Control Approach for Self-Healing Power Systems:
A Conceptual Overview

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***Abstract*—The deregulated markets and other factors are pushing power systems to their limits accentuating the need for more robust control. This paper presents a conceptual overview of a control approach for supporting a self-healing power system based on a distributed autonomous architecture and a set of coordinated closed loop controls. The proposed architecture is modular and scalable from the viewpoints of organizational, geographical and functional aspects and is applicable to systems ranging from small interconnections to continental-scale power grids. The approach calls for autonomous intelligent functional agents distributed throughout the system at various levels of control hierarchy. This paper further defines the framework for the coordination of the closed loop controls and the corresponding analytical tasks. The tasks are grouped into various execution cycles that collectively cover real-time operations of the power grid starting from hour-ahead scheduling of the market and other resources to rapid control of power system transients.**

***Index Terms*—Interconnected power systems, real-time, architecture, large-scale systems, autonomous systems, distributed systems, power system operations, power system control, coordinated operation, power system security/reliability, execution cycle, self-healing grid, IntelliGrid.**

I. INTRODUCTION

THIS paper presents an overview of the requirements for the computing and communications infrastructure to support a self-healing grid. This work was done as part of the Fast Simulation and Modeling (FSM) project sponsored by EPRI. This project is part of a larger program (IntelliGrid) aimed at transforming the electric grid into an intelligent self-healing system to realize strategic improvements in security, quality, reliability and availability.

Major blackouts around the world underscore the need for such a self-healing system for more robust monitoring and control [1,2,3]. This paper specifies a distributed autonomous real-time (DART) system to meet this need. The DART system calls for autonomous intelligent functional agents distributed throughout the system at various levels of the power system hierarchy. The agents are expected to coordinate local and global information to improve the reliability, stability, and efficiency of the power system [4].

The focus of this paper is the development of a comprehensive framework for the coordination of the closed loop controls and the corresponding analytical functions and their interactions in the context of the modular and scalable architecture. The design allows for any number of players representing transmission operators, regional reliability coordinators etc. to enable a smooth operation of a self-healing power system. It is versatile enough to allow for any degree of deregulation, any type of market design and any size of interconnection.

For developing the functional framework within the DART system, we have taken an "operations driven design" approach as opposed to a "methods driven design" approach. In this approach we first defined the operating concerns and then specified the system requirements to meet those concerns. The DART system has to adapt its behavior to the various operating states of the power system and transitions between the states. The system performs a large number of parallel operations at varying time-scales. The control approach is based on organizing these operations into various execution cycles of appropriate periods ranging from one hour to a few milliseconds. The design principles and the salient features of the execution cycles and their interactions are described.

The remainder of the paper discusses the following in order: Evolving Operational Environment, Principal Requirements, Architecture, Temporal Requirements, Control Approach, Implementation Strategy, and Conclusions.

II. EVOLVING OPERATIONAL ENVIRONMENT

The power system operational environment is continually reshaping due to evolution of the following forces:

- Market forces resulting from industry deregulation
- Emerging generation and transmission technologies
- Better measurement and control technologies
- Improvements in the information technology (IT)

A virtual hierarchy of grid operators (e.g. reliability coordinators, independent system operators, and control area

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operators) continues to emerge in response to the need for coordination of operations and evolving markets. The many decision makers significantly impact the operational reliability of the system on a minute-by-minute basis. Statistics from the US Easter Interconnection show huge swings of power transfers (up to 8000 MW) from one day to the next. Such volatility renders the usual off-line planning studies unusable [4], creating a qualitatively different operating environment that requires intensive real-time analyses and control.

Emerging power system technologies are also expected to greatly influence operational requirements of power systems. These include dispersed generation, renewable resources, distributed storage and flexible transmission controls.

Advances in measurement and control technologies offer both challenges and opportunities in dealing with the evolving changes. Equipment with embedded intelligent devices would create opportunities for innovations in sensing, modeling, analysis, simulation, prediction, control, and optimization. This is transforming the mostly electro-mechanically controlled power grid to an electronically controlled one. With latest technologies, such as PMUs (Phasor Measurement Unit), it becomes possible to get synchronized and precision measurements required for the realization of the self-healing grid. Modern information technology can provide the backbone for the enhanced computing and communications required to meet the stringent requirements.

