2.9 Distributed Grid Integration

Year 10 Projects and Participants			
Project Number	**Project Title**	**Participants**	**Institution**
Y10.ET1.1	Configuration Management & FID Integration with FREEDM	McMillin/Steurer	S&T FSU
Y10.ET1.2	Integration of Secure DGI algorithms with Testbeds	McMillin/ Kimball, Ayyanar, Chow, Baran, Steurer, Stanovich, l Schoder, Leonard	S&T NCSU FSU
Y10.ET1.3	Invariants for Cyber-Physical Correctness	Kimball/McMillin/ Chow	S&T NCSU
Y10.ET1.4	Implementation of Reputation-based Resilient Control Strategy for Cyber/physical Attacks on FREEDM System	Chow	NCSU

2.9.1 Intellectual Merit and Impact

The first key intellectual merit of DGI/RSC is the development of the new field of Cyber-Physical security and applying it to the FREEDM architecture. The term Cyber-Physical security was questioned by the review teams from year 4 onwards and it is entirely possible this term was invented by FREEDM. The concept is that cyber and physical security requires a combined cyber/physical defense of the common information flows present in a Cyber-Physical System (CPS). The Multiple Security Domain Nondeducibility (MSDND) method decomposes the CPS in multiple security domains that interact as peers rather than the hierarchical models of existing electric power system. MSDND security is good for the system to protect its confidentiality, but its dual must be prevented to disrupt integrity attacks. MSDND identifies vulnerable information flows for a system designer to rectify.

The second key intellectual merit of DGI/RSC is the development of a Fog Smart Grid system in which localized intelligence manages cooperating power electronics devices. Consensus based distributed algorithms perform energy management and master/slave group structures manage configurations and Volt/VAR support. All are made resilient to attack through MSDND.

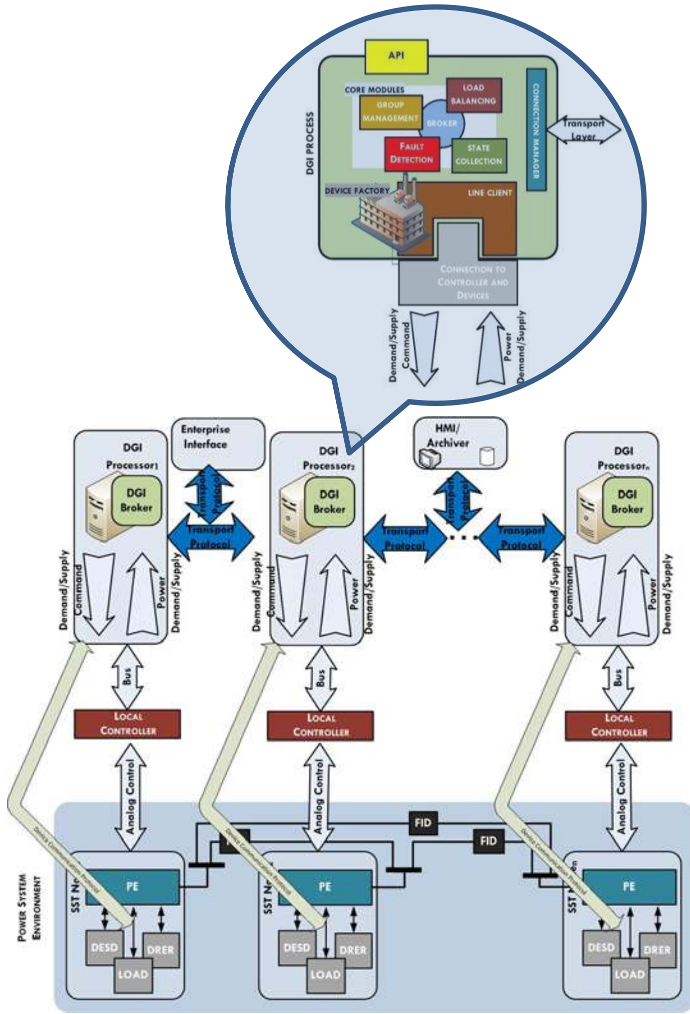

Fig. 1: The DGI Architecture

2.9.2 Technical Approach

Fig. 1 depicts the DGI which is a broker architecture that manages a peer-to-peer internet of things. In modern terms this is a Fog architecture [1]. Fog computing provides a system-level horizontal architecture to distribute resources and services of computing, storage, control, and networking anywhere along the continuum from the cloud to things. By extending these capabilities closer to the things that produce and act, Fog enables latency-sensitive computing to be performed in close proximity to the to the things it controls. Think of it as cloud on the ground.

