Abstract

This paper reports the results of Monte Carlo study of a microgrid agent scenario in which \( n \) interconnected microgrids cooperate in detecting the stability condition of a shared feeder line from the main electrical grid. Agents sample the stability behavior of the feeder line, rate the observed patterns, and use votes to express and communicate their individual inferences about system stability. Agents sent their votes through a centralized or decentralized network to be processed. In the centralized network scenario, one agent receives votes from all other agents and aggregates them into a collective inference about feeder line stability. In the decentralized network or peer-to-peer (P2P) scenario, each agent sends its votes to every other agent and each agent aggregates received votes to make a collective inference about feeder line stability.

In both types of networks, a randomly selected node was chosen to fail to simulate the effects of network structure on the processing of voting data derived from three voting systems. Monte Carlo simulations of agent ratings were generated to study the properties of voting systems and to compute the probability that a voting system produced an error-resilient collective outcome (ERCO), an inference about feeder-line stability derived from incomplete information that would have been made if all the voting data had been received. In error-resilient data fusion (ERDF) systems, reliable inferences can be made despite breakdowns or delays in network communication.

Monte Carlo simulations of ERDF systems generated results that were consistent with earlier studies of centralized networks in which one voter, one vote (OVOV) systems were most ERCO efficient, i.e., they required less elapsed voting process time to produce a high probability of producing an ERCO. However when ERCO processes operate in a P2P mode, voting systems exhibit a cross-over pattern in which no single voting system is most ERCO efficient for the entire process. These complex results provide a basis for calibrating the simulation to mirror conditions in a PSCAD microgrid testbed at Virginia Tech to conduct empirical tests of the validity of ERDF predictions about changes in the direction and magnitude of ERCO probabilities. These results can be expanded to incorporate the ERCO properties of more complex decision tasks and voting systems in which the reliability (or “competence”) of individual voters is differentiated and controlled. These models can be used to design mechanisms to support the role of humans in SCADA systems.

These Monte Carlo results are framed by a discussion of the treatment of “time” as an issue in energy production and distribution, contemporary interest in decentralized energy production and distribution (including microgrids and “smartgrids”), and the opportunities for using network communication to mobilize resources in interconnected microgrids to expand the concept of the role of microgrids in electrical grids.

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Fusing Data in Adaptive Agent Control Systems for Electrical Grids

1. Introduction

The goal of this paper is to steer the conversation about centralized vs. decentralized production and distribution of electricity in a new direction: the use of error-resilient data fusion (ERDF) systems infrastructure to stabilize electrical infrastructure (Urken, 2003, 2005). Systems for fusing data represent information with data and communicate information across a network to aggregate it into a decision. Power network control mechanisms rely on techniques that incorporate definitions of what type of data will be used to express information and how data will be aggregated into an inference about a network situation. Whether the information is statistical or associated with a model-based scoring procedure, successful communication/fusion of data is limited by breakdowns in network connections as well as errors in the reported information. Error-resilient data fusion (ERDF) systems can overcome these breakdowns and errors. ERDF capability makes it possible to increase the scope and speed of computations so that electrical grids can create new equilibria and minimize failure (cf. Haimes, 2009). The time required to produce an error-resilient collective outcome (ERCO), a result that will not change, is a measure of the efficiency of ERDF systems.

Since the conversation about centralized vs. decentralized energy systems began more than a century ago, time and speed have been dominant themes in engineering (Clark et al, 2005, Gheorge, 1985). Within this traditional framework, the role of agents in controlling outcomes has largely been confined to reacting to the consequences of change, not affecting the genesis of events themselves (Pavella, 2009, Ulieru and Dourant, 2009). Distributed agents functioned as reactive, not proactive actors. Typically, agents did not function as if they were autonomous decision makers that evaluate options and make individual and collective choices that transform what happens over time. Instead, they played a predetermined role in responding to changes over time. (Chowdury et al, 2009, Peças Lopes et al, 2005). The timing of these responses was determined by mechanical processes that controlled the direction and magnitude of change. In contrast, ERDF system design is motivated by the assumption that agents can play a more active role in affecting the direction and magnitude of systemic changes. By assuming that agents act as if they are voters in a collective choice process, ERDF systems make use of artificial voting-theoretic structure to extract order from a complex, stochastic process. Such data fusion systems can integrate dynamic low level and high level patterns in an emergent way to produce integrated, adaptive control (Mitchell, 2007). This proactive functionality could help meet the challenge posed by the scope and pace of system changes in electrical grids. Specifically, a proactive system for dealing with these volatile changes could overcome existing constraints in the design of robust, resilient, and sustainable systems for producing and distributing electricity (Zio and Sansavani, 2008).

Another reason for investigating a more proactive role for distributed agents in electricity grids is to scrutinize the expectations of advocates of decentralized energy systems. For example, ever since Scheweppe (Schweppe and Merrill, 1961, Schweppe 1981, 1988, Schweppe et al, 1980) advocated distributed energy markets, the idea of decentralizing production and distribution of electricity has taken on a certain intellectual and commercial cachet. Work on decentralized (or distributed) energy systems in the US has had a reputable—if commercially small scale—standing among power engineers. This status has been enhanced by investments in experimentation with “smart” meters and other devices in microgrid (or “smartgrid”) networks. Schewpe’s vision, revitalized by current efforts to reengineer “perfect power” systems (Galvin and Yeager, 2008), has created a sense of anticipation about if and how these systems might work. Experimentation may refine intelligent devices, improve their operational properties, and reveal if and how consumers use them to change our energy culture. But current researchers are not considering if and how networks of smart devices might coordinate their actions to enable microgrids or minigrids to cooperate with each other to adapt to changing relationships with main grids and/or synchronize their autonomous actions to create a stable and sustainable energy culture.
To guide conversations about data fusion in electrical grids in a new direction, this paper presents an example of an ERDF-enabled distributed agent control system in a “power park,” a set of interconnected microgrids. Monte Carlo simulation of centralized and decentralized control mechanisms enables us to evaluate the efficiency of alternative system designs in detecting and communicating information in time for an electrical grid to adapt. To be robust, an electrical grid must adjust to preserve a normal operating state despite the occurrence of a given class of failures. And to be resilient, a grid must automatically return to a normal operating state in a reasonable amount of time despite the onset of unexpected, potentially catastrophic failure (Haimes, 2009).

