Real Time – Optimal Power Flow Based Distributed Energy Resources Management System (DERMS)

Cooperative Research and Development Final Report

CRADA Number: CRD-20-16909

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5D00-80013
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Cooperative Research and Development Final Report

Report Date: 5/12/2021

In accordance with the requirements set forth in the terms of the CRADA, this document is the CRADA final 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: Utilidata

CRADA Number: CRD-20-16909 *(Mod 1: Project 2 of a Multi-Project CRADA)*

CRADA Title: Real Time – Optimal Power Flow Based Distributed Energy Resources Management System (DERMS)

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Sponsoring DOE Program Office(s):

Advanced Research Projects Agency - Energy (ARPA-E)

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$0.00
TOTALS	$0.00

Executive Summary of CRADA Work:

The integration of behind-the-meter distributed energy resources (DERs) into distribution systems brings transformative changes to power systems. This requires operators and planners to find solutions to modernize electric grids and to effectively manage DERs for grid services. NREL developed novel DER management algorithms (referred to as Real-Time Optimal Power Flow, RT-OPF) through U.S. Department of Energy (DOE)-funded efforts, including Advanced Research Projects Agency–Energy (ARPA-E) Network Optimized Distributed Energy Systems (NODES) funding. This cutting-edge control technology aims to modernize distribution systems with large amounts of DER integration, which will help utilities solve issues brought by renewable integration and build resilient and renewable-based electric grids nationwide. Utilidata worked with NREL to investigate the commercialization opportunity of this RT-OPF-based distributed energy resource management system (DERMS). In this project, NREL performs the technology transfer of the RT-OPF to Utilidata to help them fully understand the RT-OPF solution, to identify potential engineering hurdles, and to assess the expected commercial value of various RT-OPF use cases and deployment. The technology transfer work includes two major tasks. First, NREL performs an in-depth knowledge transfer of the entire RT-OPF solution to Utilidata to help them gain an extensive and detailed understanding of the complete RT-OPF solution. In this task, NREL provides exhaustive information (e.g., documentation, code packages, laboratory and field trial data, performance results) while conducting in-depth training sessions to provide a thorough explanation of the entire solution. NREL hosts meetings to present different topics related to the RT-OPF solution, and question-and-answer sessions are included in each meeting to better explain the RT-OPF-related work. Second, the RT-OPF simulations are performed in a laboratory environment. The main objectives of this task are to walk through with Utilidata engineers how to set up a simulation of RT-OPF, identifying each RT-OPF code block/component in operation, learning how these components interact with each other, and eventually running RT-OPF simulations under various system conditions. This task helps Utilidata engineers understand performance limitations and constraints while also quantifying the commercial value of the RT-OPF for different use cases. Based on these two tasks, Utilidata engineers should be able to define and prioritize the next steps of RT-OPF implementation with an eye toward commercial success and scalability of the solution. The next steps are expected to be part of a new project following the conclusion of this project.

Summary of Research Results:

This project delivered two tasks that help Utilidata engineers fully understand the RT-OPF technology for DER management.

Task 1. In-depth knowledge transfer of entire RT-OPF solution

The subtasks are as follows:

1. Provide an explanation of all components/modules within the RT-OPF solution (e.g., central, distributed).

NREL will explain the RT-OPF and its control framework—including algorithm fundamentals and schematics, communications, and architecture—at a high level.

Explanation: NREL presented detailed explanations of the RT-OPF, including fundamental principles, control architecture, communications, use cases, and validation. In particular, the fundamental principles[1]—such as the mathematical model of the power system and DERs, the problem formulation of the RT-OPF, the solution of solving the optimization problem, and the systematical implementation—were clearly illustrated, which helped Utilidata engineers build the basis of the RT-OPF, understand what the RT-OPF is, and gain the capability to use the RT-OPF

[1] E. Dall'Anese, et al., "Optimal Regulation of Virtual Power Plants," IEEE Tran. Power System, vol. 33, no. 2, March 2018, pp. 942-952.

solution on their own. At the end of each meeting, question-and-answer sessions were included, and Utilidata engineers asked questions related to real-world considerations/constraints. NREL answered all the questions based on our project experiences, which helped Utilidata engineers understand the constraints/limitations of the RT-OPF solution in real-world deployment.

