Final Scientific/Technical Report

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Sponsoring Agency	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Lead Recipient:	University of Tennessee, Knoxville (UTK)
Project Team Members	EPB of Chattanooga, Electric Power Research Institute, Green Energy Corp, National Instruments, Tennessee Valley Authority
Project Title:	A Smart and Flexible Microgrid with a Low-cost Scalable Open-source Controller
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Public Executive Summary

This project aims at developing a community-based flexible microgrid (FMG) with smart grid features, including multiple utility feeders and dynamic boundaries that utilize intelligent switches and ultra-high-speed communication links already in a smart grid. The project also aims at developing a corresponding controller for such an FMG with low cost and high scalability. With distributed renewable energy resources (DERs) and the intelligent microgrid controller, the FMG will achieve aggressive emission reduction, increased energy use efficiency, and reliability improvement goals. The FMG and its controller design will be scalable for different geographic areas, load sizes, distributed generation source number and types, and even multiple MGs within a distribution electric power system. In order to achieve these project objectives, three main development tasks were carried out: FMG design, FMG controller development, and FMG controller testing. The fourth task was technology to market.

The project team worked closely to design and implement the concept of the flexible microgrid in a section of the electric distribution system in EPB of Chattanooga, TN. EPB is one of the pioneers among distribution utilities to implement smart grid technologies, such as fiber optical communication networks and intelligent switches with pulse-reclosing capabilities, into their distribution network. To meet the emissions reduction, energy use efficiency increase, and reliability improvement targets set forth by the team, two battery energy storage systems (BESS) and one backup generator was designed. The PV system owned by the Chattanooga Airport was also part of the FMG. A grounding transformer was also designed and installed in the FMG to provide a grounding source during islanded operation of the microgrid. In the duration of the project, the UTK team formed a set of microgrid design guidelines based on existing guidelines and literature, as well as engineering practices used during the project. The guidelines focus on the sizing and siting of FMG assets, placement of reclosers, protection system design, and grounding system design.

The second objective of the project is to develop a low-cost and scalable open-source controller for the FMG. The team surveyed existing microgrid control products offered in the market space and made additional innovations to the controller functions to support the operation of the FMG with *dynamic boundaries*. *Dynamic boundary* is a concept of a microgrid that can dynamically change its service area in islanded mode based on available DER generation and scheduling. The team has developed the following functions for the microgrid central controller (MGCC): 1) online topology identification, 2) model management, 3) finite state machine, 4) state estimation, 5) black start, 6) reconnection, 7) PQ balancing, 8) protection coordination, 9) energy management, 10) PV forecasting, 11) load forecasting, 12) datalogging, 13) communication. The controller is programmed using LabVIEW by National Instruments, and implemented into National Instruments' general-purpose programmable controllers, CompactRIOs.

The developed controller was extensively tested in four environments: algorithm validation in Matlab/Simulink, hardware-in-the-loop simulation using an Opal-RT real-time digital simulator and using the converter-based grid emulator developed in UTK (Hardware Test-Bed or HTB), and field testing at the Chattanooga Airport microgrid. A final version of the microgrid controller has been deployed in the Chattanooga Airport microgrid.

The project team has also worked towards bringing the technology developed in this project to market. In addition to deploying the FMG and its controller in EPB, the team. led by Green Energy Corp, also performed detailed cost analyses and competitive analyses of the microgrid controller. The team also hosted an online demonstration event to showcase some of the unique features in the FMG and its controller. Based on positive feedback from the audience and general market trend, the team will continue to make efforts to bring the developed technology to the broader market.

Acknowledgements

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Accomplishments and Objectives

This award allowed UTK and partners to demonstrate a number of key objectives. The focus of the project was on design and implementing a flexible microgrid with dynamic boundaries in the Chattanooga Airport and developing a low-cost, scalable and open-source controller.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1 Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: MG Planning and Design 1.1 Obtaining permits 1.2 Implementation of data ingestion software 1.3 Collect and analyze data 1.4 MG design 1.5 Design guideline development	Q3: Assets permission obtained EPB acquired permission from TVA to install BESS and additional PV. Completed 03/31/17. Q1: Software system upgrades installed in ingestion platform EPB purchased data center software and hardware and upgraded storage capacity. Completed 09/30/16. Q2: Required database structures implemented and tested Data tables created in database. Completed 12/31/16. Q2: Profile queries designed and tested Queries written to obtain load and generation data. Completed 12/31/16. Q3: Data collected and analyzed Load section data and PV generation data obtained from EPB data base. The load section profiles are analyzed. Completed 03/31/17. Q1: Designated area determined MG area identified. Critical loads determined with help from Chattanooga Airport. Delayed due to communication efforts with Chattanooga Airport. Completed 12/31/16. Q2: Operational objective defined and protection impact evaluated MG objectives, including emissions reduction, energy use efficiency increase, reliability improvement defined. MG protection issues and potential solutions analyzed. Completed 12/31/16.