Cloud-only models have serious latency, network bandwidth, and geographic focus challenges. Reliability and security are also significant challenges. By bringing the computation and communication closer to the distribution system, Fog computing reduces these challenges.

Over time, Fog and Cloud will converge into unified end-to-end platforms offering integrated services and applications from anywhere along the continuum from the Cloud to things. The same application developed and deployed for the Cloud will be able to run in the Fog and vice versa. It's not just computing or communications or storage or control; Fog supports all of these key capabilities in an integrated and distributed manner. Key to developing Fog computing are distributed algorithms that run on the devices in the Fog that receive and act on locally sensed information. Within the FREEDM system, localized energy management, configuration management, and volt/VAR control are secure Fog operations and long range planning and pricing are cloud applications. The Fog must be semantically-aware, understanding the physics of power, transportation, and environment coupled with psycho-socio dynamics.

2.9.3 FREEDM's Fog services

The Distributed Grid Intelligence (DGI) operating system architecture contains a 'broker' that integrates plug-in software modules (Fig. 1). These include a group manager, state collection, energy management and volt-VAR management subsystems. In this way, changes in the configuration of the FREEDM system can be reflected in the power management and state collection modules. The following gives further details on these components.

Broker

The broker runs as a process that manages individual POSIX threads that invoke the CBroker class which instantiates each software module. A ConnectionManager object maintains network connections with peer DGI nodes. This object tracks new and existing connections via the universally unique identifier (UUID) generated uniquely per-host when first executed. This UUID allows the ConnectionManager to uniquely map connections to a specific peer node tracked in the group manager. This allows for nodes entering and leaving the network due to transient failures and initial activation of the DGI.

The individual connections are managed by an event-triggered system that responds to message transmission, reception, and configurable timers. Each software module registers at runtime which types of messages it is interested in sending and receiving. Incoming messages are dispatched to the registered modules. Each message may contain more than one type of sub-message, allowing the modules managed by the broker to interact in a coordinated fashion. The incoming message is passed to the module message handlers in order that they were registered. Modules also handle outgoing messages, if needed. This is the case in the state collection module, as described below. In all cases, a prioritized selection of messages is delivered to their respective destinations, as directed.

Group Manager

The group manager maintains the state of the system regarding the status of each IEM node, active, disabled, requesting entry, and requesting departure from the FREEDM system. In the event of DGI node failure or complete system failure and recovery, the group manager collaborates with its peer DGI nodes to reconstruct the FREEDM system using the Invitation Algorithm of Garcia-Molina [2]. In this fashion, DGI nodes become plug-and-play members of the FREEDM microgrid.

State Collection

The state of the system consists of the states of each DGI, their software modules, and any messages in transit. The state collection module is invoked when a consistent state of the system is required (such as for fault diagnosis). The Chandy-Lamport [3] state collection algorithm is used to collect a logically consistent state (one in which causality between actions is preserved).

Fault Detection

DGI is responsible for detecting internal software and hardware faults and receiving reports and sending commands to/from the Integrated Fault Management (IFM) system of FREEDM. Fault detection uses the state collection algorithm to obtain a consistent system state and employs correctness predicates to determine correct/faulty behavior. If a fault is detected, the consensus system and group manager are contacted to initiate reconfiguration around the failed component. In effect, this feature is automated restoration. One example of an automated distribution system restoration algorithm is shown in [5],[6]. The use of digital controllers in this application and the use of electronic circuit interruption make possible a substantial increase in reliability at networked distribution system buses.

Load Balancing

The load-balancing module is a distributed application that schedules and balances the power load among DGI nodes. Load Balancing negotiates via message passing with IEM nodes within the FREEDM system to control individual SSTs to add or subtract power to / from a shared power interconnection bus, thereby balancing the power on the microgrid in a way to meet the net demand/supply [4]. Original targets are set by consensus among the DGI nodes.

Consensus System Economic dispatch problem (EDP) aims at minimizing the total generation cost while satisfying the system and devices constraints. The consensus system uses a variant of distributed agreement [7] to solve EDP in a distributed manner. In the consensus system, the IEM nodes uses local information to reach an approximate consensus on appropriate measures, such as incremental cost and system power imbalance. The estimated measures is used as a feedback mechanism to adjust local energy dispatch commands for each Distributed Energy Storage Device (DESD). With a tactical initial setup, eventually, all IEM nodes converge on to the appropriate consensus values and the energy dispatch commands reach the optimal operational points.

This consensus approach may be extended to include different operating scenarios including various disturbances and faults on the grid. For example, to address the uncertainties in Distributed Renewable Energy Resources (DRER) generations, a double-layer coordinated control approach based on consensus system has been used. It consists of two layers: the schedule layer and the re-dispatch layer. The schedule layer obtains an economic operation schedule based on 24-hour ahead forecast profile. The re-dispatch layer collects real-time generation profile and updates dispatch commands to satisfy real-time system requirement. The two-layer control framework corresponds to the day-ahead and real-time energy market, respectively [8].

