Vanderbilt University
Final Scientific/Technical Report
Resilient Information Architecture Platform for Smart Grid (RIAPS)
DE-AR0000666

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Sponsoring Agency	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Lead Recipient:	Vanderbilt University
Project Team Members	North Carolina State University, Washington State University
Project Title:	Resilient Information Architecture Platform for Smart Grid
Program Director:	Dr. Mario Garcia-Sanz
Principal Investigator:	Dr. Gabor Karsai
Contract Administrator:	Madeline DeFreitas
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This Report contains no Protected Data.

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Public Executive Summary

A number of emerging trends will substantially alter the operation and control of the electric grid over the next several decades. These trends include ensuring resiliency under severe weather events, increasing integration of renewable electricity generation, supporting changing electricity demand patterns, and the improving cost effectiveness of distributed energy resources. To address these challenges, the future "Smart Grid" management will need to transition from centralized to *coordinated distributed control paradigm*. Reliable operation of the Smart Grid depends on distributed intelligence realized through software applications that run on distributed computing devices attached to the power system to collect data and collaboratively manage resources. However, much of the existing software for Smart Grid-enabled devices is either proprietary or developed with custom solutions, which limits interoperability among the heterogeneous devices and hinders the ability to manage system-level reliability, security, and resiliency requirements. Additionally, this approach makes Smart Grid applications hard to maintain, evolve, verify, and replace; resulting in high development and deployment costs. Further development of the Smart Grid requires a reusable software base-layer to move from hard-coded functionality to a plug-and-play architecture capable of managing system-level objectives and constraints in addition to providing consistent common services across heterogeneous devices and applications.

Vanderbilt University, in collaboration with North Carolina State University and Washington State University has developed a foundation 'software platform' for developing and deploying robust, reliable, effective and secure software applications for the Smart Grid. The Resilient Information Architecture Platform for the Smart Grid (RIAPS) provides core services for building effective and powerful smart grid applications. It offers unique services for real-time data dissemination, fault tolerance, and coordination across apps distributed over the network. The platform allows plug-

and-play architecture by providing a software layer that isolates the hardware details making software applications portable across multiple devices and enabling interoperability among heterogeneous devices and applications. Additionally, the RIAPS is supported by a model-driven development toolchain to reduce the software development effort. The platform allows apps to be upgraded and dynamically reconfigured in the field and enables a marketplace of hardware device vendors, app developers, and end users to sell and buy products and services that can interoperate. In summary, RIAPS is a software layer that supports Smart Grid apps, as shown on Figure 1.

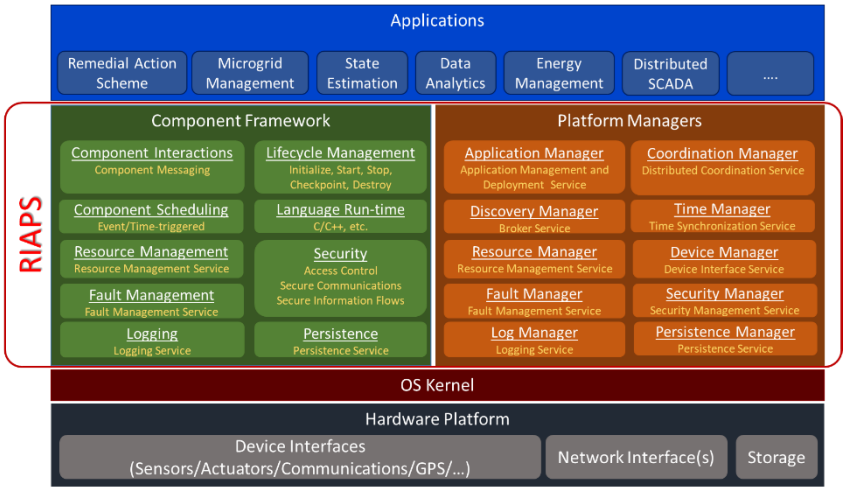

Figure 1: RIAPS Architecture

The research team has developed, prototyped, and demonstrated the platform using an open source code base. The team has also constructed representative open source energy management software apps that demonstrated the effectiveness and dependability of the system, while offering a starting point for commercial implementations. The team expects the platform to become an open-source industry standard on which Smart Grid applications can reliably run, much in the same way Android and iOS have become industry standard platforms for smartphones. To that effect, the platform already became an open source project, under the Linux Foundation Energy Foundation.