	Q4: MG design completed MG assets, including BESS and backup generator, are sited and sized using optimization models, with objectives to meet resiliency requirements and minimize cost. Completed 06/30/17. Q5: MG performance evaluated and energy storage installed Performance was evaluated using historical data. BESS delivered on 01/22/18, interconnect complete March 2018. This milestone is delayed due to the lead time in BESS procurement. Completed 03/31/18. Q5: Go/No-Go checkpoint MG performance achieves targets using historical data. The project passes the checkpoint. 09/30/17. Q5: Transition MG requirements to EPB systems MG design approach was implemented on a feeder from EPB. Completed 09/30/17. Q6: Transition MG requirements to any utility Differences between EPB and typical distribution utilities identified and the design guideline was adapted accordingly to accommodate any utility in the U.S. Completed 12/31/17.
Task 2: Advanced MG Controller Research and Development 2.1 MG controller architecture and functionality determination 2.1.1 MG controller performance requirements definition and architecture design 2.1.2 Definition of MG controller functionality 2.2 MG control algorithms development and tested in simulation	Q1: Controller performance requirement determined and architecture designed Based on literature review and EPB system evaluation, the central hierarchical control architecture is selected. Completed 09/30/16. Q2: Controller functionality defined Commercial MG controller products surveyed. Controller functionality defined based on industry standards and project requirements. Completed 12/31/16. Q3: Generic simulation model of MG system built MG system model built in Matlab/Simulink, based on EPB system parameters. Completed 03/31/17. Q4: Control algorithm implementation in simulation and basic functionality test All controller function defined have been developed and tested using simulation. Completed 06/30/17.

2.2.1 Build generic simulation model of MG 2.2.2 Implement and test control algorithms in simulation 2.2.3 Simulation model adaptation and control algorithm test in transition and fault conditions 2.2.4 Build and test MG simulation model with different assets 2.3 Control implementation	Q5: Simulation test completed under transition and fault conditions Planned islanding, unplanned islanding and resynchronization functions are tested in Matlab/Simulink. Completed 09/30/17. Q5: MG controller test in simulation completed in different MG systems. MG controller tested in another feeder in EPB. Completed 09/30/17. Q6: MG control algorithm implementation completed MG control algorithm implemented to NI's CompactRIO platform. Completed 12/31/17. Q6: Go/No-Go checkpoint All defined functions implemented in controller. Project passes go/no-go checkpoint. Completed 12/31/17.
Task 3: MG System and Controller Testing 3.1 Test preparations 3.2 Real-time HIL test 3.2.1 HIL test setup 3.2.2 HIL testing 3.3 Hardware Test-bed test 3.3.1 Hardware Test-bed upgrade 3.3.2 Test on Hardware Test0bed 3.4 Field test in EPB system 3.4.1 Preliminary integration test 3.4.2 MG controller installation 3.4.3 Field test for MG and MG controller	Q6: Test preparations completed Test scenarios defined. Communication structures proposed. Completed 12/31/17. Q7: HIL test setup completed EPB microgrid model transferred onto Opal-RT real-time HIL simulation platform. Completed 03/31/18. Q10: HIL test completed All functions defined in the microgrid central controller tested in Opal-RT real-time HIL simulation platform. Completed 12/31/18. Q7: Hardware Test-bed upgrade completed Hardware Test-bed upgraded to represent FMG circuit and controllable switches. Completed 03/31/18. Q11: Hardware Test-bed test completed All functions defined in the microgrid central controller have been tested in the Hardware Test-bed platform. The milestone was delayed due to protection device modeling and testing. Q5: Preliminary integration test completed

