i.e., when a line flow exceeds a defined percentage of its emergency loading. After the necessary actions are identified, system conditions within the simulation (before detection of the failure conditions) are appropriately modified, and the simulation is resumed. We may include voltage security constraints (bus voltage limits and loadability limits) in the optimization if we replace DC power flow constraints with AC power flow constraints. Detection of out-of-step or oscillatory conditions in the simulation and construction of associated constraints within the optimization can be done but will require further work.

F. Tree storage and updating

A DET is a rich container of information about the power system when the power system resides in a state corresponding to the DET root node. We store DETs for possible later use. The DET storage bin contains many trees. Each DET is indexed according to conditions that indicate whether the DET is applicable to a given state. These “DET indexing conditions” are loading trajectory, network configuration, and weather conditions and forecast. It is possible to find a tree having indexing conditions that are very similar to the existing power system conditions but not exactly the same. In this case, one may quickly update the tree using approximate methods rather than generate a new one. Such DET updating occurs to the probability values, the severities, or the selected actions.

G. Generating the Day Ahead DET

Figure 6 shows multiple DETs generated for the next 24-hour period, where each root node corresponds to a SES that spawns a large number of first branches corresponding to different initiating events followed by a sequence of successive events and actions.

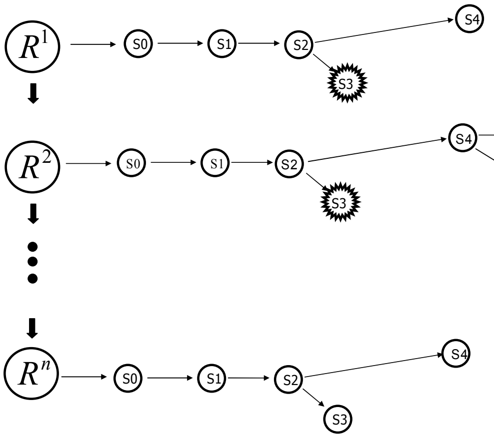

Fig. 6 A day-ahead dynamic event tree

Algorithm A given below identifies the procedure to produce a DET for each SES in a 24-hour period, where the contingency list of step 2 is based on the predicted operating condition and topology information.

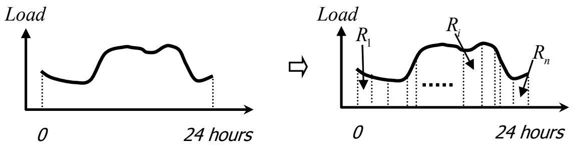

Fig. 7: Discretized root states

Algorithm A

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1) run base case (non-contingency) dynamic simulation of power system for next day's 24 hours period.
2) discretize the behavior of power system of 24-hour period into a limited number of root states $\{R_1, R_2, \cdots, R_n\}$ as illustrated in Fig. 7.
3) loop 1: for each $R_i, i=1,2, \cdots, n$, do step 4 to step 19
4)   root node $S^0 \leftarrow R_i$
5)   initialize $DET_i$ with root node $S^0$
6)   generate extended contingency list $ECL_i=\{C_1,C_2, \ ,C_n\}$ for $R_i$ by scanning the predicted system topology.
       ▪ $ECL_i \leftarrow$ functional group trip contingencies
       ▪ $ECL_i \leftarrow ECL_i$ + stuck breaker trip contingencies
       ▪ $ECL_i \leftarrow ECL_i$ + inadvertant Trip Contingencies
       ▪ $ECL_i \leftarrow ECL_i$ + other system specific contingencies
7)   loop2 for each contingencies $C_j$ in $ECL_i$
8)       run long term dynamic simulation for $C_j$ for $T_{max}$ seconds
9)       store the system responds in $RPS_i$
10)          scan $RPS_i$ to diagnose & identify any problem caused by $C_j$
11)          construct node $S_j^i$ with system status being in problem caused by $C_j$
12)          construct branch $C_j^1$ as a link between $S^0$ and $S_j^1$.which includes the event $C_j$ and the response of system between $S^0$ and $S_j^1$
13)          search the available action set to identify a feasible (ideally optimal solution) decision $A_j$ for the problem caused by $C_j$
14)          run long term dynamic simulation to verify the effectiveness of $A_j$ for $T_{max}$ seconds
15)          construct node $S_j^2$ with system status as the result caused by $A_j$
16)          construct branch $A_j^2$ as a link between $S_j^1$ and $S_j^2$.which includes the event $A_j$ and the response of system between $S_j^1$ and $S_j^2$
17)   end of loop2
18)   save $DET_i$
19) end of loop1
20) end of Algorithm A
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Each R_i indicates a condition for which a DET is generated. However, the time domain simulation performed in generating the DET may extend beyond the next R_i, depending on the need and computation capacity. It is quite possible that a single DET will provide simulation extending more than 2 hours beyond its initialization point R_i. This time frame is in accordance with our observation of many cascading events listed in Table I. If we treat $\{R_1, R_2, \ ,R_n\}$ as nodes in an event tree, then the structure of Fig. 6 becomes a large DET that is applicable to the 24-hour time interval.

