Dynamic Decision-Event Trees for Rapid Response to Unfolding Events in Bulk Transmission Systems

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***Abstract*—In order to defend against rare but catastrophic power system events, this paper proposes a generalization of the system protection scheme (SPS) that we call the Dynamic Decision-Event Tree (DDET). As a new adaptive approach, DDET takes rapid response to unfolding events before they degenerate into uncontrolled cascading, islanding or load interruption. The basic concept, together with some implementation issues, are described and discussed within this paper.**

***Keywords* — electric power system, system protection scheme, defense plan, dynamic decision-event tree, risk-based security assessment, multi-criteria decision-making, multi-agent system.**

I. INTRODUCTION

Most catastrophic events in power systems occur as a result of multiple events that unfold over a time interval. Many such events occur as a result of a first-fault followed by a series of cascading events, the occurrence of each event successively a consequence of the preceding events. Given such a scenario a-priori, one may design systems that are triggered on recognition of the scenario to take certain pre-arranged actions designed to mitigate the impact of the disturbance. This has been done in some parts of the world, and the designed systems generally fall under the phrase of *defense systems*. Defense systems are comprised of a set of coordinated defensive measures whose main purpose is to ensure that the overall power system is protected against major disturbances and multiple contingency events. A defense system can be considered as an additional level of protection, designed to initiate the final attempt at stabilizing the power system when a widespread collapse is imminent. Defense systems may be thought of as a sub-class of the more familiar *system protection schemes* (SPS), also known as *remedial action schemes* (RAS).

A recent CIGRE effort [1] has resulted in the development of an excellent resource on SPS. It identified the function of SPS as *to detect abnormal system conditions and take predetermined, corrective action (other than the isolation of faulted elements) to preserve system integrity and provide acceptable system performance*. Figure 1 [1] illustrates the general structure of an SPS. A key SPS feature illustrated in Figure 1 is that it includes a decision process. The decision logic uses the inputs to determine whether the SPS should actuate or not. SPS can be classified as response-based or event-based according to the nature of the control variables used as inputs to the decision logic. Response-based SPS are based on measured electric variables, such as voltage, frequency, etc., and they initiate their protective actions when a contingency causes the measured value to hit the trigger level. Event-based SPS are designed to operate upon the recognition of a particular combination of events such as the loss of one or more lines in a substation.

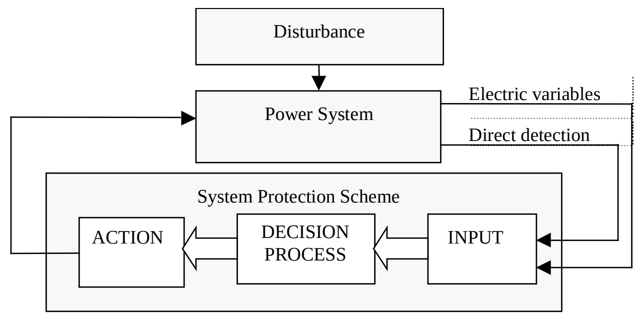

Figure 1: General Structure of an SPS [1]

In this paper, we propose to extend the idea of a defense system by generalizing the decision-making abilities of the SPS. Section II describes and classifies the type of events that are addressed by the approach. Section III develops a concept at the heart of the approach that we call "rapid response to unfolding events (RRUE)." Section IV describes a dynamic decision event tree (DDET) to coordinate RRUE. Section V provides a discussion on several questions related to the approach, and Section VI concludes.

II. CLASSIFICATION OF N-K EVENTS

Major blackouts are typically caused by low probability, high consequence events, properly said to be rare events. This section describes an operational approach for avoiding or mitigating these types of events. We classify events into one of two classes based on their likelihood.

N-1 events: These are often called "credible" events, and they form the basis of traditional security assessment. They result in loss of a single power system component, such as a line, transformer, or generator. Although N-1 events range in probabilities, this range will typically not be more than one or at most two orders of magnitude. Therefore, we say that all N-1 events have *probability order* P.

N-K events: Here, it is implied that K>1, indicating an N-K event may be loss of 2 or more power system components. These events, otherwise known as "high-order" events, are invariably of lower probability than N-1 events. They can in turn be divided into two sub-classes:

- *Independent N-K events*: These are typically very rare; they have probability order of P^K, where K is the number of faulted components.
- *Dependent N-K events*: These are typically not so rare as independent N-K events; they have probability order p ranging from $P^K<p<P$ and can often approach the probability of an N-1 event. One cause of dependent N-K events is cascading, where the first event creates equipment stress that cannot be sustained, resulting in further equipment outages due to *proper* action of protective relays. Another cause of dependent N-K events is where a first event triggers *improper* action from a protective relay. Such failure modes have been identified in the recent literature as 'hidden failures" [2-4]. A third cause of dependent N-K failures is exposed substation configurations, where maintenance or switching actions, usually temporary ones, expose one or more N-K outages to occurrence of a single fault.

We are primarily interested in the dependent N-K events for two reasons. The first is that, as indicated, they are the most frequent cause of high order contingencies. The second is that dependent N-K events are comprised of two or more successive-in-time events. The existence of time delay between successive events provides an opportunity to identify and take actions to avoid the later events or to mitigate the impact of the later events. Our approach, to be described in the next section, does exactly this.