Volt-VAR Control

Distributed Volt-VAR Control (VVC) advances this fundamental control component into a master/multiple slave relationship suitable for a non-SCADA environment.

2.9.4 Technological barriers and fundamental research

VVC is one of the main real-time control functions on a distribution system. Project focused on the development of decentralized control schemes for VVC. Decentralized schemes make use of the DGI to facilitate actual implementation, and thus achieve the main benefits of a decentralized control. The main challenge in developing a decentralized approach for a complex optimization problem like VVC is that there are only a few formal methods.

2.9.5 Unique Approaches

We have developed a gradient-based VVC scheme for the FREEDM Systems and tested it on a LSSS and HIL testbeds. In Y10, we focused on migrating the VVC to GEH system, which is the final goal. We have also extended the VVC scheme for a practical system which employs both the traditional voltage control devices such as voltage regulators (VRs) and the new devices such as SST. In this case, the goal for VVC is to minimize voltage variations while also avoiding the excessive operation of Voltage Regulators (VRs) and Cap Banks which may occur due to high variability in PV output. To achieve this, we make use of the fact that while the VRs are mainly designed to adjust the voltages, Cap Banks and Smart Inverters are mainly reactive power support devices for power factor correction. These features helps us to decompose the problem into two loops, a slower voltage control loop and a faster Var compensation loop. The proposed coordinated two-level VVC scheme is computationally efficient, easy for practical implementation, and accommodates the operating constraints.

The Volt compensation method employs a search-based method as the control actions are discrete and we have usually limited no of devices. The volt compensation method adopts a gradient-based method in which the control actions (Q_{inj} for the SSTs) are updated using a gradient of an objective function. We also used the gradient information to decompose the problem into a master-slave scheme. This facilitates implementing VVC in DGI, as one DGI node implements the master, and SSTs are grouped and managed by a few DGI nodes which serve as slaves.

The Volt Compensation scheme has been tested on the 7-node HIL testbed. This year the method will be tested on GEH. The coordinated VVC been tested using the 123 node system on the LSSS testbed.

2.9.6 Cyber-Physical Security

The FREEDM system is protected from security attacks and system failures by deriving secure algorithms for FREEDM management, including secure reputation-based energy management through static and dynamic invariants that govern system behavior. The reputation-based system governs the distributed calculation of economic dispatch under the DGI and removes a failing or compromised computational process if its computation diverges from that of its peers. Static invariants enforce rating constraints, such as line flow limits, as well as other operating range restrictions, and are also used to identify erroneous information via attestation. Dynamic invariants use the time required to transition among level sets of Lyapunov functions to determine and encode the minimum dwell time that guarantees stability in the DGI's switching of the system.

Key to the measurement of cyber-physical security is a measurement of the system's vulnerability. FREEDM was one of the early pioneers of cyber-physical security by measuring both the cyber and physical vulnerabilities through common information flows and their potential disruption. If a system is designed with an assumption of trusted devices, important information may be hidden, or to be precise, may be multiple security domain non-deducibility (MSDND) secure [9]. In Fig. 1, each SST, or even a subsystem within an SST, forms a security domain that exchanges information with other security domains. Without suitable redundancy, the information such as the state of variable within security domain SD-B is only known to security domain SD-A if SD-A trusts SD-B. Thus, if SD-B is breached, the intrusion cannot be detected. If instead there are sufficient redundant information flows among many security domains, information within SD-B may be deduced by SD-A through its valuation. Thus if SD-B is compromised, SD-A can identify the intrusion and isolate SD-B. These flows, are physical, cyber, and cyber-physical. In this way a trusted system is built up through the interactions of components. MSDND provides the measure of vulnerability by enumerating the number of secure paths that an intruder may exploit. Invariants provide the redundant information flows in FREEDM to reduce the number of MSDND secure paths and are used to locate compromised components through attestation [10].

2.9.7 Deployment

DGI's common code base has been installed on GEH and HIL across FSU, NCSU, and S&T. DGI integrates with openDSS to support large-scale systems, it integrates in real-time with the RTDS system, and it integrates with PSCAD for offline simulation work at a desktop. The reputation-based energy dispatch has been implemented within DGI and new attacks and defenses are developed against it. Fundamental work in Lyapunov level sets is continuing. VVC has been implemented in the HIL and, using the same code base, will be implemented in the GEH.