Electrical grid infrastructures cannot be robust or resilient if they do not have timely information and the means to use it to respond appropriately. In traditional centralized legacy communications systems, grids have satisfied time constraints for robustness by expanding computational capacity and system resources. But increasingly, these grids have lacked the resilience needed to respond in time to vulnerabilities caused by inadvertent and/or malicious errors.

While analysts of legacy and decentralized electrical grids have explored the use of novel communications systems to stabilize energy production and distribution infrastructures (Birman et al 2005, 2005b, Coury et al, 2002, Adamiak et al, 1999), Van Renesse et al, 2003 and Hopkinson et al, 2003, 2009), they have not investigated the options for gaining time by reengineering the systems used to fuse (or combine) data in computer networks. All electrical grids, regardless of their size, rely on a data fusion system for representing electrical grid control messages and aggregating information in computer networks. Although the study of data or information fusion includes many systems for representing information and converting data into inferences about a network situation, these systems depend on optimistic models of communications error. This optimism can be inspired by parametric, normal data fusion models in which error is addressed analytically so that extreme cases are expected to have minimal impact on fusing data for controlling electrical grid stability (Ulieru and Doursat, 2009). Or such confidence may be derived from theoretical frameworks for modeling collective action such as neural networks (Brander, 2008, Venayagamoorthy, 2009) or swarm quorum-sensing (Seeley and Visscher, 2004) in which communications and learning take place quickly enough to enable critical data be fused in time to adapt. None of these models explicitly address the challenge of showing that their theories can predictably produce timely intelligence about power engineering systems.

Modeling collective action as a data fusion process reveals how the complexities of representing and fusing data—properly understood—can be used to reengineer adaptive control mechanisms in electrical grids (Senge et al, 1994). Our objective is to make network communications—which is increasingly recognized as a potential liability in electrical grids—into a dependable systems asset for stabilizing the production and distribution of electricity. This conception of data fusion relies on the assumption that the representation and fusing of data can be modeled as if it were a voting process. In such processes, agents—human or machine—use votes to express information about a set of choices. Then the data are transmitted across a network and aggregated to produce a collective outcome, an inference about a network situation. In the literature on information fusion, however, voting processes are often treated as interesting, complex curiosities rather than analyzed as useful models for reengineering the inputs and outputs of data processing for a physical system (see Urken, 2005).

In the voting literature and in studies of voting in data or information fusion, the multifaceted, non-obvious relationship between voting inputs and outputs is a common theme (McLean and Urken, 1995). What this paper adds is an appreciation of the effects of voting inputs on the time required to produce reliable collective inferences without processing all of the voting data. In such ERDF processes, the output that would be observed if all voting data were collected is dependably predicted with a fraction of voting input. Using non-parametric statistics, this inferential power enables agent control mechanisms to take collective actions that make an electrical grid resilient to unexpected events that can lead to disruption and systemic failure. Such ERDF distributed agent control mechanisms would enable electrical grids to adapt and maintain sustainable operations. And if unavoidable breakdown occurs, ERDF methodology could permit graceful degradation, gaining time to minimize the impact of failure. Long-tailed HOT (Highly Optimized Tolerance) distributions rather than precipitous HOT behavior would provide indirect evidence of ERDF effectiveness.

Previous work has shown that ERDF design affects how long it takes to produce an error-resilient collective outcome (ERCO) in centralized and decentralized networks (Urken, 2005). ERDF mechanisms can provide a time advantage for managing changes in microgrid culture. ERDF systems do this by predicting how much data must be fused before knowing that the inference derived from the data processed at any point in time would not change.
Regardless of whether all data are actually processed, ERDF predictions make it possible to satisfy time constraints without sacrificing reliability.

ERDF control mechanisms could have important implications for designing power parks of cooperative interconnected microgrids. Factual knowledge about power park conditions includes knowing when a microgrid should move into islanding mode, when a microgrid should control internal production and distribution, when a microgrid should act with other microgrids to share resources, coordinate peak-shaving operations in the main grid, or potentially, even synchronize inter-microgrid operations to counterbalance a deteriorating main grid system to either restabilize it or to enable graceful collapse. For any of these challenges, predictable and reliable detection of emerging changes in electrical grids is a necessary—if not sufficient—condition for coordinating microgrid action.

To provide background for presenting a distributed agent control system based on ERDF principles, Section 2 discusses time as a factor in conventional analyses of the relationship between communications infrastructure and energy production and distribution. Section 3 analyzes how advocates of distributed energy operations treat time in controlling operations. Section 4 illustrates the use of error-resilient data fusion (ERDF) in a power engineering control scenario involving $n$ microgrids. Each microgrid samples the stability condition of a shared feeder line from the main grid and uses votes to communicate its observations to form a collective inference about the stability of the feeder line. The feeder link is assumed to service small, medium, or large sized microgrid power parks. Monte Carlo simulation is used to study the effects of alternative ERDF system designs on the reliability of agent detection of feeder line instability. The investigation compares results for centralized and decentralized agent data fusion strategies and the structure of agent decision-making processes. Section 5 outlines plans for extending and testing these findings in a microgrid testbed and discusses the broader implications of using ERDF communication systems to control electricity grids.