III. Operational Approach to N-K Events

Planning studies often include severe event testing of the type discussed above to facilitate transmission design decision-making. Operating approaches, on the other hand, might include (1) preventive control measures that relieve the system via generation re-dispatch or load curtailment, or (2) responding rapidly just after a potential N-K event begins to unfold. Option 1, preventive control, is normally not used to mitigate the impact of potential N-K events. This is because the likelihood of occurrence of N-K events within the decision time frame (typically the next hour) is so small that one cannot justify incurring preventive control costs to mitigate their impact should they occur. Option (2) is clearly attractive, as it does not require action (and therefore much 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 N-K event and its consequences proceed without interruption or mitigation. We give this approach the name "rapid response to unfolding events" (RRUE), and note that it is a generalization of today's special protection scheme (SPS). The difference is in terms of flexibility; whereas SPS utilize pre-set fixed logic, responding to a very limited set of conditions with a very limited number of possible actions, RRUE utilizes a high level of logic intelligence, and is, ideally, capable of responding to a wide range of conditions, with a wide range of possible actions.

Yet, a major challenge for implementing RRUE is speed; it must recognize the 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 seconds or even milliseconds - an information-intensive *decision* problem that must be solved very quickly. We propose the use of a dynamic decision-event tree (DDET) to guide the RRUE decision-making process. We describe the DDET in Section III. Use of the DDET depends on fast and consistent coordination and negotiation between the decision-makers. We describe an approach to facilitate this in Section V.

IV. The Dynamic Decision Event Tree

We observe that N-K events are actually a chronological sequence of multiple lower-level dependent events. If an initiating event occurs, the probability of a dependent event can increase significantly. We desire to enable identification and implementation of actions following the initiating event to eliminate or mitigate the dependent event or events subsequent to the dependent event.

N-K events can unfold very quickly, and identification and implementation of actions can require a heavy computational burden and therefore much time. The philosophy behind our approach to this problem is to *prepare, revise, and store*. This philosophy manifests itself in the DDET, an extension of the more familiar event tree. 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 DDET is extended from some ideas in the probabilistic risk assessment (PRA) community [5], which largely emanate from the nuclear power industry [6]. 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 the event consequences. Second, *it is dynamic*; it grows according to a set of branching rules, tree structure, branch probabilities, and consequence values, and decisions are updated as necessary to reflect changes in the physical network. An attractive feature of DDET is 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 event begins to unfold, the amount of available information can be very 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. Generating a DDET occurs via the procedure illustrated in Fig. 2. We describe each of the main functions illustrated in this figure.

1) *Model generator*

The function of the model generator is to accept a desired future time and produce corresponding models appropriate for assessment. This function is broader than traditional load forecasting available in most EMS as, in addition to predicting load, it also predicts network configuration (unit commitment, circuit topology) and probabilities associated with possible events.