Acknowledgements

The research documented in this final report has been supported by DOE ARPA-E under contract DE-AR0000666. The guidance of the two Program Directors for the project: Dr. Sonja Glavaski and Dr. Mario Garcia-Sanz has been essential for the success and the results of the project. The three universities participating in the project have provided financial support in the form of cost sharing. The project team included three Co-Principal Investigators: Dr Abhishek Dubey (Vanderbilt University), Prof Srdjan Lukic (NCSU), and Prof Anurag Srivastava (WSU), whose leadership on the project are acknowledged. Finally, and most importantly, the effort of all project participants: research scientists, research engineers, postdocs, and graduate students are hereby recognized.

Accomplishments and Objectives

This award allowed Vanderbilt University, North Carolina State University, and Washington State University to demonstrate a number of key objectives. The focus of the project was on building and demonstrating the capabilities of a 'Resilient Information Architecture Platform': an 'operating system' for Smart Grid 'apps'. The project has developed the software platform (that has been open sourced), and demonstrative applications in three areas: (1) Remedial Action Schemes (WSU), (2) Microgrid Control Technology (NCSU), and (3) Energy Management (NCSU). All objectives of the proposed project have been achieved.

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 and Milestones	Actual Performance
Program Element 1: Analysis, Design, Documentation	
Task 1.1: Initial analysis and design, code base selection	
Milestone 1.1.1: Analysis results and initial design are documented, code base selected	Completed, documented in report titled 'Analysis Results and Initial Design of the Resilient Information Architecture Platform for the Smart Grid (RIAPS)'
Task 1.2: Test plan development for the initial capability	
Milestone 1.2.1: Test plan for initial capability developed.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Initial Design Capability Test Plan'.
Task 1.3: Literature and industry survey	
Milestone 1.3.1: Literature and industry survey completed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Literature and Industry Survey'
Task 1.4: Analysis and Design for Enhanced Capability	
Milestone 1.4.1: Analysis results and design for enhanced capability are documented.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Analysis and Design for Enhanced Capability'
Task 1.5: Test plan development for the enhanced capability	
Milestone 1.5.1: Test plan for the enhanced capability developed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Enhanced Capability Test Plan'
Task 1.6: Continuing Analysis and Design (1) : secure deployment and communications	
Milestone 1.6.1: Analysis results and design for supporting secure deployment and secure communications are documented.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Analysis and Design for Secure Deployment and Secure Communication'
Task 1.7: Test plan development for the advanced capability with basic security features	

Milestone 1.7.1: Test plan for advanced capability: basic security features developed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Test Plan for Secure Deployment and Secure Communication'
Task 1.8: Continuing Analysis and Design (2) : secure information flows	
Milestone 1.8.1: Analysis results and design for supporting secure information flows among applications are documented.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Analysis and Design for Secure Information Flows Among Applications'
Task 1.9: Test plan development for the advanced capability with advanced security features	
Milestone 1.9.1: Test plan for advanced capability: advanced security features developed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Test Plan Secure Information Flows Among Applications'
Task 1.10: Final documentation	
Milestone 1.10.1: Final documentation for the platform completed.	Completed. Final documentation of the project is available on https://riaps.github.io/ . Code base is open source, available from https://github.com/RIAPS Project website: https://riaps.isis.vanderbilt.edu/
Program element 2: **Component Framework: Detailed Design, Implementation, Verification**	
Task 2.1: Initial Capability Component Framework: Design and implementation	
Milestone 2.1.1: Development environment, build system, testing environment is set up	Development environment is Ubuntu Linux, build system is Jenkins, test system is hand-crafted. The first two are industry-standard tools.
Milestone 2.1.2: Initial capability support for component interactions and component execution.	Completed, documented in report titled 'RIAPS Initial Capability Component Interactions and Component Execution Testing'
Milestone 2.1.3: Initial capability support for component lifecycle.	Completed, documented in report titled 'RIAPS Initial Capability Component Lifecycle Testing'
Milestone 2.1.4: Demonstration of a simple application.	Simple application: a transactive energy controller has been developed and demonstrated.
Task 2.2: Enhanced Capability Component Framework: Design and implementation	
Milestone 2.2.1: Enhanced Capability support for resource and fault management	Designed, developed, and tested a resource management approach. Example tests are included in the code base.
Milestone 2.2.2: Enhanced Capability support for time-sensitive messaging	Designed, developed, and tested an approach to time sensitive messaging.
Milestone 2.2.3: Demonstration of an enhanced application.	Developed and demonstrated an enhanced application: a transactive energy management application with blockchain, running on 10 nodes.

