Integrate Latimer Controls' Solution into RTAC

Cooperative Research and Development Final Report

CRADA Number: CRD-23-24672

NREL Technical Contact: Jing Wang

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-92535
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NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: December 18, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Latimer Controls, Inc.

CRADA Number: CRD-23-24672

CRADA Title: Integrate Latimer Controls' Solution into RTAC

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources Government In-Kind
Year 1	$20,000.00
Year 2, Modification #1	$.00
Year 3, Modification #2	$.00
Year 4, Modification #3	$.00
TOTALS	$20,000.00

Executive Summary of CRADA Work:

Latimer Controls, Inc. was awarded two vouchers under the Department of Energy's American-Made Solar Prize Round 6 to conduct collaborative research at a national laboratory. The National Renewable Energy Laboratory (NREL) was selected as a partner to assist Latimer Controls in the performance evaluation of its photovoltaic (PV) control software. This collaboration focuses on developing a hardware-in-the-loop (HIL) testbed at NREL, which will be used to test and validate the Latimer PV control technology in a realistic yet de-risked environment. Both Latimer and NREL teams will work together to analyze the collected test data, derive insights, and disseminate the scientific findings.

Recent studies underscore the potential of solar energy as a zero-marginal-cost and zero-emission flexibility resource within the bulk power system, particularly when integrated with advanced control systems. To enhance the performance of such systems, Latimer Controls has developed leading-edge technologies, including machine learning (ML) algorithms and hierarchical inverter set-point allocation methods. These innovations are designed to estimate the operational headroom of large PV plants for grid integration and control. However, comprehensive validation under real-world conditions remains necessary.

To address this gap, the concurrent CRADA project proposes the real-world application and validation of the Latimer Control solution within a HIL environment. Initially, the Latimer algorithm was developed and tested within MATLAB Simulink, a platform suitable for research-level simulations and iterative development. However, transitioning this technology to a real solar site as an industry-ready solution necessitates implementation in a format compatible with widely used solar power plant controllers.

In this additional CRADA work, the MATLAB Simulink-based logic will be translated into Structured Text, a programming language compliant with IEC 61131 standards, which is commonly used for custom logic implementations in industry-leading programmable logic controllers (PLCs), such as the Schweitzer SEL real-time automation controller (RTAC). This transition will facilitate the deployment of the Latimer Control solution in real-world solar power plants, thereby advancing the technology towards commercialization.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Uses the laboratory's core competencies.

Summary of Research Results:

This report delivered one task that integrates the MATLAB /Simulink code into Structured Text (ST) coder run in SEL RTAC power plant controller.

Task 1: NREL will integrate, validate and test the PHL algorithm in RTAC.

Task 1.1: NREL will integrate the ST code into RTAC, debug the code and make sure there is no errors in the code.

Explanation: NREL integrated the ST code into RTAC, troubleshoot the errors and made the code work in RTAC. During the code integration, there were bugs related to ST code converted from MATLAB directly. MATLAB is a high-level programming environment renowned for its capabilities in numerical computing, data analysis, algorithm development, and visualization. It offers significant simplification and automation for matrix operations, linear algebra, and other mathematical computations. In contrast, the Structured Text (ST) programming language is akin to traditional imperative programming languages but is tailored specifically for real-time control logic in industrial automation systems such as PLC. The key challenge in this work arises from adapting the extensive mathematical operations, particularly those required for executing a trained machine learning algorithm, to the more constrained logic of Structured Text used with the RTAC chosen as the power plant controller to validate the Latimer Controls algorithms.

Latimer Controls' algorithm employs a pre-trained neural network to process real-time voltage and current measurements, enabling the estimation of the potential high limit (PHL) for each inverter's power output. Although the neural network training is conducted offline, executing the neural network in real-time involves thousands of arithmetic operations based on trained weights and biases. To implement this within a simple PLC, the machine learning algorithm must be "un-black-boxed" and reconstructed through a series of multiplications and additions of these trained floating-point values. By doing so, the computational demands of the machine learning-based PHL estimation can be met by even basic PLCs with sufficient processing power.

An SEL RTAC 3532 was chosen as the PLC to run Latimer Controls' MATLAB /Simulink code with the ML algorithms and hierarchical power setpoint allocation control of inverters. With the resource-intensive computation of the neural network in real-time, other methods to optimize computation were explored, such as using an SEL library for matrix multiplication and the possibility of developing a low-level custom library for SEL's AcSELerator programming environment for RTAC. Ultimately, NREL found that running the neural network computation in RTAC with simple element-by-element multiplication and addition was the most efficient solution for computing the neural network matrix operations with weights and biases in real-time.