2. Provide an explanation of the RT-OPF work done to date—a deep dive into two field demonstrations and any laboratory demonstrations (with explanations of lab and field trial data—e.g., use case objective, expected results, and operating conditions). NREL will present two selected field demonstrations (e.g., Stone Edge Farm Microgrid and Holy Cross Energy) and one lab demonstration (NODES/Southern California Edison). In each demonstration, we will explain the use case objective, the test scenario, the expected results, the operating conditions, and the trial data.

<u>Explanation</u>: *NREL highlighted multiple projects at NREL that use the RT-OPF for DER management. Two field demonstrations (Stone Edge Farm Microgrid and the Holy Cross Energy high-impact project) and one lab demonstration (from ARPA-E NODES) were presented. Representative laboratory testing results of virtual power plant is shown in Figure 1. Each demonstration covered the use case objectives, the operating conditions, the key results, and the trial data for each project. We had intense discussions regarding the field deployment, especially regarding the communications-related issues, such as how the performance of the RT-OPF is affected by the communications between the coordinator and local controllers, which communications connections need to be redundant, and what are specific examples of redundant communications for them? Scalability was also discussed extensively to understand how it can be achieved. NREL provided comprehensive and deep answers for each question; however, communications-related issues still need more clarification and exploration because of the lack of more practical implementation experiences.*

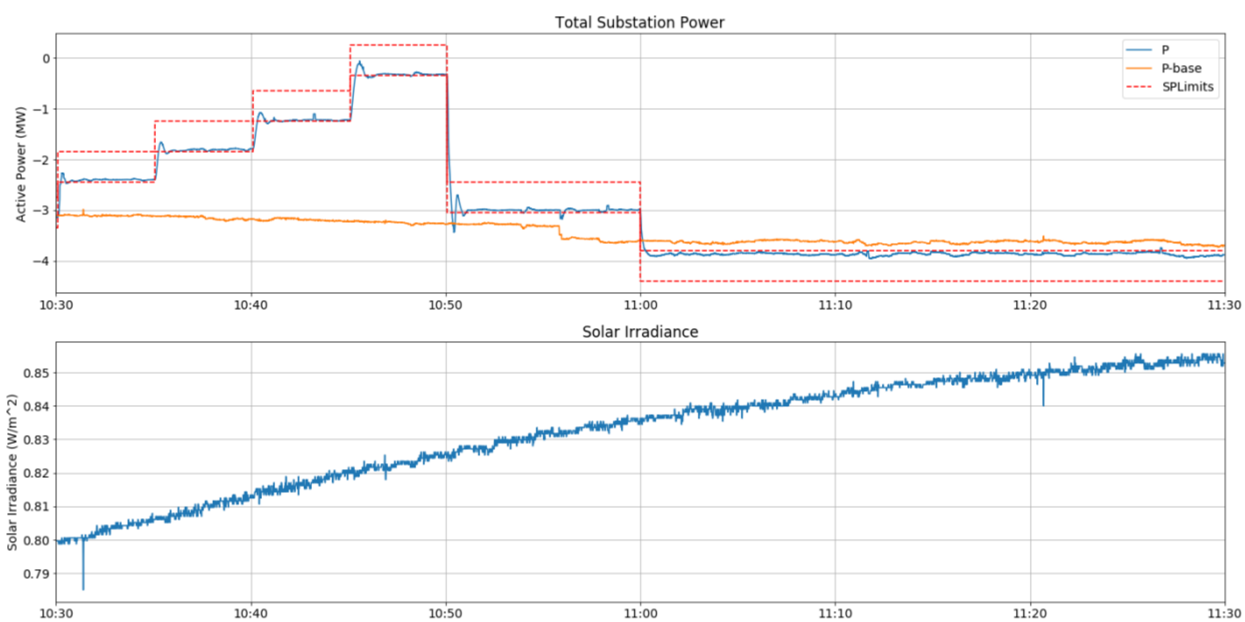

Figure 1 Representative laboratory testing results of virtual power plant.