Task 2.3: Advanced Capability Component Framework: Design and implementation	
Milestone 2.3.1: Advanced Capability support for basic security features: secure deployment and secure communications on the component level	Designed, developed, and tested basic security features. Tests results have been documented.
Milestone 2.3.2: Advanced Capability support for advanced security features: secure information flows on the component level	Designed, developed, and tested advanced security features. Tests results have been documented.
Milestone 2.3.3: Demonstration of an advanced application.	Developed and demonstrated an advanced application: a load shedding (energy management) application, running on 32 nodes.
Task 3: **Platform Services: Detailed Design, Implementation and Verification**	
Task 3.1: Initial Capability Platform Services: Application deployment, device interfaces, and time synchronization	
Milestone 3.1.1: Design document for the Initial Capability Platform Services: Application deployment, device interfaces, and time synchronization is completed	Completed, documented in report titled 'RIAPS Initial Capability Platform Services'
Milestone 3.1.2: Initial Capability support for component application deployment in the form of deployment service is functional.	Completed, documented in report titled 'RIAPS Initial Capability Component Application Deployment Testing'
Milestone 3.1.3: Initial Capability support for device interfaces is functional.	Completed, documented in report titled 'RIAPS Initial Capability Device Interface Testing'
Milestone 3.1.4: Initial Capability support for time synchronization in the form of time synchronization service is functional	Completed, documented in report titled 'RIAPS Initial Capability Time Synchronization Testing'
Milestone 3.1.5: Demonstration of a simple application.	Simple application: a transactive energy controller has been developed and demonstrated.
Task 3.2: Enhanced Capability Platform Services: Fault Detection, Isolation, and Recovery and Distributed Coordination	
Milestone 3.2.1: Design document for the Enhanced Capability Platform Services: fault management service and distributed coordination service completed.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Detailed Design for Enhanced Capability Fault Management and Distributed Coordinated Services'
Milestone 3.2.2: Enhanced Capability support for fault detection, isolation, recovery in the form of a fault management service implemented	Designed, developed, and tested an approach to fault detection and, isolation, and recovery. Algorithms have been integrated into the 'deployment manager' service.
Milestone 3.2.3: Enhanced Capability support for distributed coordination in the form of a coordination service implemented	Completed, documented in report titled 'RIAPS Enhanced Capability Testing'
Milestone 3.2.4: Demonstration of an enhanced application.	Developed and demonstrated an enhanced application: a transactive energy management application with blockchain, running on 10 nodes.
Task 3.3: Advanced Capability Platform Services: Support for Security Features	
Milestone 3.3.1: Design document for the Advanced Capability	Completed, documented in report titled 'Resilient