III. PRINCIPAL REQUIREMENTS

To deal with the more complex environment in a modern interconnection and address the relevant operating concerns at all levels of the control hierarchy, a high performance IT infrastructure is needed. The DART system, intended to meet this need, has to be capable of non-stop service in terms of:

- Providing situational awareness throughout the grid
- Predicting, preventing and containing problems
- Enforcing operational plans and required margins
- Supporting restoration

Increasingly intensive challenges in grid operations include:

- “Larger footprint” and correspondingly larger models
- More frequent close-to-limit operations/lower reserves
- Smaller error margins and shorter decision times
- Coordination of local and global controls
- Greater degree of automation

Meeting these challenges requires the use of on-line decision support tools with intensive computational and communication requirements. The design is based on:

- Distributed system where the locations of hardware, software and data are transparent to the user
- Flexible system-wide communications to allow synchronous and asynchronous operations for point-to-point and multicast messaging and data exchanges
- System-wide enhanced visualization capabilities
- Autonomous functions distributed throughout the system to allow local, global or cooperative processes

This design supports evolutionary implementation and integration with legacy systems.

The DART system can be organized in a virtual hierarchy in the following three dimensions:

- Control hierarchy (substation, control area, etc.)
- Geographical area (control area 1, control area 2, etc.)
- Functional area (alarming, voltage management, etc.)

In contrast to the conventional control centers, operators and processes throughout the grid may access and maintain any data – subject to business needs and authorizations. They will be aided by grid-wide alarm processing and visualization with global navigation and drill down capability.

IV. ARCHITECTURE

The architecture of the DART system has to be modular, flexible and scalable to meet the challenges brought about by changes in the operator hierarchy, the power system and the information infrastructure. A self-healing grid requires large-scale automation using the following enabling technologies:

- Computing and communications technologies
- Autonomous systems with interoperable components
- Integrated messaging/data
- Visualization

A. Computing and Communication Architecture

DART’s design is based on a distributed computing architecture involving a large number of computers and embedded processors scattered throughout the system (Fig. 1). They communicate with each other through networks with standardized interfaces using message-oriented middleware and web services. The network, possibly dedicated, would enable local and global data exchanges and decision processes using distributed databases integrated through open interfaces. To the extent possible, the system would be constructed out of plug-and-play hardware and software components with automated learning features.

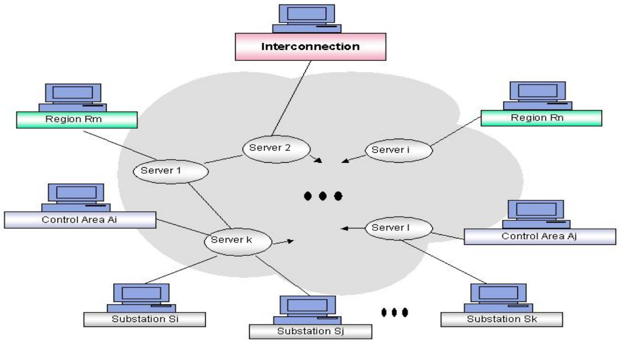

Fig. 1. Computing and Communication Architecture

The dynamic synchronous or asynchronous point-to-point and multi-cast communications would require an arbitrary, widely dispersed network topology that has the capability to adapt to changing deployment and security needs. The infrastructure is divided into independent functional layers such that the system can continue to operate at a higher layer even if a lower layer is evolving. Power industry standards (e.g., ICCP, CIM data model) and other standards will be used.

The infrastructure should be capable of handling the necessary requirements for computations, storage, communications, latency, availability, scalability, synchronization, and failure recovery. Functional components will require dynamic expansion of available computing and storage capability during periods of peak demand. A comprehensive set of system-wide services should include: directory and name, time, mail & paging, file sharing, logging, data mining, etc.

Quality of Service (QoS) mechanisms should be provided to guarantee the availability of the required level of computing and communication services. Ideally, a self-healing infrastructure should provide non-stop service and mask the complexity of the system from the users and processes.

Security mechanisms of the DART system must allow for proper authorization and authentication of all users and processes. They should also allow for adequate data privacy and encryption mechanisms. Audit trails and mechanisms that guarantee non-repudiation must also be provided. The capability to partition the overall infrastructure into separate security regions will be critical.

The technologies in this infrastructure include but are not limited to: embedded intelligent devices, High Performance Technical Computing (HPTC) clusters, Local Area Networks (LANs), Wide Area Networks (WANs), High Speed Interconnects, and Network Based Storage Technologies (SANs, iSCSI, and others.

B. *Autonomous Systems*

Deployment of closed-loop control schemes is essential to respond to changing local and global circumstances. It is envisioned that such control schemes would be implemented using autonomous systems where tasks are performed by intelligent agents distributed throughout the system organized in a virtual hierarchy. Such agents can ultimately reduce operator errors and improve control performance by responding to problems faster than a human operator [5].

This system of autonomous intelligent agents can be visualized as a three dimensional system as shown in Fig. 2. These dimensions are:

- Control Hierarchy: The levels may include Substation, Control Area, Region and Interconnection. The lowest level agents interact directly with the actuators (control equipment) in the power system.
- Functional Diversity: At each control level, there may be agents with specific functional responsibilities. For example, in Fig. 2, the agents of control area Ci are vertically layered in a stack at the control area level. In this example, the agent in the very first layer, i.e. voltage management F1, exists everywhere.
- Geographical Distribution: For each control level and functional responsibility there may be several agents each covering a particular geographical portion of the power system. This is shown in Fig. 2 as several groups of functional agents at the same level.