3. End-to-end description of the implementation and operation of the RT-OPF.

NREL will explain and document the implementation and the operation procedures of the RT-OPF. In particular, we will work through the control code and explain what the code is and how to modify it to be applied to a different power system model.

Explanation: NREL explained the black-box implementation and flowchart of the RT-OPF code at a high level and clearly explained the input and output data and control parameters. We walked through the RT-OPF control code line-by-line and explained how to modify the control code to apply it to a different power system model. We also revisited the fundamental theory we presented in Subtask 1 to link the implementations (the RT-OPF code) with the key formulas of the RT-OPF. Finally, we listed the implementation details/processes that need to be modified for a different project. We also discussed multiple interesting questions, such as the time needed for each process, the communications requirement for the RT-OPF, and how the RT-OPF should coordinate with the advanced distribution management system (ADMS) using the Solar Energy Technologies Office-funded Enhanced Control, Optimization, and Integration of Distributed Energy Applications (ECO-IDEA) project. This subtask gives the full and detailed picture to Utilidata engineers about what the RT-OPF is and how to apply the RT-OPF to a different project.

4. What are the requirements for all critical elements of the solution (e.g., inputs, outputs, algorithms, conditions/constraints)?

NREL will explain all the critical elements of the solution in the view of the production line, including inputs and outputs, control settings, tunings, expected performance, algorithms, and conditions/constraints.

Explanation: NREL explained the critical elements of the RT-OPF using a schematic diagram that covers all critical elements of the RT-OPF and the implementation processes, such as data needs, analysis, implementations, inputs, and outputs. The data needs for the project include photovoltaic (PV) and load profiles, the detailed network model, the DER list, and nominal voltage profiles, but they are not limited to these data. The analysis included a baseline study for the overall system voltage profiles and the nodes of interest for control and measurements, the Ymatrix calculation, and the network coefficients calculation. The implementations consist of selecting the nodes of interest, the RT-OPF coordinator and the RT-OPF local controller implementation, and the RT-OPF tuning. The inputs include measurements from the meters (voltage measurements and feeder head power measurements), the set points and command from the distribution management system (DMS)/ADMS (voltage limits, feeder head power set point, enable/disable RT-OPF service), and the DERs' measurements (active and reactive power outputs and state-of-charge of battery/electric vehicle (EV)). The outputs are the optimal power set points for the DERs. We identified two more things that need to be added to the local controllers: the inputs of user preferences (e.g., time to use a certain device) and the tariff/electricity price. The expected performance of the voltage regulation and the virtual power plant (VPP) were discussed as well, such as the initial response, the settling time, and the dynamics/trends of the RT-OPF progression. The conditions and constraints of the RT-OPF were discussed in detail, and the limitations (e.g., the need for a detailed network model and tuning) and improvements of the RT-OPF (tuning and customer preference implementation) were also discussed. Finally, the techno-economic analysis was discussed by using two projects from NREL. This subtask helped Utilidata further and deeply *understand the technical side of the RT-OPF and understand the limitations and improvements of the RT-OPF toward commercialization.*

5. Deliver the entire code package(s), including all components/modules of the RT-OPF, and clearly explain each code package/block and design. NREL will deliver a fully explained RT-OPF code package (SWR-18-27) to Utilidata, including all components/modules of the RT-OPF, for use in the performance of this joint work statement (JWS) only. Any use of NREL's code outside the performance of this JWS will require a separate license agreement. In the meeting, NREL will provide step-by-step explanations of each code package/block and design (e.g., code flow, initialization, main function, called functions, tuning, key control parameters to understand for the algorithms, and the time resolutions of the control code).

<u>Explanation</u>: NREL delivered the entire RT-OPF code package (SWR-18-27) to Utilidata, including all components/modules of the RT-OPF, for use in the performance of this JWS only. In the meeting, NREL provided step-by-step explanations of each code package/block and design (e.g., code flow, initialization, main function, called functions, tuning, key control parameters to understand the algorithms, and time resolutions of the control code). The RT-OPF code package is well structured, and each line was explained, which makes the code easy to understand and apply. NREL walked through the RT-OPF code twice. Based on the responses from the Utilidata engineers, we understand that they already have a good master of the code and the implementations of the RT-OPF.