Platform Services: support for secure deployment and secure communications completed.	Information Architecture Platform for the Smart Grid (RIAPS) Advanced Capability Platform Services: Support for Secure Deployment and Secure Communication'
Milestone 3.3.2: Advanced Capability support for secure deployment and secure communications in the form of a security management service is completed.	Designed, developed, and tested an approach to secure deployment and secure communications. Algorithms have been integrated into the deployment service and the component framework.
Milestone 3.3.3: Design document for the Advanced Capability Platform Services: support for secure information flows completed.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Advanced Capability Platform Services: Support for Secure Information Flows'
Milestone 3.3.4: Enhanced Capability support for secure information flows in the form of a security management service	Designed, developed, and tested an approach to secure deployment and secure communications. Algorithms have been integrated into the component framework and deployment service.
Task 3.4: Validate proper functionality of combined services.	
Milestone 3.4.1: Proper functionality of combined services is validated.	Using the advanced application as an example, the combined capabilities: resource and fault management and security support have been validated through extensive testing.
Milestone 3.4.2: Demonstration of an advanced application.	Developed and demonstrated an advanced application: a load shedding (energy management) application, running on 32 nodes.
Task 4: **Development toolchain design, implementation, verification**	
Task 4.1: Model-driven design tools for Initial Capability: domain-specific modeling language, code generators, and deployment engine	
Milestone 4.1.1: Support for Initial Capability: domain-specific modeling language and code generators.	Completed, documented in report titled 'RIAPS Initial Capability DSML and Code Generators Testing'
Milestone 4.1.2: Support for Initial Capability: model-driven deployment engine.	Completed, documented in report titled 'RIAPS Initial Capability Model-Driven Deployment Testing'
Milestone 4.1.3: Demonstration of a simple application.	
Task 4.2: Model-driven design tools for Enhanced Capability: support for resource and fault management, and integration with another model-driven tools: Simulink/Stateflow.	
Milestone 4.2.1: Support for Enhanced Capability: supporting resource and fault management by the model-driven development environment.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Resource and Fault Management Support in the Model-Driven Development Environment'
Milestone 4.2.2: Support for Enhanced Capability: supporting integration with other model-driven development tool: Simulink/Stateflow.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Simulink-based Application Design and Development'
Milestone 4.2.3: Demonstration of an enhanced application.	Developed and demonstrated an enhanced application: a transactive energy management

	application with blockchain, running on 10 nodes.
Task 4.3: Model-driven design tools for Advanced Capability: support for security features; engineering, commissioning, and maintenance.	
Milestone 4.3.1: Support for Advanced Capability: supporting engineering, commissioning, and maintenance of applications.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Advanced Capability Platform Services: Application Management and Deployment'
Milestone 4.3.2: Support for Advanced Capability: supporting security features for applications.	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Support for Advanced Security Features'
Milestone 4.3.3: Demonstration of an advanced application.	Developed and demonstrated an advanced application: a load shedding (energy management) application, running on 32 nodes.
Program element 5: **Representative Applications Development and Evaluation**	
Task 5.1: Specification for coordinated microgrid islanding application	
Milestone 5.1.1: Specification for coordinated microgrid islanding application delivered	Completed, documented in report titled 'Specification for Coordinated Microgrid Islanding Application on a RIAPS Platform'
Task 5.2: Prepare verification plan for coordinated microgrid islanding application	
Milestone 5.2.1: Verification plan for coordinated microgrid islanding application delivered	Completed, documented in report titled 'Verification Plan for Coordinated Microgrid Islanding on a RIAPS Platform'
Milestone 5.2.2: Simulation based demonstration of an early prototype of the microgrid islanding application	Designed, developed, and tested the microgrid islanding application against an OPAL-RT simulation. Application has been demonstrated at the ARPA-E Energy Innovation Summit.
Task 5.3: Develop and deploy microgrid application in real-time simulation	
Milestone 5.3.1: Microgrid application for use in real-time simulation completed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Develop and Deploy Microgrid Application in Real-Time Simulation'
Task 5.4: Validation of RIAPS platform time synchronization capability	
Milestone 5.4.1: Benchmark RIAPS time-synchronization capability	Demonstrated in the lab and documented in H. Tu et al., "An Adaptive Interleaving Algorithm for Multi-Converter Systems," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2018, pp. 1-7, doi: 10.1109/PEDG.2018.8447801.
Task 5.5: Validation of controller hardware-in-the-loop RIAPS deployment	
Milestone 5.5.1: Controller hardware-in-the-loop deployed in	Demonstrated in the lab and documented in H. Tu, Y.