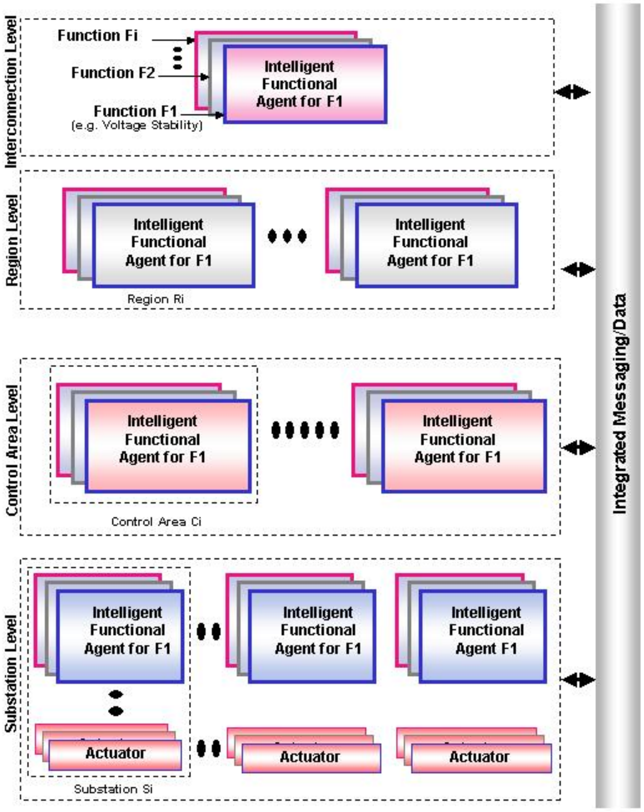

Fig. 2. Autonomous Structure

The data (static and dynamic) will be distributed throughout the system and maintained by various parties at different locations. The agents at each level continuously monitor their environments and take decisions and control actions based on the changes in their environments subject to pre-specified operating procedures incorporating a wide degree of intelligence. They potentially perform the following tasks:

- Gather necessary information from the lower level agents and selected peers.
- Analyze the performance of the relevant part of power system subject to directives from the agents at higher levels and requests from peers.
- Alert the agents at higher levels and selected peers as needed, based on the results of the analysis.

- Issue directives about the system operating limits observed by the lower level agents and selected peers.
- Should automatically discover the information and abilities available from other agents

Some of the remedial action schemes (RAS) in current use may be seen as examples of intelligent agents whose effectiveness can be improved by more frequent directives from a higher-level control tier.

The degree of autonomy at each level and the protocols for resolving conflicts between the levels can be a major design decision. Generally, the higher level agents need to consider data for a larger portion of the power system and consequently their response times would be longer. Therefore they can only periodically update the directives given down to the lower level agents. The lower level agents on the other hand can act very fast based on the local information subject to the most recent guidelines received from the higher level agents.

C. Functional Layers

Each functional area in DART is represented by a number of autonomous intelligent functional agents that collectively perform the relevant tasks throughout the grid. Each functional agent has several components that can be considered building blocks for functional areas. The functional agents are not merely local objects, but rather they are local enablers of system-wide coordinated analyses and actions. Each functional agent needs to perform specific tasks that can be broadly organized into four functional layers:

- Data acquisition and maintenance layer
- Monitoring layer
- Performance enhancement layer
- Controls layer

D. Integrated Messaging and Data

In the DART system, data is distributed in virtual relational database(s). Access to these databases can be improved using directory services based on hierarchical tree structures. Any data should be made available to the appropriate functional agents at all times using real-time integration of data from multiple sources. Such integration can be achieved through web services using XML with standard schemes.

E. Visualization

Effective presentation of information is necessary to enhance the situational awareness of the operator and expedite his/her reaction to the situation. In this sense, visualization is an integral part of analysis and control. Quality information has to be presented to the user in a timely and meaningful manner that allows, at a glance, the operator to understand the state of the system and respond in a timely manner.

Visualization is a vital technology that can enable the operators to navigate and drill-down to the particular information they need from the vast distributed data warehouses of the proposed architecture. Enhanced graphics are necessary to extend the state-of-the-art visualizations to the 3-D context. Tools necessary to build and maintain the various diagrams have to be provided along with icons with controllable size, color, animation and appropriate default settings. In time, such features may evolve to create a “virtual reality” environment. Fig. 3 provides an example of visualizing results of contingency analysis. Red cones (pointing to lines) indicate location and severity of line overloads, blue cones (pointing to buses) indicate location and severity of low bus voltage violations. Lines are drawn from the cones to the contingency elements causing overloads.