6. Specifications of embedding the RT-OPF code into a hardware platform. NREL will show what kind of hardware platforms have been used to implement the RT-OPF and then discuss the hardware implementation-related aspects, such as what kind of hardware platform is needed to implement the RT-OPF (e.g., CPU and communications), how to transfer the code into the hardware controller, what the communications protocols and communications channels are, what is the acceptable latency, and how fast the controller should run.

<u>Explanation</u>: NREL used the NODES project as an example to discuss the specifications of embedding the RT-OPF code into the hardware platform, the Beaglebone microcontroller. The hardware implementation-related topics—such as transferring the code into the hardware controller, setting up communications, testing the communications delay, and the inverter response time—were covered and explained in detail. In particular, to transfer the code into a hardware controller, NREL explained that the key modifications needed are receiving inputs and sending the output optimal set point, and key implementation steps were provided to communicate with a hardware inverter for receiving inputs and sending out the set points. The takeaways from the laboratory hardware implementations are: (1) the grid edge control (coordinator) requires only modest computational capabilities and can be implemented on low-cost, single-board, computer-type hardware; (2) relatively low network bandwidth is required, and information flow requirements fit multicast or pub-sub models well; (3) a data concentrator or Gateway can be advantageous and used for additional security and/or protocol translation; and (4) communications protocols (HTTP REST application programming interface for communications between local controllers and the gateway) and local devices such as Modbus or custom(s) protocols can be used.

7. List the third-party software programs required to operate the RT-OPF.

NREL will explain what the RT-OPF is and what software environment can be used to run it.

<u>Explanation</u>: NREL revisited the theory of the RT-OPF and illustrated that the computational power needed for the RT-OPF are mostly linear algebra-type calculations (shown in Figure 2) and trigonometric function calculations in the DER projection functions. Overall, the RT-OPF requires relatively low computational power. Basically, the RT-OPF can be coded in any software, such as MATLAB and Python, and power system modeling can be done in the distribution system simulation tool for the power flow solver, such as OpenDSS, GridLAB-D and MATLAB/OPAL-RT. No specific third-party software is required to operate the RT-OPF.

Real-time virtual-power-plant regulation.

[S1a] Collect voltage-magnitude measurements $\{|\hat{V}_n^{t_k}|\}_{n \in \mathcal{M}}$.
[S1b] Collect measurement of $\hat{P}_0^{t_k}$.
[S2a] For all $n \in \mathcal{M}$, update $\gamma_n^{t_{k+1}}$ and $\mu_n^{t_{k+1}}$ as follows:

$$\gamma_n^{t_{k+1}} = \text{proj}_{\mathbb{R}_+} \left\{ \gamma_n^{t_k} + \alpha \left(V^{\min} - |\hat{V}_n^{t_k}| - \epsilon \gamma_n^{t_k} \right) \right\} \quad (12a)$$

$$\mu_n^{t_{k+1}} = \text{proj}_{\mathbb{R}_+} \left\{ \mu_n^{t_k} + \alpha \left(|\hat{V}_n^{t_k}| - V^{\max} - \epsilon \mu_n^{t_k} \right) \right\} \quad (12b)$$

[S2b] For the feeder head, if $h^{t_k} = 1$ update dual variables as follows:

$$\lambda^{t_{k+1}} = \text{proj}_{\mathbb{R}_+} \left\{ \lambda^{t_k} + \alpha (\hat{P}_0^{t_k} - P_{0,\text{set}}^{t_k} - E^{t_k} - \epsilon \lambda^{t_k}) \right\} \quad (12c)$$

$$\zeta^{t_{k+1}} = \text{proj}_{\mathbb{R}_+} \left\{ \zeta^{t_k} + \alpha (P_{0,\text{set}}^{t_k} - \hat{P}_0^{t_k} - E^{t_k} - \epsilon \zeta^{t_k}) \right\} \quad (12d)$$