H. Using the results from DET

The state of readiness for existing and near future conditions is maximized by the availability of a DET corresponding to those conditions. Once a contingency occurs, the operator is immediately shown the corresponding tree of events and recommended actions, which includes the time intervals between different events and between events and actions, giving the operator the benefit of viewing the future for different alternatives that are available. The operator may then actuate or prepare to actuate one or more actions, depending on how far down the tree the decision node is from the node corresponding to the current conditions.

The DET also serves as an efficient preparatory tool operators may use during their shift to study the variety of contingency scenarios and recommended actions for those scenarios. Studying the appropriate DET provides insight into how to respond to the various contingencies that might happen under conditions that exist or that are expected in the near future. It could be expected tha operators who have spent a significant time studying DETs on their system for various conditions would develop a unique familiarity with how their system responds under severe contingencies and with the typical actions necessary to avoid or mitigate resulting consequences.

I. Computational requirements

The algorithm to generate a DET for a large-scale power system is computationally intensive. Suppose the maximum number of nodes that result from any initiating contingency is bounded by m and the maximum time needed to generate the sub-tree is T_m, which is reasonable given that we can control the depth and width of the sub-tree from any initiating contingency. If the number of initiating contingencies to be simulated is $C(N)$, then the total time spent on generating a DET is bounded by $C(N) \times T_m$. Better algorithms, parallel processing, or faster machines and other emerging new technologies can be employed to minimize T_m. For example, the analog simulator [18][19] provides a promising simulation tool reported to be10^4 times faster than the conventional digital computer.

V. DET FOR A TEST SYSTEM

We selected the 9-bus-3-generator system in [20] as the basis for our test system. We designed the substations for this system and doubled system size by adding an identical system below the original system as shown in the appendix of this paper. Data needed to represent system dynamics was contrived based on experience and the data published in [20]. We denote the two subsystems as upper area and lower area. We also add four tie lines (and four transformers) to connect the upper and lower area. To create the tie line flow, we scaled down all the loads in the upper area by a factor of 0.8 and scaled up all the loads in the lower area by a factor of 1.2 so that 20% percent of total load (630MW) flows on the tie lines. The generation configuration remains unchanged. We also designed a one-line breaker diagram for each of the substations. We use breaker-and-a-half bus configuration for generating substations and ring-bus for load substations. In summary, there are 22 buses, 6 generators, 6 loads, 40 lines (including 4 tie lines), 6 step-up transformers, 4 tie line transformers, and 128 breakers.

The test simulation uses the current system topology to generat an extended contingency list as the first tier of event nodes. An iterative programming technique and an LP optimizer are then employed to build a DET for each contingency as illustrated in Fig. 8 The branches B1, B3, and B5 represent the initial contingency, the system reconfiguration, and the emergency loading respectively, The branches B2 and B4 represent the “do-nothing” decision. The nodes (Si’s) in Fig. 8 represent the status/trajectory of the system after/before the actions (Bi’s) are applied to the system.

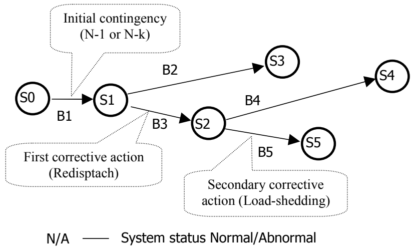

Fig. 8 Dynamic event tree structure for test system

A. Test Scenario

We studied the possible cascading for a one hour time interval during which the load ramped 20% from 900 seconds to 2700 seconds for a scenario where the system is in a weakened condition due to outage of a tie line. Line loadings are monitored, and the most effective redispatch & load curtailment actions are identified for overloaded lines.