All the traditional graphical features (graphs, one-line diagrams, etc.) need to be appropriately enhanced and coordinated. Animation techniques such as flow arrows, blinking, should be exploited. Different views of the same object may be needed to present different aspect to different users. The design must seamlessly combine navigation and graphical presentation of information to fulfill operator needs.

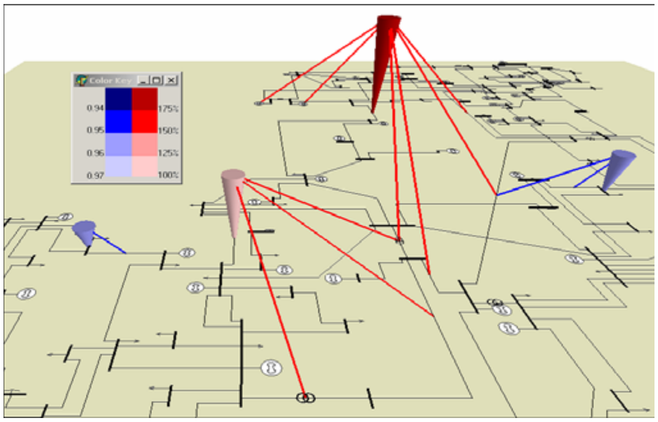

Fig. 3. Visualizing Results of Contingency Analysis

V. TEMPORAL REQUIREMENTS

In the "operations driven design" approach adapted in this work, we first consider the various system operating concerns to be addressed by the DART system. To deal with each of the concerns, the system has to perform a large number of parallel information processing tasks driven by synchronous and asynchronous events as well as the operator commands. These numerous tasks are to be distributed throughout the three-dimensional virtual hierarchy described in the previous section, and organized and coordinated in the temporal dimension according to the time-scales of the relevant physical phenomena. This temporal organization can be accomplished through a set of execution cycles. At any given time the tasks performed should be adapted to the needs of the power system in its current operating state. The following subsections briefly discuss the fundamental elements underlying this design:

- Operating Concerns
- Operating States
- Tasks

- Methods and Models
- Execution Cycles

A. Operating Concerns

Properly addressing a comprehensive set of operating concerns is essential to realize a self-healing grid. The large variety of operating concerns can be organized into the categories of performance enhancement, equipment limit, system operating reliability, system stability and system protection. The following list provides examples of concerns in each category:

- Performance enhancement concerns
    - Adequacy of market procurements
    - Efficiency enhancement
    - Secondary voltage control
    - Tertiary voltage control
- Equipment limit concerns
    - Line/Generator/Transformer Thermal limits
    - Bus voltage maximum limits
- System operating reliability concerns
    - Bus voltage minimum limits
    - Voltage stability limits
- Sustained stability concerns
    - System frequency oscillations
    - Generator Transients
    - System wide-area (or inter-area) swings
- System protection concerns
    - Primary protection against faults
    - Back-up protection against faults

B. Operating States

Reliable operation of the DART system depends on a comprehensive design that accounts for normal and abnormal operating states of the power system. Based on industry practices and regulatory requirements [6], the following power system operating states and their sub-states are defined in the DART system:

Normal:

No violations in real-time or contingency conditions, i.e., not in alert or emergency state. **Cautionary Normal** sub-state is characterized by low margins.

Alert:

Violations of known operating limits exist in contingency or look-ahead conditions. The sub-states include: 1) **Non-Severe Alert** where adequate time is available for a normal cycle of calculations and control actions after the contingency takes place, and 2) **Severe Alert** where there is no time for detailed analysis after the contingency takes place; requires immediate calculation of control actions.

Emergency:

Violations of known operating limits already exist. Sub-states include: 1) Non-Severe Emergency where adequate time is available for a normal cycle of calculations and control actions, 2) Severe Emergency where there is no time for detailed analysis; usually involves control actions or limit violations relevant to severe stability problems, and 3) Crisis where unfamiliar operating conditions likely to lead to further deterioration during major disturbances.

Restoration:

Un-served load exists. Need to minimize time to restore service without further degradation of system state.

C. Tasks

DART tasks can be organized in various ways based on their shared common features such as inter-dependency, geographical scope, complexity of calculations, relevant operating states and required response times. They collectively provide the following required capabilities:

- Acquire, validate, store and compute accurate real-time data in a timely manner suitable for the context.
- Analyze current operating conditions in terms of stability, reliability, operating margins, and market constraints using suitable means: performance indices, analytical procedures, statistical analyses, etc.
- Calculate/extract derivative information useful to other tasks and contexts (e.g., adapting limits in real-time).
- Identify and implement appropriate control actions (e.g., iSPS/iRAS) to improve the reliability and efficiency of the power system using suitable means: simulation, performance indicators, optimization, etc.
- Identify appropriate models in terms of geographical scope and model detail, depending on its context.