[S3a] Measure output powers $\hat{P}_i^{t_k}, \hat{Q}_i^{t_k}$ at each DER $i \in \mathcal{G}$.
[S3b] Update power setpoints at each DER $i \in \mathcal{G}$ as:

$$\begin{bmatrix} P_i^{t_{k+1}} \\ Q_i^{t_{k+1}} \end{bmatrix} = \text{proj}_{\mathcal{Y}_i^{t_k}} \left\{ \begin{bmatrix} P_i^{t_k} \\ Q_i^{t_k} \end{bmatrix} - \alpha \nabla_{[P_i, Q_i]} \mathcal{L}^{t_k}(\mathbf{p}, \mathbf{q}, \mathbf{d}) |_{\hat{P}_i^{t_k}, \hat{Q}_i^{t_k}, \mathbf{d}^{t_{k+1}}} \right\}, \quad (12e)$$

[S3c] Dispatch setpoints to each DER i, and return to **[S1a]**.

Figure 2 Key implementation steps of RT-OPF[1].

Task 2. Perform RT-OPF simulations in a laboratory environment

The subtasks are as follows:

1. Provide an explanation of the steps required to set up and perform RT-OPF simulations. NREL will first present the third subtask in Task 1 to explain the steps/procedures to set up and to perform RT-OPF simulations. Then, a specific distribution feeder (e.g., Southern California Edison Titanium feeder) will be used as an example to show how the implementation steps/procedures can be applied.

<u>Explanation</u>: NREL, again, presented the subtasks in Task 1 to explain the steps/procedures to set up and to perform the RT-OPF simulations, including the data needs, analysis, implementations, inputs, and outputs. Then, the SCE Titanium feeder used for the NODES project was used as an example feeder to show Utilidata engineers how to apply the implementation steps/procedures. We explained the power system model, including the load and DER model, the battery state-of-charge calculation, reading the PV and load profiles with fixed intervals, and running the power

system model in real time. We also showed the implementations of the RT-OPF coordinator and multiple distributed local controllers. Finally, a demonstration was given in RT-LAB to show the VPP performance of the RT-OPF tracking the active power set points in real time.

2. Provide an explanation of how to simulate various system conditions. Based on Subtask 1, NREL will show how to simulate various system conditions (e.g., high/low load, low/smooth/intermittent solar irradiance).

<u>Explanation</u>: *NREL presented the various system conditions based on load and PV profile data—such as a low-load and high-solar irradiance day, a high-load and low-solar irradiance day, and a low-load day and fluctuated-solar irradiance—to effectively evaluate and demonstrate the RT-OPF. For the techno-economic analysis, representative days across the whole year are usually selected to spread out and represent the whole year. Based on our experience, it is necessary to talk to the utility partner to get historical events and to try to find days showing problems on the grid for demonstration. For various scenarios, NREL suggested running the baseline mode without DERMS control and PV operating in fixed power factor or smart inverter function mode and a scenario with DERMS control by varying the voltage set points and active power set points. Sometimes it is necessary to simulate the scenario with the ADMS and the RT-OPF coordinated, and the control objectives of the ADMS need to be carefully selected.*

3. Identify how to obtain and store simulation data for analysis (e.g., what outputs are expected, data types, time intervals, data storage location and requirements) NREL will explain how to obtain and store simulation data (e.g., outputs, data types, time intervals, data storage locations and requirements) for analysis in general and will use one project as an example to show those data.

<u>Explanation</u>: *NREL explained the data needed to be collected, including VPP (upper and lower power set point, feeder head active and reactive power measurement, and enable service), voltage regulation (voltage limits, voltage measurements of selected and the whole system voltages, and enable RT-OPF), selected DER local controllers (20-ish, the terminal voltage, dual variables, DER measurements, total PV available, and optimal power set points), and other measurements (total load of the feeder, total active and reactive power of the PV, total available PV output, and legacy devices). A resolution of 1–2 seconds for data collection is recommended.*

Based on the interactive discussions with Utilidata engineers throughout the project, we agree that the following aspects need to be improved/further worked on to make the RT-OPF more commercializable:

- **Communications**: Three communications paths are involved: (1) between the ADMS and the RT-OPF DERMS coordinator, (2) between the RT-OPF DERMS coordinator and the RT-OPF DER local controllers, and (3) between the RT-OPF DER local controllers and the DERs. The first two communications paths are achievable with existing communications infrastructures and technologies. The third communications path is the bottleneck that hinders the deployment of the RT-OPF DERMS because using a single unit that controls a variety of DERs with various communications protocols is not easy. We should engage multiple DER inverter manufactures (PV, battery, and EV) to get their industry insights on communications specifications between DERMS and DER inverters for broader communications capability. Further, we should develop feasible communications infrastructure architectures of the RT-OPF DERMS to integrate the legacy and the latest standards for DER communications (e.g., SunSpec Modbus and 2030.5 set of communications) in downstream and upstream communications with utility DMS/ADMS.