B. Contingency set

We generated a comprehensive list of initiating contingencies for the selected scenario, as summarized in Table II, based on the procedure described in [17]. The count “*k*” in “*N-k*” includes components that are open ended as well as those that are completely disconnected from the system. There are 12 *N-0* contingencies that do not result in losing any components; these are bus faults at substations with breaker-and-a-half protection design.

TABLE II
Identified contingency summary for test system

Contingency Category	N-0	N-1	N-2	N-3	N-4	N-5	N-6	total
Functional Group Removal (line fault, bus fault, etc.)	12	48	6	0	0	0	0	66
fault plus stuck breaker	0	49	63	3	1	0	0	116
Inadvertent Tripping (Simultaneous loss of two branches)	0	0	114	89	15	2	2	222
Total	12	97	183	92	16	2	2	404

C. Decision set

Whenever an overload is identified after a contingency, the simulator attempts to correct the problem by generator redispatch, and if this is insufficient, it sheds the minimal load. Therefore the decision set is the combination of all the redispatch of all the available generators and load curtailment, if it is necessary. We assume any of the available generators can generate between zero MW to their maximum output.

D. Results

The result of the DET engine computations for this scenario is a large repository of information that includes: contingency specification, the response curves of all key variables for that contingency, and necessary actions. Of the 404 contingencies we analyzed, 10 resulted in fast (within 1 minute) instability and 394 of them resulted in stable, but unacceptable performance. Our implementation of the DET engine does not generate a corrective action for cases resulting in instability within 1 minute since this is not enough time to implement operator-initiated actions. Of the other 394 contingencies, all of them resulted in overloading problems that were corrected by proper generator and load reconfiguration as identified by our optimization approach.

Fig. 9 illustrates a representative contingency via the one hour trajectory of power flow on each line after the loss of the largest generator (G-101) in the upper area, which serves as B1, the initial contingency in the DET in Fig. 8. We see that line L401 is the most loaded line for the entire system. Figure 10 shows the time domain simulation results of the flow on Line L401 with and without the first and second actions (B3 and B5 in Fig. 8) applied. The effectiveness of the first redispatch only holds until time 1100s. After that, load increase causes the flow on that line to exceed 100% again. To prevent further loading, an emergency load-shedding scheme is identified and executed to prevent circuit loadings from exceeding their ratings. The initiating contingency and system trajectory with and without actions, as shown in Fig. 8, are mapped to the DET branches and nodes shown in Fig. 8.

Since our DET engine has the capability of slow dynamic simulation, we can also observe the voltage variation in the test system. We find that, even through the DET engine for the test system is designed to solve the overload problems only, the action taken by the DET engine solves the voltage problems as well. Of the 394 stable, but unacceptable contingencies, 29 exhibited low voltages in the southern part of the system that were corrected by either the first (redispatch) or second (load interruption) actions taken.

Figure 11 illustrates a representative contingency, resulting in overloading and low voltage, via the flow on the most severely overloaded line after loss of lines L106 followed by the inadvertent tripping of L116. Figure 12 shows the voltage of the most severely depressed bus following the same contingency. The contingency, decisions, and system behaviors of Figs. 11 and 12 are mapped to the branches and nodes of the DET in Fig. 8. The voltage collapses after 1800 seconds (point E in Fig. 12) if the operator does not take any action. Following the system reconfiguration (a redispatch) at 1 minute (point A in Fig. 12), the system behaves well until point D, where a low voltage problem shows up. If the secondary action at point B is applied, the system will avoid both the overloading and the voltage problems.

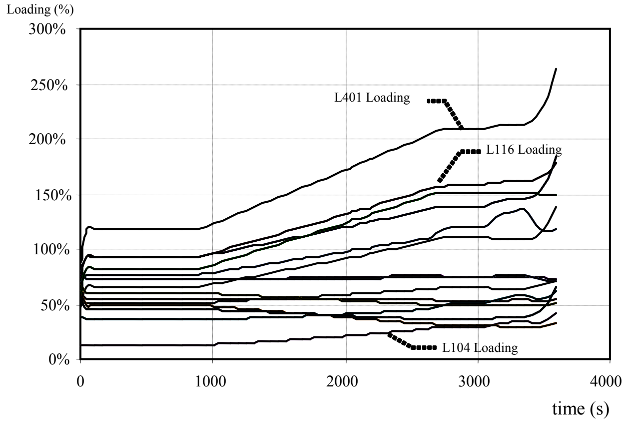

Fig. 9: Branch loadings after lost of the largest generator of the test system for the testing scenario