A generic organization of the DART analytical tasks based on the four functional layers of the DART architecture is presented below:

- Data Acquisition and Maintenance Layer
    - Acquire, Validate, Sequence
    - Store, Retrieve
    - Forecast
- Monitoring Layer
    - Obtain current state
    - Base-case analysis
    - Postulate contingencies
    - Perform contingency analysis
    - Perform look-ahead analysis
- Performance Enhancement Layer
    - Compute system operating limits
    - Compute control target values and limits
- Controls Layer
    - Implement controls
    - Confirm control actions

The above organization is generic in the sense that each task can possibly have its counterpart in every execution cycle tailored to the context at hand. In principle, the tasks in different execution cycles can be performed simultaneously in parallel but coordinated with each other through latest available data. Tasks within the same execution cycle can be coordinated as needed in a pre-specified order.

D. *Methods and Models*

Given the complexity of the DART system, there is no single analytical method that can perform all the necessary tasks. A systematic approach is required to implement a comprehensive solution involving a coordinated use of several methods. For each state and each execution cycle, the relevant tasks should be selected along with the following information:

- Most appropriate method(s) and their best applications
- Techniques for coordinated use of the methods
- Identification of new methods as needed

The selection of the appropriate methods is based on:

- Complementary usefulness to relevant task(s)
- Derivative information necessary for other tasks
- Response times allowed for each task

The feasibility and efficacy of a method for a specific task depends on the context of the task in terms of its geographical scope, the operating state and the execution cycle.

Based on the tasks and methods specified, the necessary modeling requirements should be identified in terms of:

- Geographical scope of the models
- Frequency of updating model data
- Context-dependent details in the models

For each substation, models are maintained at several different levels of detail for the following purposes:

- Protection system and substation operations model: requires models including all bus sections, switches, breakers, relays, transmission lines, transformers, other series devices, shunt devices, loads, feeders, etc. for protection and reconfiguration.
- Substation and vicinity model: Less detailed models are adequate for network analysis type of functions at the substation and vicinity.
- Control area level model: Some elements may be approximated away (switches as hard connection or open, feeders as injections etc.)
- Regional level model: Similar to control area models, but approximated to a greater degree.

A particular functional agent would request an appropriately detailed model of each substation that it requires. For example, a control area level agent may assemble a regional model by requesting the "control area level" model of its own substations and "regional level" model of the other substations in the region. However, if an external line outage has a significant effect on itself, it may request a "control area level" model of several relevant external substations.

E. *Execution Cycles*

An execution cycle refers to a set of related DART tasks executed in a coordinated manner. Each execution cycle should be able to accomplish the following objectives with respect to the physical phenomena relevant to it:

- Identify the current operating state
- Assess the vulnerability to undesirable transitions
- Prevent imminent transitions to undesirable states
- Identify control actions to maintain current state or realize transitions to more desirable states

The execution cycles and their periods are defined based on operating needs, physical phenomena in the power system, and engineering judgment. Each cycle can be justified by required control response times, computational burden, and historical practices. The specific periods and activities of the DART execution cycles can be configurable according to the relevant operating concerns. These cycles cover time-scales ranging from 1 hour through 10 milliseconds. The exact periods of the cycles may be different in each implementation. A representative set of execution cycles is presented in Table 1.

Cycle	Represents
Hour-ahead	Assure adequacy of resources (markets, forecasting, scheduling, etc.) Identify system bottlenecks
5-minute	System reliability, efficiency, and calculation of control parameters and limits for next 5 min. Look-ahead (about 10 to 20 min.) Alert system operator and/or hour-ahead cycle
1-minute	Maintaining efficiency and reliability using the parameters identified by the 5-min. cycle. Adapting the results of the 5-min. cycle using the more recent models of the 1-min. cycle.
2-second	Data collection/validation for use by control area or interconnection: Data may be from the 10-msec. cycle (PMUs). Traditional closed loop controls (AGC, etc.) Adapting control parameters and system operating limits for faster cycles
1-second	Control of extended transients using advanced closed loop controls (secondary voltage control, etc.) and adapting control parameters and system operating limits for faster cycles
100-millisecond	Recognizing and reacting to imminent system instabilities including execution of intelligent special protection schemes (iSPS) based on adaptive models or criteria identified by slower cycles. Also control actions as guided by the parameters determined in the slower cycles
10-millisecond	Primary cycle for intelligent protection and faster iSPS (load shedding, generation rejection, system separation)
Continuous	Traditional protection systems monitoring

Table 1: Execution cycles in DART

In general, more intensive computations using data from a larger geographical area of the system are performed in the slower cycles. Other tasks requiring data from a substation and vicinity can be performed at the faster cycles. In the foreseeable future, the communication command and control (3C) technologies impose a qualitative dichotomy at about 2 seconds because of the latency of real-time data acquisition for larger areas. This dichotomy is depicted in Fig. 4 with slower cycles (i.e., over 2 seconds) and faster cycles (i.e., under 2 seconds) along with interactions among the cycles.

