Self-Healing Multi-Sequence Control of Interactive Power Network using Evolving Hybrid Multiagents under varying Communication Network Capacity Constraint

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1. MOTIVATION AND IDENTIFICATION OF THE RESEARCH ISSUES

The confluence of information technology, alternative-and-renewable-energy-based microgrid/distributed-generation (DG/m-Grid) [1], [2], and legacy interactive power network leading to the synthesis of large interdependent heterogeneous ENFONET (ENergy Distribution and InFOrmation NETwork) with capabilities for ubiquitous spatio-temporal sensing, pervasive computing and distributed algorithms, and distributed control and actuation, has opened up possibilities in cyber domain that were hitherto impossible [1]-[4]. Given the dwindling gap between energy demand and energy supply, increasing internal, external, and infrastructural threats, the modern vision of such cyber-based ENFONET is the synthesis of a seamless, robust, and resilient interdependent intelligent interactive energy-distribution/power network [5], [6] where every node will be adaptive, energy-sure and energy-secure, real-time agile, and interconnected with everything else. In addition to reactive and adaptive operating mode, each node will perform proactive function consisting in incessant probing of possible vulnerabilities and relentless buildup of system-of-system (SOS) resiliency.

There are several challenges to this process. First, is the nonexistence of an integrated *dynamical* ENFONET network model [1], [2]. Traditional power-network model, based primarily on top-down load-flow based equilibrium model [7], is inadequate for *non-stiff* dynamical ENFONET and have limited scope with regard to handling impulsive and discontinuous dynamics [3], [4]. A dynamic multiscale and multiresolution evolving multiagent modeling mechanism of the network synthesized from the local agents (using *bottom-up* instead of top-down approach) needs to be developed [2]. An added challenge is to incorporate the *effects of information-network dynamics* in the overall control-communication model [4], [8], [9]. Traditional graph-theoretic modeling based on Poisson distribution or on Markov-chain modeling is inadequate for integration with power-network model and addressing dynamic change in network configuration, channel disruption, and burstiness of information flow [10].

A second key problem is related to the mechanism for *synthesis of the global complexity and dynamics of the multiagent adaptive ENFONET [2]*, which, despite advances in chaos theory and fractals, remain elusive because of nonlinearity, nonergodicity, heterogeneity, nonstationarity, and high dimensionality. Most scientific understanding based on the reduction of the complexity at a higher level to simpler phenomena at lower level has not worked very well [11]. It is being understood that network theory, which addresses emergence and structural evolution of the framework of a complex system, is not a substitute for a theory of complexity itself [12]. In fact, at the heart of the complexity are autonomous interactions among the nodes. Despite the apparent unpredictability of the randomness of their interactions, there exists an underlying set of fundamental laws and organizing principles that can effectively address the complex interplay of topology and dynamics.

Finally, owing to the massive dimensionality of the interactive power networks [13]-[15], conventionally, the approach to control has been decentralized, based entirely on local control and feedback [7]. While such controls have high redundancy, the implications of localized control on the global dynamics of the network are overlooked and as such, these schemes are not optimal. It is now being recognized [16], [17] that, the synthesis and implementation of the distributed-algorithm based globally-stable constrained optimal phase-transition control, which incorporates adaptation as an integral part leads to superior autonomous fault protection, stabilization, and self-healing [1], [18] is a necessity for mitigating emergent vulnerability. The key to such multi-sequence [18]-[21] multi-impact [22]-[26] self-healing is real-time clustering, which yields fast sequence of topological reconfigurations that can enable quick isolation of the fault region (or islanding) followed by cluster restoration and reconnection to the network, thereby restoring the interactive power network and possibly yielding higher stability margin. Of further importance, is the issue of evolution and proactive and reactive adaptation of the multiscale and spatial control architecture for seamless transition from distributed to pseudo-decentralized implementation enabled by self-organizing algorithms and reconfigurable clustering for true robustness against gradual or sudden degradation in power and communication network connectivity.