3.5 Test data analysis and finalize MG design and MG controller	Communication tested between EPB SCADA and MGCC, as well as MGCC and MGLC. Completed 09/30/17. Q6: MG controller installation completed MG controller installed in the EPB system. Communication with EPB SCADA set up. Delayed due to delay in battery installation and contract negotiation with National Instruments. Completed 03/31/18. Q11: Test cases completed UTK team visited EPB on 03/06/19 and 03/27/19 to conduct controller function tests in grid-connected mode. Completed 03/31/19. Q12: Test results analyzed and applied for MG design and MG controller improvement Interruption Cost Estimator values the improvement in reliability from microgrid technology at $1.2M (2019) over the next 20 years. Resolved issues from MG testing and open questions are documented. Completed 06/30/19.
Task 4: Technology to Market 4.1 Pathways to adoption and IP arrangement 4.2 Competitive analysis 4.3 Techno-economic analysis 4.4 MG controller software packaging and release 4.5 Distribution plan development and execution 4.6 Define controller hardware requirements 4.7 Commercialization activity	Q2: Commercialization strategy plan developed and approved The Commercialization strategy plan is created as a working document. Completed 12/31/16. Q3: IP arrangement finalized IP arrangement document has been prepared and signed by all parties. Completed 03/31/17. Q5: Competitive analysis completed Competitive analysis created including value proposition, competitor review, market segmentation and strategies. Q8: Techno-economic analysis completed Analysis includes basic inventory of costs specific to the microgrid controller. Completed 06/30/18. Q8: Beta release Beta version maintained in repository and provided to EPB (Beta Customer) using a beta license. Completed 06/30/18. Q8: Documented distribution plan

	The plan includes the description of the code base, documents and basic hardware and software requirements. Completed 06/30/18. Q9: Controller hardware requirement documents Completed 09/30/18. Q12: Marketing plan executed The basic version of the controller was released open-source to GitHub. Completed 06/30/19.
Task 5: FMG design technology development 5.1 Smart switch siting strategy for FMG 5.2 Coordinated grounding design	Q13: Siting strategy developed Magnetizing inrush currents from distribution transformers during switching simulated. Completed 09/30/19. Q15: FMG grounding scheme designed Grounding schemes are compared: grounding transformer, DER transformer, controllable DER transformer. Detailed grounding requirements summarized. Completed 03/31/20. Q15: Design guideline updated Updated design flowchart, smart switch placement considering transient stability requirements, added list of common design requirements and referenced standards. Added protection and grounding system design. Completed 06/30/20.
Task 6: FMG controller enhancement 6.1 Control function update to support multiple energy sources at different locations 6.2 Protection scheme development 6.3 Controller enhancement	Q13: Dynamics model + Control specifications Fresh simulation model based on Taxonomy Feeders built. Completed 09/30/19. Q14: Controller designed and implemented Controller modified to allow multiple sources. Updated functions tested in simulation. Completed 12/31/19. Q15: Control and protection validation Protection scheme enhanced to protect microgrid with multiple sources at different locations and under asymmetrical faults. Completed 03/31/20. Q15: FMG controller implementation Updates to the controller algorithm has been implemented into NI CompactRIO.

Task 7: Test cases defined 7.1 HIL test on OPAL-RT 7.2 Test on HTB 7.3 FMG fully functional in EPB and tested	Q14: HIL simulation circuit updated HIL model updated based on new Simulink model. Completed 12/31/19. Q16: Controller tested in HIL platform Controller tested with multiple sources microgrid in HIL platform. Completed 06/30/20. Q15: HTB upgraded HTB configuration updated to emulate additional source at different location. This milestone has been delayed by one quarter due to lab shutdown in light of the pandemic. Completed 06/30/20. Q17: Controller tested in HTB platform Updated controller tested in Hardware Test-bed. Completed 09/30/20. Q13: Generator selected Stowers/CAT has lowest bid and met specifications in the Request for Proposal process and has been selected as the vendor. Contract signed on 02/26/20. Q16: Generator installed and commissioned Installation and commissioning process delayed due to pandemic. Completed 12/31/20. Q22: Controller tested in EPB system The team conducted several remote/online and on-site field tests after vaccines for COVID-19 became available. The final test was conducted in October 2021. Black start, PQ balance, reconnection functions have been tested in the field. Completed 12/23/21.
Task 8: Technology to Market (second phase) 8.1 Quantify and benchmark of controller deployment cost 8.2 Update controller software for release	Q15: Deployment cost quantified Updated hardware and software cost analysis, competitive analysis, and open source strategy. Completed 03/31/20. Q17: Open source controller released Source code uploaded to Github. Completed 09/30/20. Q22: FMG ready for demonstration Due to social distancing recommendations, the demonstration of the FMG was changed to an online event, held

8.3 FMG showcase in EPB	

Project Activities

This project focuses on the design and implementation of a flexible microgrid with dynamic boundaries, along with a low-cost, scalable and open-source controller. The team used innovative control algorithms and conducted rigorous testing across multiple simulation and hardware-in-the-loop platforms to validate the control approach and overall controller performance. The outputs of the project are a guideline for designing microgrids with dynamic boundaries, and a prototype flexible microgrid controller that has been deployed into the field.

The project received a no-cost extension at the end of Q12 (2019'Q3), and modified milestones on 08/09/2019, and another no-cost extension due to the COVID-19 pandemic.