RTAC supports two parallel processes called the Main Task, and Automation Task cycles. To optimally combine the complex neural network computation with the necessary communications, the ML-based PHL estimation was allocated to the Automation Task and the Latimer Controls hierarchical setpoint allocation algorithms, communications, and all other computations were allocated to be computed in the Main Task. Due to the resource-intensive matrix computations needed for the ML algorithms, the automation task was set to execute at a 1-second task cycle, while the main task was set to a 4-millisecond task cycle to handle communications exchange with minimal latency. NREL designed the project in RTAC to allow for future updating of the weights and bias matrices used for the ML algorithms by having text files with the weights and biases uploaded to the RTAC file system.

Task 1.2: NREL will configure the communication protocols (DNP3 and Modbus) and SCADA in this RTAC.

<u>Explanation</u>: For the HIL testing, NREL configured the RTAC to communicate with an RTDS NovaCor, simulating the IEEE 39-bus model, exchanging power setpoints and inverter-level voltage and current measurements over the Distributed Network Protocol (DNP3) and an AGC plant-level setpoint and the PHL estimation computed by RTAC over Modbus Transmission Control Protocol (TCP)/Internet Protocol (IP). A DNP3 client was configured in RTAC to receive the AGC plant-level setpoint every 6 seconds from RTDS and send back the PHL estimation every 6 seconds. A Modbus client was also configured in RTAC to receive the voltage and current measurements every 1 second from RTDS and send back inverter-level power setpoints every 1 second that were calculated with Latimer Control's hierarchical control for setpoint allocation and the PHL estimation. NREL also implemented a User Datagram Protocol (UDP)-based interface in RTAC for Supervisory Control and Data Acquisition (SCADA) to aggregate data from RTAC and RTDS for visualization of the HIL testing, debugging, and analyzing resulting data from HIL simulations. Figure 1 below shows the communications setup with RTAC and RTDS for the HIL setup.

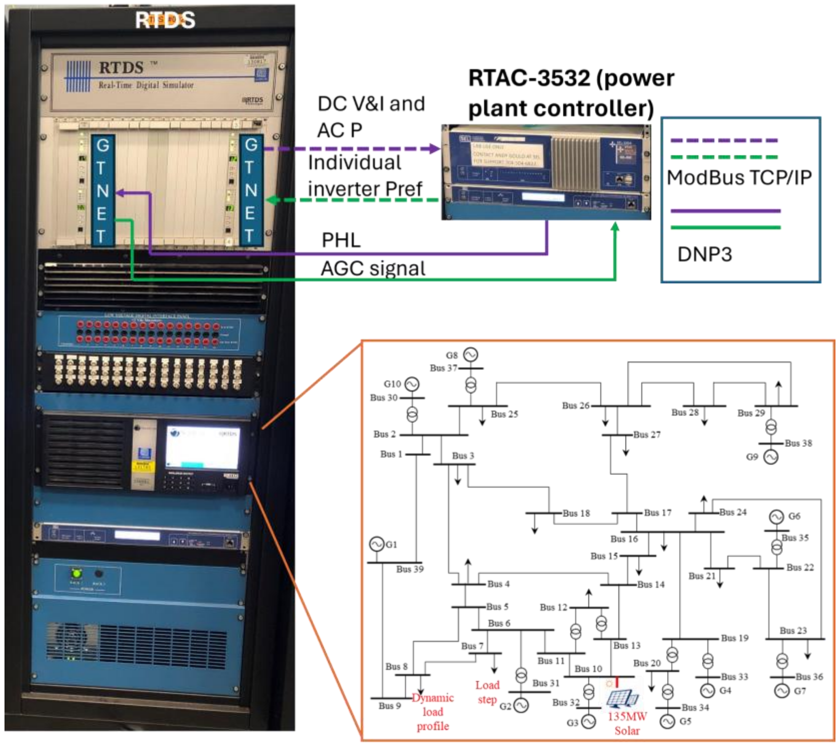

Figure 1. HIL setup with RTAC and RTDS

Task 1.3: NREL will debug and test ST code and ensure the PHL estimation algorithm achieve similar/comparable performance compared to the PHL estimation algorithm embedded in OPAL-RT from the first voucher. NREL will implement ST code in RTAC for a reference-inverter method for PHL estimation as a benchmark to compare the performance of Latimer Controls' PHL estimation algorithms.