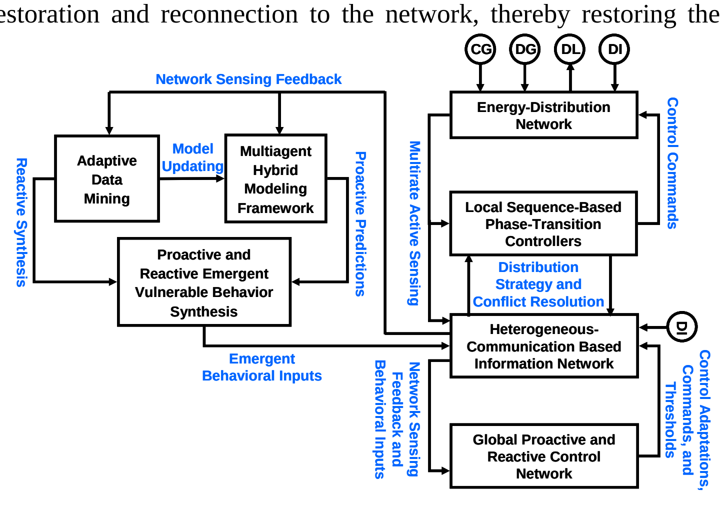

Fig. 1: Vision of the proposed ENFONET research methodology. Here, CG and DG represent conventional and distributed power generation, DL represent distributed load, and DI represent destabilizing influences.

2. RESEARCH OUTLINE

The overall vision of the proposed research methodology is outlined in Fig. 1, illustrating the adaptive multiscale vulnerability emergence-capture and resilient-mitigation scheme for the ENFONET. The pseudo-decentralized implementation is supported by a heterogeneous communication network enabling distribution of cyber-physical ubiquitous-distributed-computing-algorithm-based proactive and reactive controls, ubiquitous active sensing, and dynamic mode-changing actuation, all based on multiagent-hybrid-model- and phenomenological-approach-based emergent-behavior synthesis. Although the overall research paradigm is multidimensional, our research emphasis pertain to i) formulation of a generalized hybrid agent models with self-adaptation capabilities, ii) evolving multiagent framework for capturing global emergent and nonlinear vulnerable dynamics, and iii) sequence-based proactive and reactive vulnerability-mitigating control.

2.1 Unified Adaptive Hybrid Dynamical Models for Agent Representation

The accurate multiresolution mathematical model of the ENFONET needs to be represented by hybrid nonlinear dynamical system [18], [27] whose states are defined on arbitrary metric space and evolve along some notion of generalized abstract time. Such a unified framework, which is an indexed collection of dynamical systems along with some map for transition among them obtained by deterministic as well as stochastic events, encompasses autonomous as well as controlled behavior. The transition occurs whenever a set of system states satisfy certain conditions, given by their membership in a specified subset of the overall state space. With regard to the transmission/distribution and link/channel agents for power and information networks, respectively, Mazumder, as a part of his CAREER work, has demonstrated that, these networks can be represented by *switchable dynamics*. For instance, if a generating and load agents are connected over a power distribution/transmission link, the net power flow is dependent on the distribution/transmission-line passive/controlled behavior and if the link is activated or not. The latter can happen due to intentional isolation or due to fault. On a similar note, the information-link agents can be described as well. For instance, the TCP New Reno version, currently the most widely deployed, uses either packet losses or ECN (explicit congestion notification) marks as an indication of the network congestion. Congestion avoidance, the main TCP phase, corresponds to AIMD (additive increase multiple decrease) congestion control scheme with a binary feedback. The evolution of the TCP sending rate can, therefore, be viewed as a piecewise deterministic process. Similar argument holds true even for wireless channel modeling [28], [29], where the status of link connectivity can be attributed to a discontinuous function that is reflection of the measure of the channel dynamic capacity and throughput.

Overall, the multiagent framework based on generalized hybrid behavioral modeling yields validity with varying topological structure and operating conditions, encompass multiscale and multiresolution dynamics, which current theory of complexity associate significant importance with reference to analyzing emergent dynamics [9]. Thus, we propose a generalized high-resolution hybrid agent model that encompasses the power and information networks at the "component/local level" in steady as well transient states. The evolution of these agent models will be based on their interactions with other nodal and network agents via a process of cooperation and competition to meet a combination of goals or fitness functions by analogy with biological, ecological, and social evolution. Adaptation has direct implications on the proactive and reactive preparedness of the ENFONET for robust stabilization and evolutionary mechanisms in nature have demonstrated significant computational efficiency in this regard with reduced sensory inputs. It is believed that, such efficacy is the direct result of *adaptation based on the mismatch between the dynamical prediction of the natural agent of its external world (based on an internal model) and the feedback from its situational-awareness sensor measurements*. A multidisciplinary research needs to explore these highly efficient evolutionary feedback and adaptation mechanisms.