2.9.8 Fundamental Barriers and How They Were Addressed

The technological barriers in implementation are multiple languages, implementation platforms, and the challenges of fitting systems designed for SCADA control into a distributed environment. For the energy management algorithms, the fundamental barriers are relating mathematical computation and theory to distributed implementation within a physical system. These barriers are overcome by developing run-time semantics for these mathematical functions by innovation in what can be calculated within a distributed environment.

From a disciplinary aspect, one of the most challenging barrier has been the concept of a single code base deployed across multiple testbeds and the selection of standard testbeds and simulation platforms. FREEDM is mature enough to host distributed application development without “one-off” simulations, but getting buy-in is still a challenge, as is the concept of systems engineering of the entire project.

2.9.9 Unique Approaches:

FREEDM is built in a completely distributed manner and is self-organizing and self-governing and does not require a centralized coordinator. This is similar in concept to the emerging openFMB concept that unifies device to device communication to manage electric power systems. The approach has gained interest among utilities. S&T has an active project to understand the potential of deploying a Fog architecture within our local electric utility.

The consensus-based energy management module follows the completely distributed manner built in FREEDM. The computation burden of solving an optimization problem is distributed among IEM nodes. The computation and communication are managed in a quick and efficient way: in essence, each IEM nodes acquires its own measures, and starting from it, solves a local optimization problem and exchanges information with its neighbors. This distributed energy management approach is appealing to rural and remote distribution system, where there is no powerful center to manage various distributed energy resources. NCSU is working with local electric cooperatives to further develop and implement the distributed energy management approach in self-organizing microgrids.

Different engineering domains use different mathematical tools and techniques to express correctness. FREEDM uses invariants as the lingua franca between the cyber domain and all physical domains. Invariants encode correctness in a particular domain, such as power system voltage stability, as a logical function that may be evaluated in the cyber controller.

2.9.10 Scientific Breakthroughs:

The consensus-based energy management module promotes the control paradigm shift from centralized control to a completely distributed one. It highlights the following breakthroughs that is aligned with FREEDM’s goals.

1. Enabling Play-and-play: once a new device is connected in the system , e.g., a DRER or a DESD, it will be recognized by the neighboring IEM nodes and will be configured to participate in the energy management module.

2. Protecting privacy: The IEM nodes do not need to disclose their private information such as load profile, storage states or cost functions to other devices. Only estimations of global variables are exchanged among them.

Detecting misbehaving IEM nodes: A reputation-based neighborhood watch mechanism for validating data in a distributed way is being developed. The new method uses linear algebraic properties of the system discrete-time dynamics to detect false data of neighbors, that is, data inconsistent with the dynamics.

2.9.11 Technology Innovations:

One of the significant innovations from FREEDM is the concept of cyber-physical security. Often security is considered as an add-on with protecting the system by firewalls. A typical distribution system relies on establishment and maintenance of trust among components within a security domain. FREEDM takes a different approach by considering cyber, network, and physical interactions as information flows among untrusted components each within their own domain.

The novelty of the consensus-based energy management module is to estimate the system states based on local information. It uses a variant of well-established consensus algorithm, in which each IEM node instantiates a local estimation of the system states and coordinate with the neighbors. With a tactical initialization, the summation of all the local estimated information is preserved and exactly equal to the actual system states. The IEM nodes uses the local estimation to adjust its dispatch commands.

Another novelty of the consensus-based energy management module is to build an embedded monitoring system for the distributed system. The embedded security mechanism guarantees the outputs of the energy management module to be feasible in presence of misbehaving nodes. Borrowed from the watchdog concept in computer science, a reputation-based neighborhood watch mechanism is used to check the validity of the exchanged information. Mitigation methods are developed to eliminate the impacts of misbehaving nodes on the dispatch results.

Key to development of the cybersecurity and distributed energy management was the relation between the testbeds and the enabling technologies flowing back down the three plane hierarchy to drive basic science.

2.9.12 Validation of the Research:

The following paper pioneered the ideas of unified information flow as a security paradigm

Analysis of information flow security in cyber–physical systems, R Akella, H Tang, BM McMillin, International Journal of Critical Infrastructure Protection 3 (3-4), 157-173

The concept of peer-to-peer energy management first appeared in the following paper.

Distributed power balancing for the FREEDM system, R Akella, F Meng, D Ditch, B McMillin, M Crow, Smart Grid Communications (SmartGridComm), 2010 First IEEE International

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2.9.13 References

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10. T. Roth and B. McMillin, "Physical Attestation in the Smart Grid for Distributed State Verification," in *IEEE Transactions on Dependable and Secure Computing*, vol. 15, no. 2, pp. 275-288, March-April 1 2018. doi: 10.1109/TDSC.2016.2577021