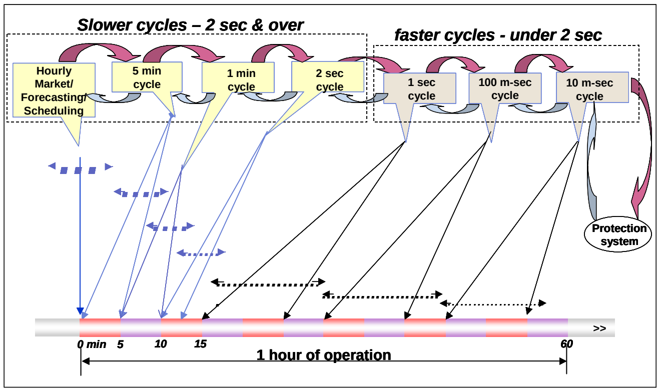

Fig. 4: Interactions of execution cycles in operations

Generally, it is envisioned that the slower cycles perform computations required for system-wide coordinated controls, performance optimization, and control strategies. The faster cycles address local analytical needs to respond to rapid events using the control strategies developed by the slower cycles.

DART execution cycles interact with each other through exchange of the following:

- Event triggers – issued on significant events, sent by faster cycles to slower cycles or agents at the same cycle but with different geographical scope. Depending on the event, the receiving cycle may either complete or interrupt on-going executions before restarting.
- Control parameters – slower cycles can analyze a larger portion of the system and therefore make better, coordinated decisions and advise faster cycles. A faster cycle informs a slower cycle about new system parameters whenever it detects a significant change that requires immediate consideration by the slower cycle.
- On-going oscillations and adverse trends- All affected areas would recognize the oscillation/trend in the same cycle. The highest geographical level affected should determine the appropriate control action. The cycle that recognizes a problem should determine the appropriate remedial action and instruct faster cycles as needed. Faster cycles should inform the slower cycles messages to confirm the implementation of control actions requested by slower cycles.
- Contingency information - A slower cycle informs faster cycles about contingencies that may significantly affect their geographical areas. Then the faster cycle at the affected substation(s) may analyze the situation using models of its own protection systems and control devices to determine if there would be any consequential outages. The faster cycle can inform the slower cycle to consider those consequential outages in the next execution of its contingency analysis.
- Problem conditions - If a cycle cannot meet its requirements, it can request for help from a relevant slower cycle or a peer. For example, if a substation level faster cycle cannot maintain a bus voltage within prescribed limits, it should request help from the control area or another substation in its vicinity.

One can envision a DART system as a collection of functional agents performing their functions while interacting with each other as orchestrated by the execution cycles. Each execution cycle includes activities by several agents and similarly each agent may perform tasks relevant to several execution cycles.

VI. CONTROL APPROACH

In addition to providing situational awareness of the power system operating conditions to the relevant system operators, a primary purpose of DART is to make operating decisions and determine control actions based on comparison between current operating conditions and all known limits. All control actions are calculated based on operating limits (simple or calculated). In this sense, operating limits are essential to the operations of DART. The operating states of the power system (i.e. Normal, Alert, Emergency, etc.) are recognized by the DART system based on the various operating limits.

To enable the DART system to automatically address a given operating concern it is necessary to express the concern as a corresponding limit on some system variable or a function of a set of variables. When such a limit is specified, one has to also specify the time available to correct any violations of the limit. Then the corresponding system variable has to be monitored and controlled within a fraction of that time to allow timely recognition of potential and actual problems with respect to the relevant limit. This also allows time for tuning the response as needed for a smooth control and operation of the system.

In case of some limit violations, the calculation of remedial actions can take significantly more time than can be allowed by the monitoring and control periods. The analytical tasks relevant to such limits should be performed periodically at an appropriately lower frequency. The control actions so calculated should be pre-assigned for implementation by a faster cycle if and when the violation actually happens. As an extreme example, the corrective action parameters may be calculated in off-line operational planning studies.

Thus, the tasks associated with each defined limit should be assigned to potentially three different execution cycles for the purposes of monitoring, performance enhancement and control. This is an essential requirement for the hierarchical organization of control actions. If an infinite time is available to correct a limit violation, then that limit is as good as non-existent. For example, if the required time-to-correct is 10 seconds for a given limit, it must be checked in an execution cycle faster than every 2 seconds to allow for the timely detection of the emergency as well as the identification and actuation of the appropriate corrective actions.

In each DART cycle the relevant tasks process the real-time data from the field and operator instructions along with feedback based on the results of previous executions of the same task, tasks at slower cycles, other tasks at the same cycle but with different geographical scope, and tasks at faster cycles. The results of each task can directly be used in closed loop controls. This additional feedback is essential to support a self-healing grid.