2. Time and Network Control in Electrical Grids

Network-centric electrical grid control systems are based on a set of agents, human and/or machine, that communicate messages to produce collective outcomes. Conventionally, in assessing these outcomes, the success and failure of the communications process is defined in terms how many sender messages are received by recipients. Centralized or decentralized strategies can be used to transmit data to produce these outcomes. In centralized operations, senders and recipients of messages are hierarchically related and all routing is controlled through specified channels. In decentralized operations, agents can send messages to any other agent in the network without relying on central control of the routing process to deliver information. Eventually, via such peer-to-peer messaging, all members of the network would receive the same message.

Thinking about what is possible in controlling communications and outcomes in electrical grids has been heavily influenced by centralized adaptive network methodology. In this approach, most often associated with Shannon’s work on phone networks, the fundamental problem of communication is “that of reproducing at one point either exactly or approximately a message selected at another point in the network.” In this conception of network control, collective outcomes are characterized by how many messages are received throughout the network and how long it takes to transmit the messages. Implicitly, it is assumed that if network communication operates efficiently and effectively, all members of a network will share the same outlook. How this consensus is produced, which is taken as obvious, is not explicitly modeled.

Time was an important criterion for designing communications protocols in classical telephone networks. In fact, protocols were designed to transmit the maximum amount of information throughout the network in the shortest possible time with minimal distortion. Shannon showed that if all information in messages were broken down and encoded in homogenized data sets, the entropy of communication systems could be controlled to balance the rate of information (or data) flow and the carrying capacity of network architecture. These classical models contain no explicit technique for assessing the reliability of the content of the messages or for deriving inferences if messages from subordinate agents to a centralized agent are erroneously aggregated across a network. Information was assumed to be complete and perfect. If network agents in the network are “alive” or working, they will operate perfectly, and eventually, data will be transmitted successfully. Early efforts to build more adaptive and predictable network communication focused on weighting agent decisions and channel capacity to decrease network communications time. Subsequent work, including the invention of the IP protocol, introduced new mechanisms for adaptive routing in complex networks without specifying how long it would take to transmit messages.
In this legacy communications network paradigm, “data” are given, “neutral,” basic starting points in a chain of reasoning that allows us to make inferences from collecting and processing (i.e.” fusing”) the “facts.” By contrast, “information” or knowledge is communicated by interpreting data in the context of semantic and syntactic rules that give meaning and significance to communications content combined in a particular context.

“Data” are not necessarily free of implicit theoretical significance that can shape the choice of semantic and syntactic rules (governing the meaning and logical relationships in message content) and can affect perceptions of a network situation. Connotations, gestalts, and other embedded structural aspects of message representation and transmittal can affect inferences about “information” derived from the data.

One of the challenges for designers of interdependent critical infrastructures (ICIs) is to regulate message delay and distortion to control the gap between communications outcomes and the time needed to respond to changing conditions electrical networks to meet time-sensitive constraints associated with producing and distributing electricity.

In the centralized production and distribution of electricity, fused data is employed to update the parameters of models used to control network resources and operations to preserve stability. In extremely stochastic environments, centralized control, monitored by human supervisors, is constantly working to update information about the state of the network so that network operational parameters can be adjusted to maintain stability.

If communications systems fuse data that distorts factual descriptions about the state of the electrical grid, the adaptive capacity of the control mechanism may be overcome by stochastic changes that can produce extreme instability and collapse. Potential mismatch can be exacerbated by relying on a conventional linear engineering model of system specifications which can be out of synch with the structural dynamics and produce reactive—rather than proactive—inferences about adapting system parameters

3. Energy, Time, and Adaptive Systems

Although “time” is a crucial attribute of energy production and distribution, there is no comprehensive model of the complex and potential role of time in communication and energy processes. For example, in conventional thermodynamic models, the “arrow of time” is accepted as a predictor of the direction of degrading energy capacity “over time” associated with entropy. However, in models of non-equilibrium thermodynamics, time may actually increase potential energy.

Theoretical differences in perceptions of how energy systems work over time is also revealed in a more refined model of thermodynamic change associated with exergy. Exergetic (or “exergoeconomic”) analysis reveals the lifecycle costs of alternative technologies that are only implicit in entropic models. Still, while it is more complete, exergoeconomic accounting depends on limited snapshots or samples of qualitative changes associated with the expended cost of materials and systems used in energy production and distribution. This accounting methodology provides a more precise and accurate representation of thermodynamic changes that have taken place. Explaining the actual rate of change in the future requires integrating quantum theory and thermodynamics, a theoretical challenge facing energy theorists.

A strategy for integrating time into adaptive communications control of electrical grids can be based on system robustness or resilience. A robust solution depends on having system resources that can be mobilized quickly enough to collect data, carry out computations, and make adjustments to system parameters to enable the grid to operate within the bounds of “normal” stability. But expanding system capacity to increase the agility of a grid is limited by cost, computational capability, and communications error (Mili, 2011). In legacy electrical grids, cost has been accommodated and computational capability has been expanded so that data can be collected and processed using computationally intensive resources to reset system parameters within the minutes required to preserve grid stability. But such conventional solutions are not sufficient because grids can collapse in less time than it takes to collect and analyze data and then make adjustments. Typically, centralized grids require approximately 15 minutes to adjust the operating parameters of an electrical grid to maintain normal operations. Researchers studying “real-time” or “quasi real-time” monitoring of electrical grids have advanced the state of the art to design a control
mechanism that computes on a laptop to recalibrate system parameters within 4 minutes. Unfortunately, this improved performance is still not fast enough to prevent electrical grid collapse.