RIAPS and validated with real-time simulation	Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, "Resilient Information Architecture Platform for the Smart Grid: A Novel Open-Source Platform for Microgrid Control," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9393-9404, Nov. 2020, doi: 10.1109/TIE.2019.2952803.
Task 5.6: Validation of microgrid-in-the-loop RIAPS deployment	
Milestone 5.6.1: Preliminary demonstration of Microgrid-in-the-loop RIAPS deployment with real-time simulation and industrial hardware	Demonstrated in the lab and documented in H. Tu, Y. Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, "Resilient Information Architecture Platform for the Smart Grid: A Novel Open-Source Platform for Microgrid Control," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9393-9404, Nov. 2020, doi: 10.1109/TIE.2019.2952803.
Milestone 5.6.2: Final demonstration of Microgrid-in-the-loop RIAPS deployment validated with real-time simulation and industrial hardware	Demonstrated in the lab and documented in H. Tu, Y. Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, "Resilient Information Architecture Platform for the Smart Grid: A Novel Open-Source Platform for Microgrid Control," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9393-9404, Nov. 2020, doi: 10.1109/TIE.2019.2952803.
Task 5.7: Develop specification for coordinated response based RAS	
Milestone 5.7.1: Specification for coordinated response based RAS completed	Completed, documented in report titled 'Specification for Coordinated Response Based RAS Applications on RIAPS Platform'
Task 5.8: Algorithm development for coordinated response based RAS	
Milestone 5.8.1: Algorithm or for coordinated response based RAS completed	Completed, documented in report titled 'Distributed Remedial Action Schemes'
Task 5.9: Algorithm development for decentralized state estimation (DSE) to support RAS	
Milestone 5.9.1: Obtain use case and future plan from IAB with data requirements and implementation architecture	Completed, documented in report titled 'Test Cases for Remedial Action Scheme' submitted 10/2016
Milestone 5.9.2: Develop test case data using the lab similar to use case provided by industry partner and validate with industry	Completed, documented in report titled 'Test Cases for Remedial Action Scheme' submitted 01/2017
Milestone 5.9.3: Algorithm for DSE completed	Completed, documented in report titled 'Distributed Linear State Estimation'
Task 5.10: Development of decentralized coordination and computational framework to support decentralized RAS algorithms	
Milestone 5.10.1: Decentralized coordination and computation framework completed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Decentralized Coordination and Computation Framework'
Task 5.11: Validation of RAS and DSE in real time	
Milestone 5.11.1: Real Time Modeling of RAS and DSE algorithms and architecture	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid

	(RIAPS) Real Time Modeling of RAS and DSE Algorithms and Architecture' submitted 11/2017
Milestone 5.11.2: RAS and DSE validated with digital simulator	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Real Time Modeling of RAS and DSE Algorithms and Architecture' submitted 04/2018
Task 5.12: Validation of RAS with RIAPS deployment	
Milestone 5.12.1: Integration of RIAPS platform with real time testbed	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Real Time Modeling of RAS and DSE Algorithms and Architecture' submitted 09/2018
Milestone 5.12.2: RAS and DSE validated with RIAPS deployment	
Program element 6: Technology Transition	
Task 6.1. : Technology to Market plan development and updates	
Milestone 6.1.1: Technology to Market plan: Preliminary T2M plan	Completed, documented in report titled 'RIAPS IAB Charter'
Milestone 6.1.2: Technology to Market plan: (1) Novel Capabilities, (2) Pathways to adoption	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Technology to Market Plan Novel Capabilities and Pathways to Adoption'
Milestone 6.1.3: Technology to Market plan: Stakeholder analysis	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Stakeholder Analysis'
Milestone 6.1.4: Technology to Market plan: Competitive analysis	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Competitive Analysis'
Milestone 6.1.5: Technology to Market plan: Business model	
Milestone 6.1.6: Technology to Market plan: Post ARPA-E funding (A)	Developed an approach to post ARPA-E funding, reported in quarterly reports.
Milestone 6.1.7: Technology to Market plan: Post ARPA-E funding (B)	Developed an approach to post ARPA-E funding, reported in quarterly reports. Established contact with Linux Foundation Energy Foundation.
Task 6.2: Technology to Market progress updates	
Milestone 6.2.1: Technology to Market update: (1) Qualified T2M contact, (2) Industrial advisory board	Selected staff engineer as T2M contact, responsible for contact w/ IAB members, and maintaining connections to industry.
Milestone 6.2.2: Technology to Market update: Industrial advisory board established	Organized IAB, held yearly meetings to inform board about project progress.
Milestone 6.2.3: Technology to Market update: (1) Demonstration of capabilities and applications, (2) IP arrangement	Demonstrated early results to IAB. Developed IP policy: by common agreement software developed for the project will be open source.
Milestone 6.2.4: Technology to Market update: Strategic decisions	Developed and documented initial decisions for marketing.
Milestone 6.2.5: Technology to Market update: Preliminary results	Documented preliminary results and how users can benefit.
Milestone 6.2.6: Technology to Market update: Final assessment	Developed and documented first version of

(A)	assessment.
Milestone 6.2.7: Technology to Market update: Final assessment (B)	Developed and documented second version of assessment.
Task 6.3: Technology Dissemination, Demonstration, and Deployment	
Milestone 6.3.1: Technology Dissemination, Demonstration, and Deployment: Design the Demonstration of Capabilities Scenarios	Completed, documented in report titled 'Resilient Information Architecture Platform for the Smart Grid (RIAPS) Technology Dissemination, Demonstration, and Deployment Demonstration of Capabilities Scenarios'
Milestone 6.3.2: Technology Dissemination, Demonstration, and Deployment: Develop Demonstration of Capabilities Scenarios	Developed demonstrations scenarios: simple, enhanced, and advanced applications, as well as RAS and Microgrid applications.
Milestone 6.3.3: Technology Dissemination, Demonstration, and Deployment: Publications and workshop demonstrations	Participated in Energy Innovation summit, attended conferences, published papers
Milestone 6.3.4: Technology Dissemination, Demonstration, and Deployment: (1) Beta release, (2) Community building	Gave several demonstrations to IAB, established contact with LF Energy.
Milestone 6.3.5: Technology Dissemination, Demonstration, and Deployment: Demonstration of applications	Demonstrated RIAPS at several meetings of LF Energy, NCSU FREEDM center, and other venues
Program Element 7: **RIAPS Field Demonstration**	
Task 7.1: Integrate programmable power system devices (relays, inverters, SSTs).	
Milestone 7.1.1: Initial version for selected interfaces	Developed initial ChargePoint and building interfaces
Milestone 7.1.2: Update 1 for interfaces	Updated interfaces to work from recorded data
Milestone 7.1.3: Update 2 for interfaces	Developed user interface for demonstration system
Task 7.2: Develop VMware-specific microgrid applications	
Milestone 7.2.1: Initial implementation of the microgrid control application	Documented in Tu, H., et al "An LSTM-Based Online Prediction Method for Building Electric Load During COVID-19" Annual Conference of the PHM Society, 12(1), 8, 2020.
Milestone 7.2.2: Advanced implementation of the microgrid control application	Advanced implementation completed in NCSU lab, and documented in video titled "RIAPS Energy Management Application Demo"
Milestone 7.2.3: Final implementation of the microgrid control application	Final implementation completed in NCSU lab, and documented in video titled "RIAPS Energy Management Application Demo"
Task7.3: Experimentally validate applications	
Milestone 7.3.1: HIL validation completed	HIL implementation completed in NCSU lab, and documented in video titled "RIAPS Energy Management Application Demo"
Milestone 7.3.2: Integration into NCSU testbed and validation completed	Integration completed in NCSU lab, and documented in video titled "RIAPS Energy Management Application Demo"
Milestone 7.3.3: Validation at VMWare completed.	Final validation used VMWare date and completed in NCSU lab. Documented in video titled "RIAPS Energy Management Application Demo"