A. Limits

The operating limits considered in DART must include all relevant limits of individual equipment and of groups of equipment (such as flow-gates). These limits can be simple, calculated, static, dynamic, contingency security constrained, etc. These limits may be pre-specified by one of the following:

- Engineers, based on off-line studies (e.g., long-term, yearly, seasonal, day-ahead, hour-ahead, etc.)
- Operator commands in response to real-time conditions based on the operator's judgment
- Computations in various DART cycles based on weather, demand, topology changes, stability conditions, etc.

B. Scope of Limit Checking

In each execution cycle, only limits assigned to that cycle are checked. Limits assigned to monitoring by faster cycles are ignored in slower cycles. because of the following reasons:

- They are more likely to be detected and corrected by the faster cycles.
- Analytical methods in the slower cycles are likely to consider larger models and therefore too slow to identify and actuate the appropriate control actions

Similarly, many of the limits assigned for monitoring by slower cycles may be detected but otherwise ignored in the faster cycles.

C. Control Responses

A given limit violation can be seen as an emergency or otherwise by various processes differently, based on whether that limit is assigned to the process or not. For example a violation of a 20-minute thermal limit may be seen as an emergency from the viewpoint of the control area level at the 5-minute execution cycle, but may be initially ignored at the region level and at the substation or plant level. However, once the control area level analysis determines the appropriate control actions and assigns it to a faster execution cycle at the substation level for implementation, it may be considered an emergency at the substation level until it is corrected. Similarly, if no corrective action is taken at the control area or lower levels for about 10 minutes, then it may be seen as an emergency at the region level. It is also possible that a non-severe emergency (e.g. violation of a 20-minute thermal limit) may become a severe emergency as time passes by (e.g., 19 minutes have passed since the violation started). Then that violation is flagged as a severe emergency that needs corrective action immediately by a faster cycle.

Responses to various types of limits violations are described below:

In case of a **severe emergency**, there is no time to perform the normal cycle of computations. Therefore, at any given time appropriate corrective actions and corresponding conditions and parameters should be identified in a pre-assigned cycle even while that emergency does not exist. Those actions should be assigned for implementation by a faster cycle if and when the corresponding emergency actually occurs. A **severe alert** condition that exists should be handled in a similar manner since there would not be adequate time for analysis after the contingency actually happens.

In case of a **non-severe emergency**, the necessary corrective actions may be identified after the emergency.

In a **cautionary normal state**, the available margin with respect to an operating limit is too narrow. This situation is handled as if the corresponding limit violation already exists. The control response would depend on whether that hypothetical violation would be a severe emergency or a non-severe emergency.

A **non-severe alert** condition is merely brought to the attention of the operator(s) as a warning/advice since there would be adequate time for analysis and control response after the contingency actually happens.

In the **restoration** state, DART has to help in simulating and analyzing the impact of restoring a specified load (or feeder or substation, etc.) before the actual restoration. Such simulation is necessary to make sure the system condition would not further deteriorate.

D. Coordination of Responses

Corrective actions for non-severe emergency conditions and alert conditions need to be coordinated. As described above, all such conditions requiring immediate corrective action analysis are first identified, and then an optimal re-dispatch of system resources is calculated and the necessary control actions are identified for immediate implementation. The identified control actions are passed down to an appropriate faster cycle for immediate implementation. In severe emergencies, as described, pre-computed control actions are implemented by the faster execution cycles.

Usually In each execution cycle, several inter-related analytical tasks are performed at various control hierarchy levels with various geographical areas of responsibility. The cycle, the control hierarchy level and the geographical area together determine the exact nature of the tasks to be performed. Fig. 5 indicates the concepts behind this geographical coordination.

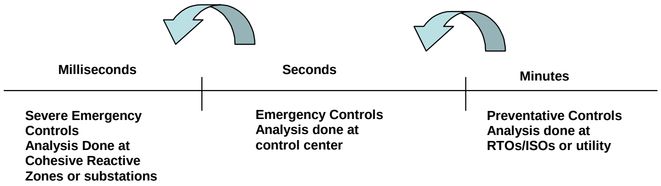

Fig. 5: Coordination of Control Responses

E. Handling Operating Concerns in DART

In the DART system, the phrase "operating concerns" includes all concerns in real-time operations and operations planning that are amenable to automatic closed loop control. They may have significant overlaps with issues traditionally considered as operator's concerns. However, they are not necessarily identical to operator's concerns.