Network communications delay can also limit the robustness of adaptive electrical grids. Conventional robust solutions based on centralized network architecture normally rely on internal control—usually operated by a collection of machines operating as SCADA (Supervisory Control and Data Administration) system. SCADA systems are interfaced with visualization tools to enable human intervention if necessary. SCADA structures are subject to single-point-of-failure failures caused by physical attacks on network infrastructure and/or cyberattacks on software systems. Cyberattacks on SCADA systems are a well-known vulnerability of standard IP communications that can be addressed by reengineering the protocols used in power intranets. One approach has been to avoid the use of the centralized IP protocol structure by using peer-to-peer (P2P) communications. In these decentralized communications systems, messages are eventually distributed to all nodes in a network by having neighboring members of the network distribute data. Experiments have demonstrated that this P2P strategy eventually delivers data to all network nodes. But the results indicate that the P2P communication mechanism is not very reliable when messages must be delivered in a few minutes, a critical requirement for designing adaptive electrical grids.

Another approach to power grid cyber protection is to reengineer the IP protocol itself by using formal methods to make the software systems used in the system less vulnerable to various forms of cyberattack. This approach depends on a variety of software engineering techniques to regulate software program structure to make computers less susceptible to attack. These systems include the use of programming languages that are “type-safe” because they can be “proved” at runtime to be free of viruses, Trojan horses, and other software threats that can leverage inadvertent software failures such as buffer overflows to penetrate software systems. Although language-based reengineering of the IP protocol has been praised by computer scientists, the costs and knowledge required to reengineer communications in power engineering networks seem to have hindered investigation of this type of solution.

In legacy electrical grids, energy users, except for some industrial customers, are normally not equipped to protect themselves against the damage and costs of energy distribution disruptions. Some disruptions are difficult to measure because their small size and infrequency makes them a challenge to detect. In contrast, catastrophic failures, extreme and sudden changes in electrical service, though infrequent, are obvious once they have occurred. For some industrial and residential users, the expected value of damage and disruption makes it reasonable to install and operate backup generating capacity to minimize the effects of collapse and reduce the time to recovery. If these backup systems automatically turn on or can be switched on quickly enough with manual control, consumers can be protected. Otherwise, in the US, energy producers and distributors bear no legal liability for the failure of their systems. For this reason, some companies take extreme risks by maximizing production close to the known robustness limits of their systems. Once these limits are exceeded, electrical grids lack resilience to restabilize themselves.

4. Decentralized Energy Culture

In Perfect Power, Robert Galvin and Kurt Yeager present a manifesto for developing microgrids, systems for decentralized production and distribution of electricity, to change the operation and management of electrical infrastructure. Their proposal outlines the potential advantages of decentralizing the design and management of electrical grids. In their view, microgrids, also known as “smartgrids” or “minigrids,” can (and should) be used to restructure (or literally “revolutionize”) centralized energy production and distribution as well as the relationship between consumers and producers. For Galvin and Yeager, quality of service to the customer should be the overarching objective.

Galvin and Yeager envision an electrical infrastructure composed of “powerparks,” collections of microgrids that would contain new decentralized grids as well as reengineered centralized systems. Coordinated or collective powerpark action would augment the capability of microgrids to do more than engage in profitable peak-shaving services for main electrical grids. If microgrid agents were able to detect impending main grid instability, they could coordinate their responses to deliver enough power to the main grid to permit graceful system failure. Or perhaps coordinated action could transfer enough power to enable the main grid to extend its margin of resilience to avoid system failure all together. Slowing main grid failure would increase the time available for industrial and residential consumers to avert harm by turning off electricity consumption, switching on back-up systems, and alerting
emergency responders to take action to mitigate loss of life and property. Moreover, if powerparks could mobilize resources in time to restabilize main grids, electrical infrastructure could avoid catastrophic failure and possibly contribute to the evolution of more sustainable, more decentralized energy operations.

Currently, microgrids are often entangled in rate disputes with main grids. From the perspective of main grids, microgrids consume too little electricity. As a consequence the marginal net profit derived from serving microgrids justifies charging them higher rates. Moreover, main grids face uncertainty when microgrids go into “islanding” mode. This transition can occur reactively if a main grid collapses or, positively, when a microgrid has resources to satisfy its own electricity needs. Regardless of the motivation, islanding only adds to the urgency of main grid appeals to regulators for rate increases. In a future energy culture, autonomous operations, particularly in powerparks, might emerge as part of normal decentralized operational cycle in which main grids no longer dominate distributed operations in the marketplace and induce regulators to charge higher rates for industrial and residential consumers in microgrids. In such a culture, main grid producers of electricity would no longer have incentives to plan to maximize production based on risk-prone assumptions about robustness. If microgrids provided a quality of service based on sharing risk with customers rather than leaving them in the lurch, legacy producers would no longer be able to avoid the externalities of catastrophic failure. For consumers, able to make autonomous energy choices in “smart” microgrids marketplaces, would no longer be subservient.

This vision of an energy system is “utopian” in the best sense of the term because it provides a theoretical orientation about goals, motivating us to imagine what may or may not be feasible in a reengineered electrical infrastructure. For, literally, the world of “perfect power” is a “utopia,” a system that doesn’t exist. But could it? Can such systems be engineered to make perfect power (perhaps more cautiously described as “more perfect” or “perfectible” power”) feasible for residential and industrial users? At a theoretical level, new systems may seem feasible or at least not infeasible. But if we investigate the design of the subsystems that would support perfected power, we may gain a more precise notion of the conditions under which changes are feasible or infeasible. If analysis shows how to design and manage perfected power systems to make them feasible, the actual engineering work can be guided by this knowledge in making systems work. It is also reasonable to expect that systematic analysis will reveal limiting conditions that must be taken into account in planning and implementing a microgrid world. These limitations may be investigated to determine if powerparks can be designed to overcome them in practice.