Project Activities

The focus of the project was twofold: (1) develop an 'Information Architecture Platform': a software package that supports the development, deployment, and operation of complex, distributed Smart Grid software applications, and (2) demonstrate its capabilities through selected examples.

The first point was addressed by an agile software design and development process that resulted in RIAPS, the actual software package. The design and development proceeded in four steps: (1) initial design and literature survey, (2) baseline prototype implementation, (3) enhanced implementation, and (4) advanced implementation. Each of these phases resulted in various documents that have been submitted as part of the project documentation. After each development stage (2-4) tests and demonstrations have shown the functionality of the software. The resulting software is available under an open source license from https://github.com/RIAPS/ and documentation at https://riaps.github.io/.

The demonstrations of the functionality included: (1) Remedial Action Schemes (RAS), and (2) Microgrid control (MG). The project has implemented and demonstrated two RAS algorithms: one for generation curtailment, and one for underfrequency load shedding. The applications were tested against standard IEEE transmission system models, running on an RTDS simulator. The MG demonstrations include a resynchronization app, a power dispatch app, and am app demonstrating networked microgrids. These apps were tested against several MG configurations, simulated, in real-time, on an OPAL-RT simulator. In both cases the RIAPS apps were running on small, networked embedded computers. The demonstrations have shown that RIAPS apps can successfully solve various Smart Grid monitoring and control problems.

The project has received an extension for a field test with an industrial collaborator: VMware, Inc., who has provided in-kind support for the project. This field test focused on microgrid energy management problem: optimizing building and EV charger operations to save energy, using machine-learning based models. The industry partner has provided operational data that was used to train a predictive model. This predictive model was then used in an on-line optimization algorithm that optimized energy used based on current and predicted energy usage. Due to COVID travel restrictions, the demonstration was done remotely, using off-line data. This application has shown the applicability of RIAPS to yet another class of Smart Grid control problems.

Project Outputs

A. Journal Articles

2017

- J. Xie, and C.-C. Liu, “Multi-agent systems and their applications”, Journal of International Council on Electrical Engineering, vol.7, no. 1, ISSN 2234-8972, pp. 188-197, Publication Date 01/01/2017, DOI: http://www.tandfonline.com/doi/full/10.1080/22348972.2017.1348890, DOE Submission: DOE-VANDERBILT-0000666-12.pdf
- R. Liu, A. Srivastava, D. Bakken, A. Askerman, and P. Panciatici, “Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform,” IEEE Transactions on Industry Applications, Volume 53, Issue 6, ISSN 0093-9994, Nov-Dec 2017, accepted 17 August 2017, pp. 5915-5926, published 11/01/17, DOI: https://doi.org/10.1109/TIA.2017.2740831, DOE Submission: DOE-VANDERBILT-0000666-13.pdf

2018

- A. Dubey, G. Karsai, P. Volgyesi, M. Metelko, I. Madari, H. Tu, Y. Du, and S. Lukic, "Device Access Abstractions for Resilient Information Architecture Platform for Smart Grid", IEEE Embedded System Letters, 12 June 2018, doi: 10.1109/LES.2018.2845854, DOI: https://doi.org/10.1109/LES.2018.2845854, DOE Submission: DOE-VANDERBILT-0000666-18.pdf
- Y. Du, H. Tu, and S. M. Lukic, "Distributed Control Strategy to Achieve Synchronized Operation of an Islanded MG", in IEEE Transactions on Smart Grid, Date of Publication: 31 July 2018, Publisher: IEEE, page 1-1, DOI: https://doi.org/10.1109/TSG.2018.2861679, DOE Submission: DOE-VANDERBILT-0000666-23.pdf, 11/29/18
- V. V. G. Krishnan, S. Gopal, R. Liu, A. Askerman, A. K. Srivastava, D. Bakken, and P. Panciatici, "Resilient Cyber Infrastructure for the Minimum Wind Curtailment Remedial Control Scheme", IEEE Transactions on Industry Applications (early access), 03 September 2018, doi: 10.1109/TIA.2018.2868257, DOE Submission: DOE-VANDERBILT-0000666-24.pdf, 11/29/18

