Executive Summary

Project Name: GR-17-10

Distributed Energy Resources; Nasiri/Balda; A Distributed Autonomous Control Concept and Architecture for Microgrids.

The concept of microgrid is experiencing a significant growth to provide reliable and efficient power and integrate renewable and distributed energy resources. Emerging smart grid concept compels microgrids to adopt decentralized control methods. Centralized methods of operation are more susceptible to failure due to single point of failure held by the single controller. A decentralized microgrid control architecture is proposed, improving system reliability and avoiding control command transmission over the network. Delays in communications are unpredictable, uncertainty of data exchange delays leads to inaccurate modeling. As solution, Hardware-in-The-Loop platform is developed using real physical communication links and network components, and applying the concept of decentralization dynamically over a network of real-time controllers. The proposed system ensures reliable data exchange between controllers and microgrid components. The control concept is truly distributed and does not require a master or main controller. It can integrate load and generation forecasting as well as energy storage operation in order to improve unit commitment and performance. Reliability analysis of the proposed controller and microgrids will be conducted as part of the project. Case study on Fort Sill and UWM microgrids are adopted for testing and verification purposes.

Prof. Adel Nasiri at UWM and Prof. Juan Balda of University of Arkansas (UA) will collaborate to perform this project. Both investigators have worked extensively on microgrid concept and integration of power electronics-based sources in microgrids. The proposed work will create expertise within GRAPES on microgrid controls. The developed distributed control concept and analysis can also be applied to other systems, e.g. DC microgrids. The work will lead to more reliable control systems for microgrids and other electrical systems.
GRAPES Project Proposal
Award Year 2017

Project Detail

Project Name:
GR-17-10 A Distributed Autonomous Control Concept and Architecture for Microgrids

1. Project Description and Objectives:
Microgrids are the best tools to integrate distributed energy resources and connect to utility grid. The concept of microgrid is growing rapidly in various sectors including defense, commercial, industrial, and grid-connected. Microgrid control and controller are critically important to integrate inverter-based sources, manage system voltage and frequency, and provide high reliability. The goal of this project is to develop the concept of a true decentralized microgrid control architecture, implement, and test in a hardware-in-the-loop (HIL) setup at the University of Wisconsin-Milwaukee (UWM). The ultimate objective of the project is implement the controller for the UWM microgrid system. The detailed objectives of the proposed research tasks are:

- Development of true decentralized microgrid control architecture.
- Development of Hardware-in-the-Loop platform intended for complex microgrids studies related to their cyber-physical architectures.
- Communication delay impact analysis and state space modeling of delayed microgrid systems due to cyber transmission.
- Microgrid control architecture reliability analysis.
- Development of microgrid failure model over cyber-physical layer.

2. Background and Evaluation of State of the Art:
Control strategies for microgrids have been developed for the past decade in order to manage system voltage and frequency, apply seamless transfer, and support variable loads. Control of microgrids is largely different with control of a traditional power system due to limited energy storage capacity, lack of inertia, fast dynamics and short response time of inverter-based distributed resources, and a high degree of parametric and topological uncertainties [1].

Many significant efforts have been performed on design of decentralized control systems for microgrids. A proof of concept has been established in [2]. Decentralized control system with a master controller (or coordinator) is proposed, which is considered a single point of failure [3]. Control commands to power components are also generated locally, thus avoiding long distance command (based on the physical location of the controller). For a distributed system, the issue of communication delays can diminish the benefits of decentralization concept. Some other efforts have proposed simulated algorithms for self-coordination without considering the system delays and their impact on these algorithms [4], [5].

In the proposed effort, each source and intelligent load is equipped with a controller that has the total map of the system. The information of the system is shared between all the controllers. The roles of primary and secondary level controls of the microgrid are to maintain voltage and frequency, apply source commitment, improve efficiency, and to integrate various forecasting are implemented in each control. The system does not have a master controller and can continue to operate if any controller or component fails to function.

3. Proposed Novel Approach:
In the proposed distributed control algorithm, each controller runs the entire algorithm including peer controllers’ controls (based on inputs from local sensors and peers reports). For natural gas generators, synchronization before connection, breaker control, active/reactive power commands, and unit commitment following energy storage SOC are performed. For energy storage inverters, voltage/frequency regulation based on the operation mode of the microgrid, power commands, and charging/discharging are applied. For inverter-based sources, running on MPPT and operating breakers for isolation in case of emergency or frequent disturbing fluctuations are applied. Generation and load demand forecasting will also be integrated in the control algorithm for unit commitment and improving performance. Each controller commands its designated power source based on local sensing, peers status, and local output of the control algorithm. Others’ commands are buffered for verification purposes.
GRAPES Project Proposal
Award Year 2017

(diagnosing faults or performance degradation). The proposed true decentralized microgrid control architecture will provide the following properties:

- **Decentralized**: It suggests having multiple local controllers in order to achieve seamless transients during the operation and acts as if the system has one central controller.
- **Resource sharing**: every controller shares the status of its own DER with other controllers in real-time. This requires naming scheme that guarantees unique identification of each controller and its local DER.
- **Concurrency**: Each controller will have an up-to-date status of the whole system, especially for the inputs to the microgrid control algorithm running in each controller.
- **Scalability**: The architecture allows the microgrid to be scaled up or down in terms of the number of power components without affecting the operation or re-engineering the control algorithm.
- **Fault-tolerance**: The system maintains availability and operating at the minimum level of reliability. This also include the recovery process in case of faults and possible redundancy that may boost the reliability of the microgrid.