The vision of distributed production and distribution of energy in microgrids or smartgrids implicitly—and sometimes explicitly--includes a model of an energy culture of shared risk and cooperative action. In this culture, consumers would benefit from minimizing the negative externalities of their choices by behaving as active, rather than passive, participants in the process of producing, distributing (and even storing) energy. In fact, they might become “prosumers” with a wider scope of options for making energy choices.

But experiments with human participation in microgrid planning suggest that residential and commercial consumers respond differently to participating in planning. While commercial organization provides goals and shared consensus that enable them to respond in time to market opportunities, consumer planning is often thwarted by difficulties in achieving consensus on goals, even in small families.

**Adaptive Agent Error-Resilient Control**

In an artificial culture of distributed microgrid agents, human constraints on achieving consensus do not apply. In such environments, communications infrastructures can be engineered to permit the expression and fusion of data to permit just-in-time distributed decisions and adaptive behavior to stabilize the direction and magnitude of system change.

Previous Monte Carlo investigations of error-resilient data fusion (ERDF) systems have shown that ERDF systems can reliably produce centralized and decentralized network control. But these studies did not include quantitative results for decentralized operations or relate the voting process to the substantive reality of power engineering in microgrids. This paper addresses these deficiencies by using a reengineered Monte Carlo simulator that generates ERDF patterns for centralized and decentralized decision making. Moreover, instead of simply postulating voting time as a random attribute of votes, this simulator makes voting process time a function of network communications structure associated our power park microgrid agent scenario.
A simple, but critical aspect of microgrid coordination is detecting and correctly diagnosing potentially destabilizing changes in their shared network environment. (Katiraei et al, 2008). Predictably quick and accurate detection of physical changes in microgrid agent network environment is a prerequisite for efficient microgrid coordination efforts as well as individual microgrid action. Figure 1 shows a power park scenario in which n microgrids, MG1…MGn, share a feeder line from the main power. In this situation, each microgrid is faced with the decision task of detecting a potential voltage threat in the feeder line. In making a decision, the communications infrastructure can be designed to assure that data sharing works effectively and efficiently to support the stability of the microgrid system.

Regardless of the internal configuration and functionality of each microgrid, all microgrids share a common interest in being able to gain time in responding to feeder line instability and breakdown. If a single microgrid were sufficiently confident about its ability to detect a feeder line threat in time to take adaptive action, relying on the collective assessment of a group of microgrids might not seem necessary. But in a network in which communications and power variability can produce differential distributions of data (and information) along network links, acting alone is dominated by collective action—unless one agent is so omniscient and reliable not to benefit from collective intelligence.

Table 1 shows four nominal stability condition categories that microgrid agents can use to classify the behavior of feeder line voltage.

![Figure 1—n Microgrids Connected to a Feeder Line from a Main Electrical Grid](image)

<table>
<thead>
<tr>
<th>Stability Condition 1</th>
<th>Stability Condition 2</th>
<th>Stability Condition 3</th>
<th>Stability Condition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Somewhat Abnormal</td>
<td>Significantly Abnormal</td>
<td>Dangerously Abnormal</td>
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</table>

Table 1--Feeder Line Voltage Stability Categories

In the model shown in Figure 2, each microgrid acts as an agent that periodically samples information about voltage stability in the feeder line. Agents autonomously rate the attributes of the stability of the feeder line, convert the rating information into vote allocation data, and send the votes across a centralized or decentralized network to be aggregated into a collective inference about the stability of the microgrid-feeder line system.

![Figure 2—Voltage Stability Condition Stimulus of Voting Process](image)

In the model shown in Figure 2, each microgrid acts as an agent that periodically samples information about voltage stability in the feeder line. Agents autonomously rate the attributes of the stability of the feeder line, convert the rating information into vote allocation data, and send the votes across a centralized or decentralized network to be aggregated into a collective inference about the stability of the microgrid-feeder line system.

Tables 2-4 illustrate the allocations of votes that individual microgrid agents can use to communicate information about the stability of feeder line voltage. If all the raw ratings from each agent were transmitted in a network, there would be no reliable structural basis for knowing when to stop data aggregation. Voting systems provide a structure...
that provides semantics and syntax for relating low-level data to high-level inferences about network situations. If an average or median voltage score were used, transmittal would be more bandwidth-intensive and could produce volatile results. In contrast, voting processes—which would take up less bandwidth—represent data at a low-level of generality and abstraction. And the collective inference emerges at a macroscopic level. This emergent outcome evolves as votes are communicated to and aggregated at a shared host (in a centralized network) or all peer microgrids (in a decentralized network).

Table 2 shows a microgrid agent that has rated feeder line voltage variation to be normal. Constrained by OVOV (One Voter, One Vote Voting System) rules, and uses one vote to indicate that “normal” is the highest rated choice in its assessment.

In Table 3, a microgrid agent, operating under an AV (approval voting) system, is allowed to cast one vote for each classification category that fits its assessment of feeder line voltage stability. In this example, the agent’s assessment of voltage stability justifies casting one vote for “normal” and “somewhat abnormal” to indicate that these classifications are consistent with its ratings.

And in Table 4, an agent ordinally ranks the voltage stability classification options and sends the rank data for each option to be fused with data from other agents. In this case, the agent has determined that “normal” and “somewhat abnormal” are tied as the best classification for observed voltage behavior, that “significantly abnormal” fits only half as well as the first two choices, and that “dangerously abnormal” is not consistent with its voltage behavior observations.