2019

- Y. Du, X. Lu, H. Tu, J.Wang, S. Lukic, "Dynamic Microgrids with Self-Organized Grid-Forming Inverters in Unbalanced Distribution Feeders", IEEE Journal of Emerging and Selected Topics in Power Electronics, August 21, 2019, pg 1, doi:10.1109/JESTPE.2019.2936741, DOE Submission: DOE-VANDERBILT-0000666-29.pdf, 09/30/19
- H. Tu, Y. Du, Y. Hui, A. Dubey, S. M. Lukic, and G. Karsai, “Resilient Information Architecture Platform for the Smart Grid (RIAPS): A Novel Open-Source Platform for Microgrid Control”, IEEE Transactions on Industrial Electronics, 15 November 2019,DOI:10.1109/TIE.2019.2952803, DOE Submission: DOE-VANDERBILT-0000666-30.pdf, 04/28/2020

2020

- Y. Du, H. Tu, H. Yu and S. Lukic, "Accurate Consensus-based Distributed Averaging with Variable Time Delay in Support of Distributed Secondary Control Algorithms," in IEEE Transactions on Smart Grid, 21 February 2020, DOI: https://doi.org/10.1109/TSG.2020.2975752, DOE Submission: DOE-VANDERBILT-0000666-31.pdf, 04/28/2020
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B. Papers

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2017

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- Y. Du, H. Tu, S. Lukic, D. Lubkeman, A. Dubey, and G. Karsai "Development of a Controller Hardware-in-the-Loop Platform for Microgrid Distributed Control Applications", 2018 IEEE Electronic Power Grid (eGRID), Charleston, SC, November 12-14, 2018, DOI: https://doi.org/10.1109/eGRID.2018.8598696, DOE Submission: DOE-VANDERBILT-0000666-21.pdf, 11/29/18
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- H. Tu, Y. Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, "RIAPS: An Open-Source Platform for Microgrid Control", 9th Microgrid Global Innovation Forum, Washington, D.C. March 18-20, 2019, http://www.microgridinnovation.com/Washington/RIAPS-session.htm, DOE Submission: DOE-VANDERBILT-0000666-25.pdf, 05/16/19
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C. Status Reports

The project has submitted quarterly status reports, starting from July 2016, until March 2021.

D. Media Reports

- News release from Vanderbilt (2016): https://engineering.vanderbilt.edu/news/2015/vanderbilt-school-of-engineering-partners-awarded-3-5-million-from-arpa-e-for-transformational-energy-technology/

E. Invention Disclosures

N/A.

F. Patent Applications/Issued Patents

N/A

G. Licensed Technologies

The RIAPS software package has been licensed under an Open Source license, and is available from https://github.com/RIAPS/

H. Networks/Collaborations Fostered

N/A

I. Websites Featuring Project Work Results

The main project website is https://riaps.isis.vanderbilt.edu/
The code base is open source, available from https://github.com/RIAPS
Final documentation of the project is available on https://riaps.github.io/

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

The main product of the project is the RIAPS code base, as well as the demonstration applications, are available from https://github.com/RIAPS

The project has created its own YouTube channel, where all the demonstration videos can be found: https://www.youtube.com/channel/UCwfT8KeF-8M7GKhHS0muawg/videos

K. Awards, Prizes, and Recognition

N/A

Follow-On Funding

Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award.

Table 2. Follow-On Funding Received.

Source	Funds Committed or Received
DoD ESTCP Program	$2.5M