Figure 2 represents the proposed decentralized architecture. As illustrated, the decentralized architecture eliminates the centralized controller is replaced with more intelligent decentralized microgrid controller (DMGC).

### 3.1. Controller Concept

Design of a reliable decentralized control system will take into consideration three fundamental models:

**A. Controller model**

The proposed design of the control agents is shown in Figure 2. For simplicity, the design is virtually divided into three main units: Processing unit, where the main control logic algorithm is running, with the interrupt handling routines in standby mode in case of any system faults. Faults will be discussed on the following fundamental model. Additionally, the processing units contain data verification and consistency algorithms.

The memory unit interacts with the processing unit in order to manage buffered data and temporary log. It also provides peer controllers’ information as inputs to the control algorithm. Dynamic DER directory holds the power components object model. The communication model interacts with other peers and provides raw data of the whole system.

**B. Interaction Model:**

This model defines the necessary data to be exchanged between controllers, the way they interact, and the frequency of data transmission. Data traffic starts from the power system layer, where the components transmit their status data and measurements through the communication layer. Status data can be breaker status, device warnings or flags, measurements of voltage, active and reactive power, and frequency of each power component. Each controller receives data from its designated DER, validates the received information and synchronizes clocks. The control system layer is a combination of the distributed controllers, communication lines, and switching/routing devices in between.

**C. Failure model**

Failure model contains aspects that relate to system reliability and availability. Most importantly, designing a self-healing distributed control system relies mainly on the robustness of the recovery
algorithm in the interrupt routine. During normal operation, it is possible to reset the controller at any time going back to the normal operation with no failures reported. If power system fault is detected, the controller moves to system fault handling routine, which is basically checks the status flags reported by other controllers and removes certain DER from the dynamic directory; then the controller goes back seamlessly to normal operation.

3.2. Communication network

One major issue considered in this project is the communication delays and its impact on the true decentralized microgrid control operations [6]. The control cycle during normal operation of each controller is divided in five main steps. Receiving and broadcasting updates with peer controllers include communication delays, these delays can be interpreted as communication faults; which can lead to unnecessary controller state transition. Similarly, the control cycle during state transition requires updates broadcasting to ensure concurrency. This allows each controller to make the correct decision. However, the normal operation algorithm halts during self-healing process, but this time should be at minimum to prevent and reflection of this fault onto the microgrid operation.

3.3. System Testing and Results

For testing purposes, a Hardware-In-the-Loop (HIL) platform [7] has been developed to study microgrid operations with real physical communication layer. Figure 3 shows the schematic of the platform and hardware setup to apply the decentralized architecture shown in Fig. 1. A dedicated workstation running microgrid simulation model is equipped with multi-Ethernet ports, binding the model with a dedicated Ethernet port serves to avoid impractical network congestion. PSCAD is an ideal candidate for our platform. Accurate model interaction between power system components and loads with various control topologies is also a preferred feature in simulation that is available in PSCAD.

Microgrid controls in this platform are developed using the real-time module of the CompactRIO from National Instruments. Its capability to run in real-time interface mode serves the purpose of the platform. Additionally, CompactRIO has the capability to build and run the controller model. The test cases for the HIL setup will be Fort Sill microgrid and UWM microgrid.

![Figure 7. Laboratory HIL Platform Schematic and Laboratory HIL Setup.](image)

4. Potential Risks to Project Success:

Due to expertise of the project team and previous extensive work of the team on microgrid control, we do not anticipate major risks in achieving success in completion of this project.

5. Milestones for Mid-Project (Y1) and End of Project (Y2):

Year 1:
- A distributed microgrid control concept and architecture
- Hardware-in-the-loop implementation of the control concept
- Communication delay analysis
- Reliability analysis
- Two publications on the proposed concept and system.
- Possible IP development.

Year 2 (to be proposed in Nov 2017):
- Implementation of the controller on UWM microgrid.
6. References:


7. Project Description for REU Summer Program

Please provide the following:

REU Project Title:
Hardware-in-loop (HIL) implementation of distributed microgrid platform

REU Project Title Description:
In this project, a HIL system based on National Instrument Compact RIO devices will be developed to model a microgrid system. The actual microgrid will be simulated in PSCAD software environment. A distributed control algorithm will be implemented on this HIL platform to control the microgrid. Each microgrid component will have a controller, which communicates with component model in PSCAD over TCP/IP line. The platform will be used to test the distributed controller, evaluate reliability, and analyze impact of communication delays.
## Relevant Data and Metrics for Project

### A. Personnel

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<tr>
<th>Demographics</th>
<th>University</th>
<th>Title/Role</th>
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<tr>
<td>Project Leader</td>
<td>Adel Nasiri</td>
<td>UWM</td>
</tr>
<tr>
<td>Other Faculty</td>
<td>Juan Balda</td>
<td>UA</td>
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<tr>
<td>Postdoctoral Scholar</td>
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*Note: Only for Continuing Project Proposals*

### B. Products (Note: include only those that explicitly acknowledge NSF support)

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## Salaries and Wages

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## Direct Costs:

- Domestic Travel: $3400
- Foreign Travel: $0
- Materials and Supplies: $2500
- Services (Consultant/Computer/etc.): $0
- Facility Usage Fees: $0

Subtotal Direct Costs: $5,900.00

## Participant Costs:

- Graduate Assistant Tuition (waiver or payment): $15,392.17
- Participant Stipend (for example, for an REU student): $0
- Participant Support (only to support students in Stipend category): $0

Subtotal Participant Costs: $15,392.17

Total Project Cost: $97,321.66