Explanation: After translating the Latimer Control hierarchical setpoint allocation and PHL ML-based algorithms to Structured Text in RTAC, NREL validated the ST code against the MATLAB code that was implemented in OPAL-RT from the first voucher since OPAL-RT natively runs Simulink models that work directly from MATLAB code. Various bugs resulting from the conversion of the MATLAB code to Structured Text arose while validating performance with OPAL-RT. One such bug was incorrect scaling of units from the measurements fed into the PHL estimation algorithm and power setpoints calculated with the PHL estimation and hierarchical control that manifested in the visual data results as a time delay. Other bugs encountered involved bugs in the original MATLAB code, such as mathematical operations with the voltage and current measurements in the initial steps of the PHL estimation. NREL resolved all bugs, and the conversion of the MATLAB code to Structured Text in RTAC was successfully validated against Opal-RT. Figures 2 and 3 below show a simulation running RTDS with RTAC and Opal-RT separately with identical results. The industry standard reference-inverter method, where a subset of the 27 inverters in the PV plant of the RTDS model was selected to operate at MPPT as reference inverters and the power setpoint of the other subset of inverters was calculated using the measured power of the PV plant and the plant-level AGC setpoint was implemented in the RTAC to benchmark the Latimer Controls' PHL estimation. This simple algorithm was implemented in RTAC, where the only bug experienced was incorrect indexing of inverters that were selected as the reference inverters. This bug was subsequently fixed, and the reference-inverter method was successfully implemented in RTAC as a separate PHL estimation and control method to compare with the Latimer Controls PHL estimation. A UDP-based interface was also implemented for SCADA and result analysis. The Latimer Controls' PHL estimation was successfully compared against the reference-inverter method.

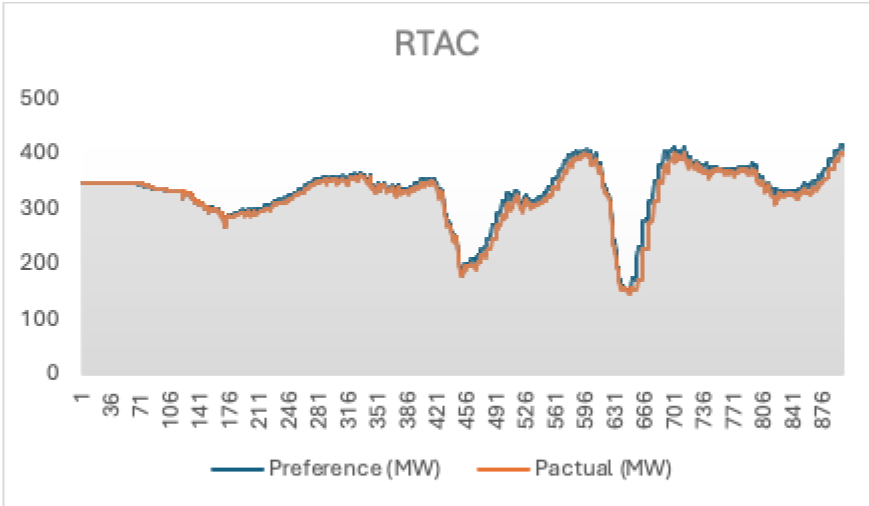

Figure 2. PHL estimation results with RTAC and RTDS

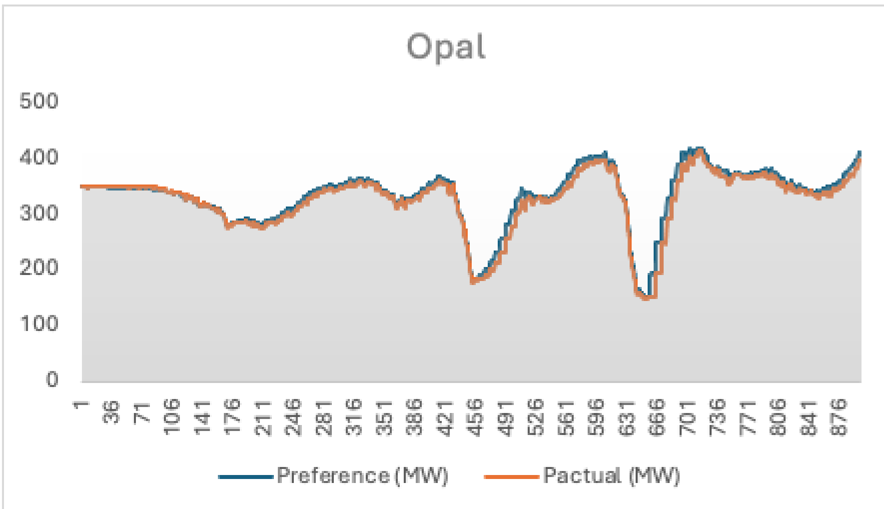

Figure 3. PHL estimation results with Opal-RT and RTDS

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X.

References: None

Subject Inventions Listing: None

ROI #: None