Although voting theorists still debate whether one voting system is “optimal” in a global sense, our study values all of these systems as tools that enable us to discern and model the complexity of individual agent inferences derived from a given set of rating inputs. For example, OVOV shows which choice is top rated, AV identifies the set of choices that satisfies individual approval criteria, and Copeland voting describes the relationship of choices in an agent’s set of voltage stability ratings.

In some cases, agent vote allocations can be consistent across voting systems, but the logic of the aggregation process defined by each voting system may produce a different collective outcome. For example, Tables 3 and 4 indicate that the agent rated “normal” and “somewhat abnormal” equally under AV and Copeland systems. But these equalities are treated differently in the aggregation processes of these voting systems. Under AV, the votes are added while under Copeland scoring, the votes are used to compute scores derived from the relative positions in rankings across the matrix of vote allocations.
Voting systems are complex structures in which changes in one part can affect the processing of information in the formation of a collective outcome. Changes in the number of voters, rating inputs and the rules for expressing and communicating information can all work to produce collective inferences that are consistent or inconsistent. Tables 5 and 6 show the same set of hypothetical rating data processed through AV and Copeland scoring.

In Table 5, a majority (or simple majority) of microgrid agents approves of “significantly abnormal.” In Table 6, the ratings used to allocate approval votes are used to derive Copeland scores. This derivation is based on the rankings of the proportional weighting of the stability conditions found in Table 5. The Copeland scores include negative numbers because the aggregation process compares the relative sizes of the collective ranking intervals. If the intervals for any two choices are the same, the difference is zero, but if one choice is stronger than a second choice, a negative number indicates that the second choice is weaker than the first. Table 6 indicates that “Significantly Abnormal” garners the plurality of the Copeland votes.

Error-Resilient Collective Outcomes (ERCOs)

An error-resilient collective outcome (ERCO) is a collective inference derived from an incomplete set of voting data that would be consistent with the conclusion reached if all the votes were counted. For example, in Table 5, if the votes of microgrid agent 2 were lost or significantly delayed, the collective score would change from 3-2 to 3-1, but the collective inference would still be that the voltage stability condition of the feeder is “significantly abnormal.” Similar effects can occur in more complex vote mechanisms such as Copeland scoring. In Table 6, the quantitative effects of missing data are not so obvious. However it is still intuitively obvious that finding the collective outcome without microgrid agent 1’s votes will change the Copeland score, but will not change the collective inference.

The Monte Carlo simulation tool used in this paper allows us to set system factors that can be fixed or controlled and to investigate the probabilistic patterns of ERCO emergence. This investigation tracks the effects of the random variable, microgrid agent voltage stability ratings, on the probability of producing an ERCO. In our power park scenario, controllable voting system factors include the number of microgrid agent voters (5, 10 or 100), centralized or decentralized voting, and the systems for fusing data (OVOV, AV or Copeland systems). In a centralized simulation, one microgrid agent acts as the power park host that collects and processes the voting information. In a decentralized data fusion structure, each microgrid agent sends a copy of its votes to every other peer in the power park. Then each peer acts as a vote counter to produce collective outcomes. In this peer-to-peer data fusion process, the decisions about the collective inference of all of the microgrid agents, if consistent, will allow each microgrid to act autonomously, without waiting to get feedback from a centralized vote-processing microgrid agent. Under certain conditions, this capability would allow P2P error-resilient systems to perform more efficiently than centralized ERDF systems in reaching timely, coordinate inferences about feeder line voltage stability.
Monte Carlo simulations are a way of generating data about ERCO patterns to enable us to develop a better theoretical understanding of what to expect if distributed microgrid structures did, indeed, “revolutionize” or restructure energy systems. The simulation results presented in this paper should be taken with three caveats. First, ERCO calculations do not predict the collective outcome itself. Rather, ERCO probabilities are metadata, abstractions that provide insight into the time required to make reliable inferences about data fusion processes with attributes matching the initial conditions of the Monte Carlo simulation. Second, the results reported here, a subset of a broader simulation data set that includes other decision tasks (including multidimensional decisions) and metrics for time. Previous ERDF simulations have used elapsed time (based on a Rayleigh distribution) measured in units of time required to communicate votes. But time has also been measured in reference to the percentage of the total votes that can be collected in a voting process. For example, if 100 microgrid agents cast a single vote, ERDF efficiency can be measured on the basis of the percentage of the votes that must be processed to yield a high probability of producing an ERCO. Each one of these models for measuring the time required to make an error-resilient collective inference is important to consider. For if the simulation is well-constructed, the results for elapsed communication time can be used to check the validity of models based on elapsed time in vote collection, and vice versa.

More detailed discussion of the simulation tools used in this paper and more extensive quantitative results—including results based on time in vote collection—can be found in “Simulating Adaptive Agent Control Mechanisms for Electrical Grids” (forthcoming). The results reported here, based on 10,000 runs, generate probabilities that may be sensitive to increases in the number of randomly-generated cases.

The third caveat about these results is that they are a milestone on the intellectual path to developing a better theoretical understanding of ERDF systems and their application to data fusion problems in electrical grids. Growing this knowledge will depend on learning from experimentation in the PSCAD microgrid experimental testbed at Virginia Tech. One goal is to derive empirical measurements to calibrate the random variables used in the Monte Carlo simulation. For example, Rayleigh distributions are a good characterization of broadcast network communication patterns, but must be scrutinized by generating results based on empirical data about vote transmittal in centralized and P2P power parks. Moreover, the results in this paper are based on creating hypothetical sets of initial conditions for the ratings that drive microgrid agent voting decisions. However, simulations in the PSCAD microgrid testbed will allow us to control the stability conditions of voltage in the feeder line to synchronize the data fusion process and the physical realities of power engineering. Once these empirical refinements in the model have been made, calibrated Monte Carlo predictions can be validated by using ANOVA techniques to identify and evaluate factors that explain deviations from idealized predictions about changes in the direction and magnitude of ERDF efficiency.