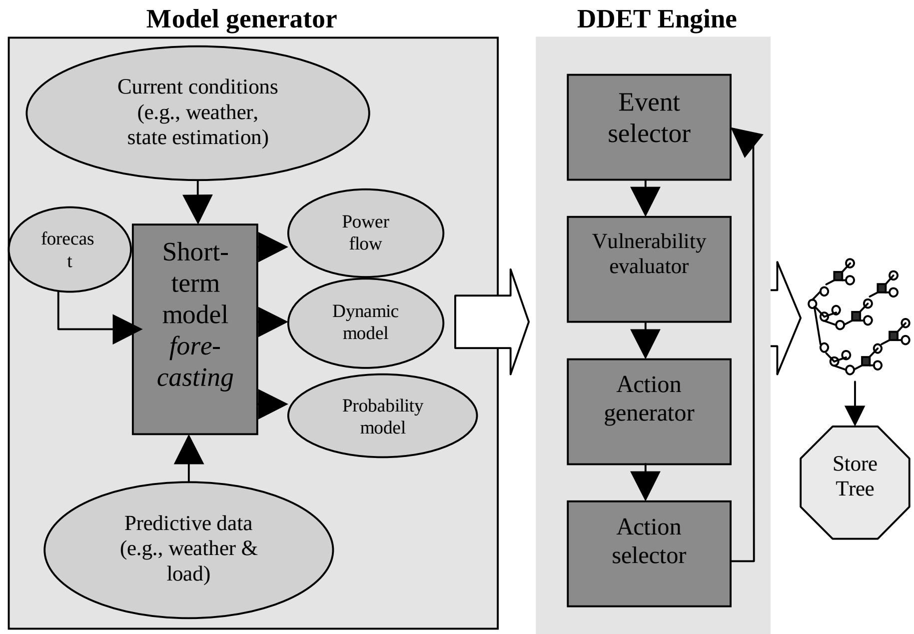

Figure 2: Generating a DDET

2) Event selector

We maintain a set of all possible event types that includes generator unit trips, line faults, and different types of protection failures. Associated with this set are two matrices. In conditional probability matrix A, the element A_{ij} provides the conditional probability of event **i** given occurrence of event **j**. In severity matrix S, the element S_{ij} quantifies the severity of event **i** given occurrence of event **j**. Both of these matrices may be generalized as multi-dimensional arrays representing, for example, the probability of event **i** given occurrence of events **j** and **k**, or the severity of event **i** given occurrence of events **j** and **k**. With this information, it is possible to select events based on one or a combination of three different rules. The breadth-first, probability-based rule selects those events that have highest probabilities. It results in analysis of most N-1 events first, before analyzing any N-K events. The depth-first, severity-based rule selects those events that have the highest severity. Following the first N-1 event selected, it results in analysis of possible N-K events caused by the first N-1 event before analyzing any more N-1 events. The risk-based tree growth rule selects those events that have highest risk, where risk is the product of event probability and event severity. It results in tree growth that is balances breadth and depth.

3) Vulnerability evaluation

The vulnerability evaluation is based on on-line risk-based security assessment (OL-RBSA). OL-RBSA provides indices for assessing the security level of a bulk electric power system based on the forecasted condition at time t together with security analysis of this condition accounting for forecast uncertainty [7,8].

4) Action generator

At each DDET decision node, we identify a list of candidate actions that could mitigate the consequences of the possible successive events. This is done by identifying the high-risk problems to the node and then accessing the *action-matching table*, to determine the candidate actions that could be effective in decreasing the risk. This table will be included in a database that will also include corresponding actuation locations and other necessary data such as time to actuate.

5) Action selector

The action selector uses risk sensitivities to compute the effect of each action on the total risk. Actions that increase risk are eliminated. Among the remaining possible actions, one is selected which minimizes the risk most efficiently. This selection is based on the solution to a multi-criteria decision-making (MCDM) problem. The various criteria will typically include: risk, variance, control cost, and actuation time. A variety of methods are available to solve MCDM problems, and we have explored many of these methods in a previous project [9]. We intend to develop a toolbox of MCDM methods to be tested for this purpose. One significant issue here is that MCDM is most effective for single decision-makers, yet today's industry is clearly comprised of multiple decision-makers. An obvious way to deal with this is to assume that during emergency conditions, all decision-making authority collapses to a single decision-maker (e.g., the ISO). Another quite different approach is to extend MCDM to include negotiated settlements among multiple decision-makers. Such negotiation must be done very rapidly. This constraint seemingly makes the negotiation approach untenable, as we deal with time frames of minutes, seconds, or even milliseconds. However, agentization, as described in Section V below, may enable this approach.

6) Tree storage and updating

A DDET is a rich container of information about the power system when the power system resides in a "state" corresponding to the DDET root node. We store DDETs for possible later use. The DDET storage bin contains many trees. Each DDET is indexed according to conditions that indicate whether the DDET is applicable to a given "state" of the power system. These "DDET 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 fast methods rather than generate a new one. Such DDET updating occurs to the probability values, the severities, or the selected decisions.

7) Using a DDET

When a condition is detected that significantly increases the likelihood of an N-K event, we identify a DDET corresponding to the existing power system conditions. All CPU resources are dedicated to updating and growing the DDET to maximize the state of readiness for existing and near-future conditions. We either actuate one or more actions or we 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. Actions may be actuated automatically or through a human operator.

8) Use of computing resources

DDET computing is done continuously. However, a key problem is to identify what DDET computing to do at each moment. We desire to optimize the "readiness" for a given time frame. *Readiness* can be thought of as the ratio of two quantities that reflect: situations for which we are prepared and know how to respond, and all possible situations that can occur. State variables for this problem are existing trees and corresponding DDET indexing conditions. Decision variables are task allocation for each CPU, where it is possible for CPUs to either contribute towards growing a new tree or contribute towards updating an existing tree. Constraints on this problem are computing resources and available time.

V. A MULTI-AGENT SYSTEMS FRAMEWORK

Our description of the DDET raises several key questions, among which are: How does the DDET obtain its information? How does the DDET initiate identified actions? Can the DDET initiate actions fast enough to make a difference for N-K events? Must DDET be centralized or may we use it in a distributed manner that better conforms to the nature of today's electric power industry? We have found that by applying concepts from multi-agent systems, these questions can be answered in ways that make the proposed technology very attractive. Specifically, "agentized" DDETs are capable of having: persistent interaction with the environment, a feature which facilitates obtaining information and initiating actions; mobility, a feature which enhances and accelerates data exchange; and rapid interaction and negotiated decision-making, a feature that enables representation of multiple, distributed information sources, functions, and decision-makers. We have spent considerable effort exploring the potential of mobile software agents operating within a multi-agent systems framework to facilitate use of DDET. This work goes beyond the scope of this paper but is described in [10,11].

VI. CONCLUSION

We propose a generalization of the SPS intended for providing rapid response to unfolding events (RRUE), especially focusing on dependent N-K events 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 (DDET), which has previously found application in the nuclear power industry. DDET 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. Clearly, the development of this approach is in its early stages, and there are a number of significant questions to be answered. We are presently engaged in developing a prototype DDET-generation system for testing and illustration.

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