In the DART system, each system operating concern is assigned to up to three execution cycles based on the answers to the following questions:

- How often (or in what execution cycle) should the facts relevant to that concern be monitored (for recognizing actual problems or predicting potential problems under contingency or look-ahead conditions)?
- How often (or in what execution cycle) can the corrective actions relevant to that concern be analyzed/computed (for preventing or mitigating the problems)? What are the significant modeling issues and control options relevant to the concern?
- How often (or in what execution cycle) should the relevant corrective actions be implemented (for controlling the problems when they happen)?

Each operating concern is monitored in parallel with all the other concerns continually at a prescribed execution cycle regardless of the state of the system, because changes in system state have to be recognized and responded to within the prescribed control execution cycle. As soon as a problem condition is identified (e.g., an equipment limit or a stability limit is exceeded), the appropriate processes and /or operator(s) are notified immediately for further analysis and control action. To avoid nuisance alarms, appropriate threshold checks and persistence checks should be made before notification.

Enhancement calculations are performed in one or more prescribed cycles. If the computational requirements are small enough, they are performed at the same period as a prescribed control execution cycle. Otherwise, they are performed at an appropriately slower cycle and implemented in the faster prescribed control execution cycle. The slower cycle calculations identify the necessary conditions and control parameters: targets, limits, participation factors, feedback gains, etc.

The relevant control actions are implemented in the prescribed execution cycle in accordance with the conditions encountered and the appropriate control parameters. For closed loop control actions, the periodicity of a control execution cycle should be long enough to cover all communication and control activation times as well as any supporting computations for monitoring and enhancement. However, for open loop controls, the periodicity does not have to include the control activation time. For example, in a 10-msec cycle, a decision to open a breaker may be made in less than 10 milliseconds, even if the breaker operation may take over 100 milliseconds after the decision is made.

Monitoring in the 10-msec execution cycle is on the fuzzy boundary between the DART functionality and the traditional system protection using digital relays. However, the 10-msec cycle is justified by the need to make the relevant decisions as soon as possible, regardless of other process delays such as communications processing, filtering of erroneous data and control actions (e.g., breaker operation times). Cumulatively these delays may be significantly larger than 10-msec. Filtering in the millisecond time-scales presents challenges because of the noise from switching transients. It may be possible to reduce the delays due to filtering by using a significant number of redundant measurements. Design of the 10-msec processes should take into account the trade off between process speed and the need to avoid inappropriate control actions.

VII. IMPLEMENTATION STRATEGY

The modular and scalable design of DART would allow a gradual evolution of the grid-wide capabilities over the years as the components of the present infrastructure are replaced or expanded by new systems deliberately designed to eventually realize the full revolutionary capabilities of the DART system. An incremental implementation can be done by equipment, substation, or function. The use of common standards for the computing, communications and data integration will facilitate the implementation at each stage.

An example of implementation by control hierarchy level is a distributed State Estimator. At a substation, the local raw data can be processed, to the extent possible, to reject the erroneous measurements and to establish the topology. The validated information can be provided to the corresponding legacy control center to improve the performance of area-wide state estimation. This capability can be gradually expanded to include other parts of the interconnection. In fact this distributed solution is essential to provide reliable data to the functional agents responsible for local control in faster cycles. A similar evolutionary implementation can be envisioned for any other functional area.

A plan to implement the far- reaching vision of the DART system should take advantage of the following facts:

- All enabling technologies called for are already in use or proven in concept in various fields.
- The evolutionary implementation approach allows necessary adjustment of the size and timing of required investments. The design allows for reuse of legacy equipment with appropriate interfaces.
- All necessary analytical tasks are being done now in off-line and on-line contexts as parts of various design processes (e.g. protection systems, generator controls, system operating limits). These techniques have to be improved in speed, degree of automation, and level of distribution.

VIII. CONCLUSIONS

This paper specifies a distributed autonomous real-time (DART) system to meet the need for a self-healing power grid underscored by recent major blackouts around the world. The architecture of the proposed system takes advantage of open interfaces and interoperable components to realize a modular and scalable framework. Such framework allows incremental deployment of autonomous intelligent functional agents as and when needed to eventually realize the implementation of an interconnection-wide system. The intelligent agents would adapt to the varying operating conditions of the system to analyze and maintain the reliability of the system in real-time and in the near future. Their interactions are orchestrated through a set of execution cycles tailored to the physical phenomena and operating concerns in the power system. The DART system is expected to take advantage of the latest enabling technologies in high performance computing, communications, integrated messaging and data, visualization, and information security. It will also depend on advances in computational methods including distributed and cooperative solutions. Its distributed architecture and the coordinated local and global control approach provide the resiliency needed to deliver non-stop service and a greater degree of automation required for a self-healing power grid.

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XI. BIOGRAPHIES

Khosrow Moslehi received his PhD from the University of California at Berkeley. He is the Director of Products Engineering at ABB Network Managements in Santa Clara, California and leads the research work sponsored by EPRI. Dr. Moslehi has over 20 years of experience in research and development in power system analysis and optimization, system integration, and architecture.

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