**ERDF Simulation Results**

A simple model of time in data fusion processes is a useful reference point in considering the ERDF results presented below. Three factors are crucial in determining the timeliness of ERDF systems:

\[
T_D = \text{time required to aggregate information into a reliable inference}
\]

\[
T_A = \text{time required to take action to stabilize an electrical grid}
\]

\[
T_C = \text{maximum time available for taking corrective action to implement resilient functionality}
\]

In this model, if \(T_D + T_A < T_C\), then \(T_D\) must be as small as possible to accommodate larger values of \(T_A\) and constraints imposed by \(T_C\). For if \(T_D + T_A > T_C\), the data fusion system will not be feasible.

In our power park model, \(T_A\) must eventually be estimated with data from the PSCAD microgrid testbed, taking account of options in microgrid power engineering networks to take appropriate action. At this point, minimizing \(T_D\) is the focus of the modeling of the number of microgrid agents, centralized vs. decentralized decision making, and alternative voting systems. ERDF results are summarized in Tables 7 and 8. Each table presents results for 3, 5, and 100 microgrid agents voting in centralized and decentralized data fusion processes using OVOV, AV, and Copeland voting systems. However, the tables contain data generated by different assumptions about the distribution of preferences. In Table 7, preferences are centrally or normally distributed over the range of four choices defined in
the microgrid agent voltage monitoring decision task. In contrast, Table 8 reports results based on a skewed distribution of preferences.

The centralized preference (or rating) scenarios summarized in Table 7 reveal the following patterns:

Regardless of the number of voters,

- CS maximum ERCO efficiency dominates P2P maximum ERCO efficiency: CS ERCO efficiency is equal to or greater than P2P ERCO efficiency.
- CS systems reach their ERCO maxima more quickly, often in one-quarter of the time elapsed time required for P2P systems.

<table>
<thead>
<tr>
<th>Number of Voters</th>
<th>Voting System</th>
<th>Client-Server Network</th>
<th>P2P Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 OVOV</td>
<td>~16% of elapsed time required to reach maximum ERCO reliability of .58; converges with results for 10 voters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 AV</td>
<td>~16% of elapsed time required to reach maximum ERCO reliability of .48; lowest ERCO maximum, no significant time advantage versus equivalent P2P pattern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 OVOV</td>
<td>~16% of elapsed time required to reach maximum ERCO reliability of .58; same ERCO efficiency as equivalent P2P condition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 AV</td>
<td>~64% of elapsed time required to reach maximum ERCO reliability of .50; more ERCO efficient than results for 100 voters for the first 64% of elapsed time; less ERCO efficient than results for 5 voters until ~32% of voting process time has elapsed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 OVOV</td>
<td>&lt;16% of elapsed time required to reach maximum ERCO of .82; significantly more efficient than results for 5 and 10 voters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 AV</td>
<td>~64% of elapsed time required to reach ERCO maximum of .68; nearly 70% more ERCO efficient than results for 10 voters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Cope land</td>
<td>~16% of elapsed time required to reach ERCO maximum of .45; ERCO results marginally less efficient than pattern for 5 voters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 provides Monte Carlo Results for Centralized Preference Scenarios in Client-Server and P2P Microgrid Networks.
• In P2P networks, voting systems with more complex voting structure (i.e. approval voting and Copeland voting) often show smaller sized groups outperforming larger groups at the beginning of the data fusion process and then show larger group ERCO probability efficiency taking off at the end of the voting process. This crossover pattern was not found in earlier studies.
• The results for OVOV system for 100 voters are consistent with the Condorcet “jury theorem” and the Monte Carlo patterns found in earlier studies: a high ERCO maximum probability (> .95) is reached very early in the voting process and remains stable.

The skewed preference (or rating) scenarios summarized in Table 8 reveal the following patterns:

<table>
<thead>
<tr>
<th>Number of Voters</th>
<th>Voting System</th>
<th>Client-Server Network</th>
<th>P2P Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>OVOV</td>
<td>~ 16% of elapsed time required to reach ERCO maximum of .73; least efficient ERCO performance compared to results for 10 and 100 voters</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>AV</td>
<td>~ 16% of elapsed time required to reach ERCO maximum of .60; lowest ERCO efficiency performance in group</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Copeland</td>
<td>~ 16% of elapsed time required to reach ERCO maximum of .70; lowest ERCO efficiency in group</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>OVOV</td>
<td>&lt; 16% of elapsed time required to reach ERCO maximum of .80; more than 15% more ERCO efficient than results for 5 voters</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>AV</td>
<td>&lt; 16% of elapsed time required to reach ERCO maximum of .80; only 10% more ERCO efficient than results for 5 voters</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Copeland</td>
<td>&lt; 16% of elapsed time required to reach ERCO maximum of .78; more than 10% more ERCO efficient than results for 5 voters</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>OVOV</td>
<td>&lt; 16% of elapsed time required to reach ERCO maximum of .98; more than 15% more ERCO efficient than results for 10 voters</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>AV</td>
<td>~ 16% of elapsed time required to reach ERCO maximum of .72; more than 10% more ERCO efficient than results for 10 voters</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Copeland</td>
<td>&lt; 16% of elapsed time required to reach ERCO maximum of .98; more than 15% more ERCO efficient than results for 10 voters</td>
<td></td>
</tr>
</tbody>
</table>

Regardless of the number of voters,

• CS maximum ERCO efficiency dominates P2P maximum ERCO efficiency: CS maximum ERCO efficiency is equal to or greater than P2P maximum ERCO efficiency.
• CS systems reach their ERCO maxima more quickly, often in one-quarter of the time elapsed time required for P2P systems.
• In P2P networks, all voting systems include crossover patterns with more pronounced differences in the beginning of the data fusion process than differences observed under centralized initial preference conditions.
• The results for OVOV system for 100 voters in a CS system are consistent with the Condorcet “jury theorem” and the Monte Carlo patterns found in earlier studies: a high ERCO maximum probability (>0.95) is reached very early in the voting process and remains stable.