2.2 Evolving Multiagent Framework for Emergent Vulnerable Nonlinear Global Dynamics

A followup issue relates to the interplay of *proactive and reactive dynamic assessments* (i.e. assessment of network dynamics, respectively, under look-ahead simulated event-driven conditions and assessment in post-event scenarios) of the collective network dynamics to ascertain emerging ENFONET vulnerabilities. Such a predictive and reactive interplay is critical for high accuracy levels of model and forecast and enhanced level of anticipation leading to superior mitigation.

The *proactive assessment* is based on the predictive algorithms based on the generalized hybrid nodal-and-network agent models of the ENFONET. In order to gain insight into the interplay between microscopic interactions and macroscopic emergent features in complex adaptive ENFONET, *distributed multiagent dynamical modeling* approach needs to be explored to deduce the structure, properties, dynamics of networks and their interdependency from agent nonlinear interaction laws. To circumvent the problem with resolution and scale in this challenging process, *one can adopt a segmented and clustered compression approach using shared awareness, along the lines of adaptive resonance theory to understand the clustering function of visual systems in biological organisms.* The unique aspect of this self-scaling high-fidelity approach is that, it circumvents the need for averaging-based reductionism that can preclude the emergence of global collective dynamics and enables one to select the level of desired spatio-temporal resolution and scale to address the issue of multiscale behavioral emergence and self-organized criticality.

The *reactive assessment* over a finite horizon can be pursued by distributed computing agents by applying adaptive search-for-interdependency data-mining [30]-[33] operator on the multidimensional data streams originated from global sensing, heterogeneous communication, and pervasive computation forming a stream data cube structure. The goal is to detect an evolving vulnerable pattern and behavior early (to mitigate/constrain damage) using spatio-temporal dependency or correlation and guided by the projected probability space based on proactive assessment. There are several challenges to this process. First, consider the *scalability issue with regard to overcoming problem with proactive detection* because of symptom vagueness and the need for real-time light weight processing of vast amount of data keeping in mind the trade-off between accuracy and processing time. A progressive detection approach based on a multistage-filtering framework can be pursued. Next, consider the *challenge of discovering the spatio-temporal dependency or correlation*. Often it is hard to detect an anomaly by just examining a single time point in isolation; whereas, the variation over time can reveal important clue to detect the anomaly. It is thus important to adopt micro and macro stream-clustering and stream-classification methods that address even highly skewed spatio-temporal data sets in dynamically changing data streams for pattern mining and event and dynamic outlier and anomaly detection, and veracity analysis. Finally, to reduce *the computational and processing overhead and avoid single point of failure, distributed multinode/multiagent data mining needs to be investigated* and challenges regarding computation and information-overhead tradeoff, detection of nodal correlation, and *convergence of distributed data-mining algorithms in the presence of network delays need to be explored.*

Of course, a fundamental issue is to have multiagent functional relationships to capture the inter- and intra-network interactions, which is especially important in bottom-up modeling. *One approach to this unknown and uncertain formulation can be based on adaptive-agent game theory to understand the evolution of cooperation or non-cooperation and the adaptation of strategies to a changing environment.* Because agents are postulated to be heterogeneous, boundedly rational, capable of engaging in interactions outside of equilibrium, and perpetually adjusting their behavior, agent-based analytical and data-mining models will play a key role, to explain phenomena such as the coordination of decisions via information exchange and sensory situational awareness, self-organized criticality [6] and holarchy, non-equilibrium (stable-to-metastable) phase transitions, and spontaneous structure formation.

2.3 Sequence-Based Proactive and Reactive Distributed Vulnerability-Mitigating Phase-Transition Control

A key issue related to the damage control and protection is the mitigation of any evolving catastrophic or destabilizing emerging dynamics subsequent to a singularity condition or in anticipation of a vulnerable condition leading to network self restoration by seamless phase-transition control adaptation of the varying switchable network topology under uncertainties of information flow and evolving network morphology. Synthesis of such a *distributed and adaptive algorithm based multi-impact optimal-sequence spatio-temporal impulsive adaptation supported by multirate and channel-constrained active sensing over heterogeneous and stationary/mobile information connectivity* is an area of significant promise and challenge. Such a controlled transition, generating a rapid sequence of controlled heterogeneous transitions, is accomplished in a seamless manner to guarantee robust system performance and is implemented when the ENFONET transitions from regular to singular/impending-singular phase and vice versa as well with/without communication disruption and under statistical uncertainty, variable delays, and change in network structure.