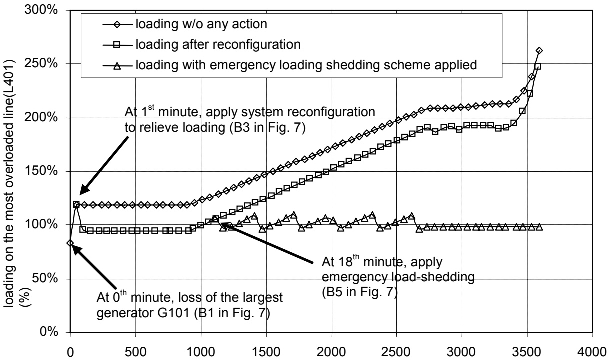

Fig. 10: The DET scheme for the lost of the largest generator in the test system for the testing scenario

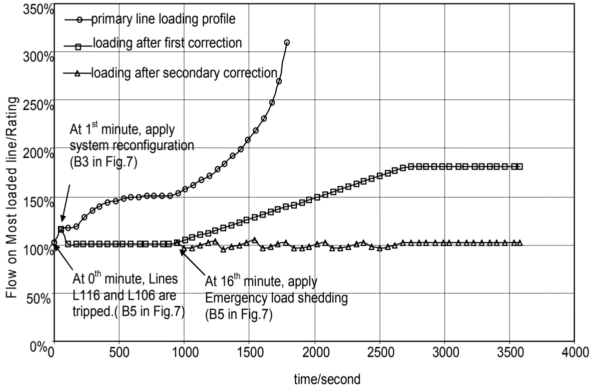

Fig. 11: The DET scheme for the tripping of lines L106 & L116 (most severely overloaded circuit)

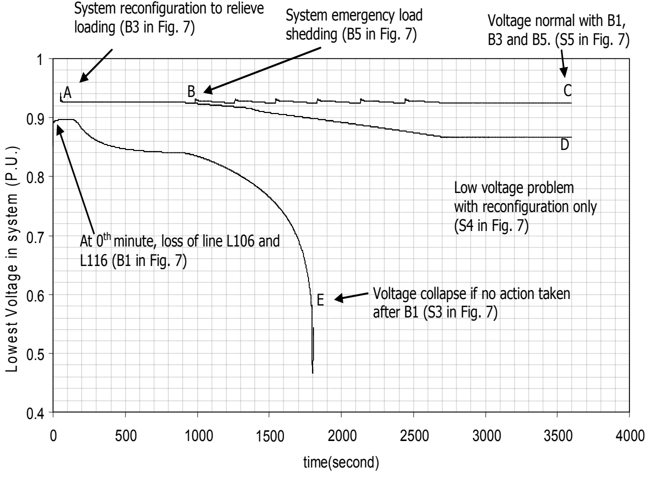

Fig. 12: The DET scheme for the inadvertence tripping of line L106 & L116 (system-wide lowest voltage in p.u.)

VI. CONCLUSION

We propose a generalization of the SPS intended for providing rapid response to unfolding events (RRUE), especially focusing on dependent N-k contingencies that would otherwise result in severe consequences. The basic philosophy underlying the approach, to continuously prepare, revise, and store assessment results and decision-making, provides that response-time following a first event is mainly limited by search-time. A key technology facilitating the approach is the dynamic-decision-event tree (DET), which has application in the nuclear power industry. DET provides the ability to adapt decision logic to conditions as they evolve, in contrast to pre-fixed, static logic usually implemented in today's SPS.

The approach described is a reasonable approach to defending against rare events. Preparing operators for rare events is fundamental to the operation of engineering systems having catastrophic potential; it has precedence in air traffic control, nuclear plant operation, and process control. It is a generalization of the already-existing event-based special protection systems, except here response is continuously developed on-line instead of off-line, and actuation is done through a human (slower, but more flexible). Proper training to build operator confidence in the approach is essential and will have the side-benefit of providing operators with experience in responding to severe contingency situations. In order to comprehensively address frequency and severity of cascading outages, this approach should be implemented in concert with additional innovation and training in design, maintenance, preventive control, and restoration.

VII. REFERENCES

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Appendix: The DET Test System