Implications for the Power Park Scenario

The power park Monte Carlo simulation generated 10,000 data sets for each condition in a nested experimental design to estimate the probability of producing an ERCO. Centralized and skewed distributions of feeder line voltage stability ratings were the random variables. The design showed how nominal classification could be used to derive the agent ratings from changes in the direction and magnitude of voltage behavior. But the actual derivation of ratings will be measured in a microgrid agent PSCAD test bed. Using postulated stability ratings, experiments investigated the efficiency of error-resilient data fusion systems using centralized and P2P network communication and three voting systems: OVOV, AV, and Copeland voting.

These simulation results demonstrate that ERDF systems can operate efficiently in centralized and P2P networks. But there is no global optimal configuration of components in the microgrid agent data fusion scenario. Although CS systems dominate P2P systems in producing ERCO maxima, the number of agents and the voting system do not necessarily produce an ERDF advantage.

5. Implications for Future Research

The simulation data suggest the following points that should be considered in future research:

• Under OVOV, ERCO efficiency tends to be more efficient earlier in a voting process when preferences are “centralized” (symmetrically distributed) than when preferences are “skewed” (asymmetrically distributed). But when OVOV operates with skewed preferences, the same maximum ERCO probability produced under centralized preferences will be reached, but take more than four times longer to emerge.
• When the distribution of ratings is centralized or skewed, increasing the number of voting agents improves ERCO efficiency, but emergence of a maximum takes longer as the number of agents increases.
• Under all voting systems, regardless of the number of agents, decentralizing the data fusion process increases the time required to reach a maximum ERCO probability.
• Under all voting systems, regardless of the number of agents, decentralized data fusion systems involve non-obvious tradeoffs derived from crossover effects. These effects occur when voting systems with delayed ERCO probability maxima outperform other voting systems early in a voting process and then perform as well as or better than other voting systems until the maxima of alternative systems emerge.

These complex results suggest that collections of microgrids will not necessarily operate more effectively under centralized or decentralized control. Although data fusion is only one criterion for evaluating microgrid operations, the potential impact of coordinated microgrid action can be important in the evolution of distributed energy systems. However the most efficient mode of coordination is still an open question. Decision tasks that involve more than four choices, fuzzy ratings, and multidimensional ratings will create more complex ERDF processes. Some tasks may operate more efficiently when voting data are centrally fused, others may work with greater reliability in P2P data fusion, and still others may function equally well under either mode of interaction. And crossover effects, particularly in P2P data fusion, may be enhanced when larger numbers of microgrid agent voters are members of the microgrid network.

It is important to note that ERDF models operate on meta-level analysis of the attributes of data fusion processes. This level of analysis provides insight into the logical properties of the systems for expressing and aggregating information. So the results do not predict the substantive collective outcome for a particular decision task.
This line of research provides a basis for rethinking the logic of communication in agent swarms or mobile agents. Voting models have been used to explain dynamic data fusion behavior in bees and ants, though it is not clear which voting system model best explains collective behavior. Moreover, the development of ERDF models will provide an impetus to consider modifying the roles of existing parts of microgrid systems such as inverters, batteries, switches, and other devices that might be engineered to include voting as part of their network personalities.

In investigating these possibilities, ERDF models can be validated by integrating known theoretical properties of voting systems. For example, the probabilities of phenomena such as ties and the paradox of voting can be used to test the simulation to make sure that the logic of voting processes is operating correctly. Moreover, once ratings are derived from feeder line voltage behavior, it will be possible to generate extreme cases to see how ERDF voting controls regulate shifts in the direction and magnitude of feeder line voltage.

**Broader Policy Implications**

This investigation of ERDF systems suggests that although time in energy processes may ultimately be beyond our control, we can affect what happens over time if we create new data fusion systems. Analysis of possibilities will allow us to scrutinize the evolution of microgrids to plan for the future. This paper has pointed out ways in which microgrids can benefit commercially from coordinated, collective action. Microgrid networks could also benefit from evolving collective intelligence to address problems of cybersecurity and sharing resources. For instance, when the time to a potential or impending cyberattack can be estimated, microgrids could use ERDF systems to minimize vulnerabilities by gaining early warning to take evasive action.

Although operational control is only one criterion for designing structural control of energy systems, it can provide experimental evidence about what to expect from electrical grids, whatever their shape or size. As more microgrids become interconnected, there is a risk that sharing power across large numbers of microgrids may unwittingly recreate the volatility and instability characteristic of conventional main grid transmission operations. With proper coordination and expansion of flexible local energy production and storage, microgrids may be able to capitalize on information to develop a flexible, nimble business model.

In the past, operational control of electrical grids has integrated human intervention and management in centralized SCADA systems. ERDF systems would open up more options for distributing control. Moreover, whether control is centralized or decentralized, the data fusion process could be reengineered to provide predictable windows of opportunity for human intervention. ERDF reengineering of communication processes will draw attention to the need for task-oriented, functional standards that go beyond conventional interoperability. Being on the same wave length may be a necessary condition for effective communication, but is not sufficient for situations in which time is of the essence.
References


NIST (National Institute of Standards and Technology), (2009) NIST Framework and Roadmap for Smart Grid Interoperability Standard Release 1.0 (Draft)