Clearly, the operating modes of the ENFONET are complex and include forced or unforced disturbances, jump or switching transitions that may or may not be periodic, parametric variations, impact of digital automata, structural change of the ENFONET model due to fault transitions, or even phase delay due to channel limitations or packet loss. Therefore, the sequence-based optimal controller for an ENFONET has to be hybrid and adaptive (to deal with structural changes that are sudden or gradual and due to parametric variations), and developed in an optimal (or near-optimal) framework to provide the best possible compromise between performance and robustness for an associated cost. *The objectives of the optimal sequence controller are to ensure global or semiglobal stabilization under destabilizing influences and accommodate phase transitions*. The choice of the cost is dependent on network emergence and system specifications. The optimal framework synthesizes the best possible control response for a given operating condition of the power network; as such, there is no need to incorporate predetermined controllers that may not always give optimal response and may not be effective for more than one operating scenario. Further, such a framework for this advanced optimal controller needs to incorporate information network's performance metrics (e.g. access and message delays, transmission and response times, percentage collisions, message throughput and percentage of packets discarded, packet size, and network utilization) to ensure quality and robustness of distributed-controlled ENFONET.

Of further importance, is the issue of evolution and *proactive and reactive adaptation* of the multiscale (spanning local to global control variables) and spatial control architecture for seamless transition from distributed to decentralized implementation enabled by self-organizing algorithms and reconfigurable clustering for true robustness against gradual or sudden degradation in power-and-communication network connectivity. The keys to adaptive spatio-temporal time-optimal self-healing are impulsive and evolving controlled transitions and real-time clustering. These techniques consist in rapid real-time adaptable sequence of topological reconfigurations that enable quick isolation of damage/fault, followed by cluster restoration and reconnecting to the network, thereby enabling rapid self-reconfigurability and self-healing of the multiagent network and possibly yielding higher stability margin under a broad range of scenarios. The inter-cluster transition from one network partitioning to another represents a controlled singularity. *One A key research objective in this regard is to control the inter-cluster transition dynamics and organize a rapid adaptable sequence of seamless controlled inter-cluster transitions under physical/communication/computing constraints and active sensing to quickly stop propagation of post-impact destabilizing influences through the network.* Of course the issue of "distribution" of control and sensing highlights the connectivity of information and control and the need for distributed overlapping estimation, aggregation algorithms, and protocols (with proven stability and performance) signifying adaptive and distributed intelligence to obviate sudden or gradual degradation in communication channel capacity and consequent cyber-dependent effects on the stability and performance of the energy-distribution/power network.

The feasibility of ENFONET distributed control scheme is heavily dependent on the effectiveness of the communication network and the control information flow that it supports. Unlike a simple discrete-time control system, where faster sampling usually implies better bandwidth and stability margin, in a network-based communication-control system there are penalties for approaching the upper and lower bounds on the rate of information flow. For communication networks, *network capacity* [34] has been defined recently as the reference, which needs to guide the information flow; however, when the latter embodies control feedback across a communication network, such standard and typically static definitions no longer applies. What is needed is the real-time measure of *dynamic network capacity* (key to control adaptation of information flow and network resource utilization), which along with control robustness benchmarks, can simultaneously optimize the ENFONET performance using an *iterative control-communication approach* based on *event-driven and need-based crosslayer-optimized cognitive communication and adaptive sensing*. *What is needed is a research approach that will address the issue of duality of information and control via joint information-systems optimization methodology [20] based on consensus and inclusion principles, which yield robust stability against structural perturbations without compromising the network capacity of the information network that has a direct impact on scalability.* The issue of scalability deserves special attention since it can limit effectiveness of distributed control, sensing, and actuation for large network size. *Approaches to scalability, besides consensus based nodal estimation, need to be synthesized with focus on developing novel clustering mechanisms based on functionality, physical partitioning, and spatial information correlation.*

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