Project Outputs

A. Journal Articles

Jiaojiao Dong, Lin Zhu, Yu Su, Yiwei Ma, Yilu Liu, Fred Wang, Leon Tolbert, Jim Glass, Lilian Bruce, Battery and backup generator sizing for a resilient microgrid under stochastic extreme events, *IET Generation, Transmission & Distribution,* (2018), DOI: 10.1049/iet-gtd.2018.5883

Tianqi Liu, Xiaotong Hu, Yiwei Ma, Yu Su, He Yin, Fred Wang, Leon Tolbert, Yilu Liu, Two-stage energy management system for distribution network under defensive islanding, *IET Generation, Transmission & Distribution,* 9 (2019), DOI: 10.1049/iet-gtd.2018.7026.

He Yin, Yiwei Ma, Yu Su, Fred Wang, Yilu Liu, Leon Tolbert, Xiaotong Hu, Jim Glass, A hierarchical control system for a flexible microgrid with dynamic boundary: design, implementation and testing, *IET Smart Grid*, (2019), DOI: 10.1049/iet-stg.2019.0115.

Xiaotong Hu, Tianqi Liu, Chuan He, Yiwei Ma, Yu Su, He Yin, Fred Wang, Leon Tolbert, Shungliang, Wang, and Yilu Liu, Real-time power management technique for microgrid with flexible boundaries, *IET Generation, Transmission & Distribution*, vol. 14, issue 16, 3161-3170 (2020), DOI: 10.1049/iet-gtd.2019.1576

He Yin, Lin Zhu, Yiwei Ma, Chengwen Zhang, Yu Su, Dingrui Li, Ishita Ray, Yilu Liu, Fred Wang, and Leon Tolbert, Planned islanding algorithm design based on multiple sub-microgrids with dynamic boundary, *IEEE Open Access Journal of Power and Energy*, vol. 8, 389-398 (2021), DOI: 10.1109/OAJPE.2021.3115713.

Lin Zhu, Chengwen Zhang, He Yin, Dingrui Li, Yu Su, Ishita Ray, Jiaojiao Dong, Fred Wang, Leon Tolbert, Yilu Liu, A smart and flexible microgrid with a low-cost scalable open-source controller, *IEEE Access*, vol.9, pp. 162214-162230, 2021, doi: 10.1109/ACCESS.2021.3131995.

B. Papers

Yiwei Ma, Xiaotong Hu, He Yin, Lin Zhu, Yu Su, Fred Wang, Leon Tolbert, Yilu Liu, Real-time control and operation for a flexible microgrid with dynamic boundary, *IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, OR 5158-5163 (2018).

Shuying Zhen, Yiwei Ma, Fred Wang, Leon Tolbert, Operation of a flexible dynamic boundary microgrid with multiple islands, *IEEE applied power electronics conference and exposition (APEC),* Anaheim, CA 548-554 (2019)

Dingrui Li, Yiwei Ma, Chengwen Zhang, He Yin, Ishita Ray, Yu Su, Lin Zhu, Fred Wang, and Leon Tolbert, Development of a converter based microgrid testing platform, *IEEE Energy Conversion Congress and Exposition (ECCE)*, Baltimore, MD, 6294-6300 (2019).

C. Media Reports

“Chattanooga Airport and Partners Plan ‘Dynamic Boundaries’ Microgrid”, https://microgridknowledge.com/airport-microgrid-chattanooga/, March 26, 2018, retrieved March 3, 2022.

“Next phase for Chattanooga’s smart grid: an airport microgrid”, https://energynews.us/southeast/next-phase-for-chattanoogas-smart-grid-an-airport-microgrid/, March 14, 2018, retrieved March 3, 2022.

“Chattanooga’s airport to become microgrid test ground”, https://www.smart-energy.com/industry-sectors/energy-grid-management/chattanoogas-airport-microgrid-test/, March 18, 2018, retrieved March 3, 2022.

D. Invention Disclosures

A Scalable Control System for Networked Community-Based Microgrids with Dynamic Boundary, 10/21/2020, S-163236.

An Inverter-Based Grounding Scheme for Microgrids, 07/13/2020.

A Controllable Distributed-Energy-Resource (DER) Transformer-Based Grounding Scheme for Microgrids, 07/13/2020.

A Scalable Controller for Community Based Microgrid with Dynamic Boundary, 02/21/2018, S-143331.

E. Websites Featuring Project Work Results

Github repository. https://github.com/GeniusMicrogrid/DynaMic_Basic. Retrieved March 4, 2022.

Video recording of field demonstration. https://www.youtube.com/watch?v=0sXiijoANBk. Retrieved March 4, 2022.