- **Integrate customer preference and benefits**: This is an open area that DERMS should address to engage end-user customers willing to enroll in an electricity management program. Based on the survey conducted by a utility, two major factors driving the customers' interests are to reduce the energy bill and to retain some control over their home appliances. We will integrate these two customers' preferences into the DERMS local controller to satisfy the customers' needs; therefore, the local controller at the home level will include system-level optimization for grid service, home-level optimization for customer benefits, and an expansion of controllable devices (from DER inverters to home appliances). The existing RT-OPF code can perform the first, and the Hold Cross Energy field demonstration preliminary demonstrated the ability of the RT-OPF to reduce customer bills and to control a variety of DERs (PV, battery, and EV) and home appliances (heating, ventilating, and air-conditioning system; water heat and heat pump). Additional efforts will be made to expand the RT-OPF algorithm to focus on home-level optimization for customer benefits and to develop a user interface to receive inputs from customers. And we should work with our utility partners to get their insights into how this can happen in real life and develop a rewarding mechanism. Additionally, each local controller should show customers their energy savings curve on an hourly basis and through a period (e.g., monthly).
- **Automated implementation process**: To improve commercialization and scalability, an automated implementation process is necessary to standardize the process and to improve the development efficiency to accelerate the project cycle. The RT-OPF algorithm should be treated as a generic black box, and only the inputs, outputs, and settings need to be configured and mapped based on each project. The following technical aspects need to be developed to make the whole process automated and user friendly.
- *Automated identification of nodes of interest*: The voltage measurements of nodes are selected manually based on the baseline study of the network. The nodes that have voltage issues, such as overvoltages and undervoltages, are the nodes of interest for voltage regulation. This process can be made automated by writing a generic code to read the PV and load profiles, run the baseline, record the voltage measurements, and select the nodes of interest based on the threshold of voltages (e.g., higher than 1.045 p.u. and lower than 0.96 p.u.).
- *Automated computation of network coefficients*: The NODES project already developed functions to compute the network coefficients. Network-related information and settings are manually set in each function when the main function calls them. To achieve an automated process, the following coding effort needs to: (1) automatically extract the Ymatrix of the distribution network, connection, and phases of all nodes; (2) list all the nodes of interest as input; (3) list the locations, connections, and phase(s) of all the DERs as input; and (4) output the list of network coefficients in the order of DERs and extract and read them as inputs for the RT-OPF local controllers.
- *Automated tuning of RT-OPF*: The RT-OPF algorithm is designed based on a gradient descent approach, and its performance (convergence and stability) mainly depends on the

gradient step parameter, α. The tuning of α is manually performed by observing selected dual variables, and the tuning is tedious and might not work all the time. An analytical study should be performed online to tune α automatically. Also, tuning α should be adaptive to respond to changes in network conditions, such as increased DER generation and reduced loading. This feature enables the RT-OPF to achieve target performance with faster and smoother dynamics.

Overall, NREL delivered the two tasks defined in the JSW to transfer the RT-OPF technology to Utilidata, including the in-depth knowledge transfer for the entire RT-OPF solution and performing the RT-OPF simulation in the laboratory environment. We also identified three key technical aspects that should be improved for the commercialization and scalability of the RT-OPF DERMS technology, including the communications between DERMS and various DER inverters, the integration of customer preference and benefits, and the automated implementation process. All those discussions show that the RT-OPF has a well-defined structure, is easy for implementation, and is flexible for adding new control objectives/functions, and the three technical improvements are feasible and practical for real-life deployment. The next step is to work with Utilidata to define a new project following the conclusion of this project.

Task 3. Project Management and Delivery:

NREL will serve as project manager, with Utilidata. NREL will conduct weekly project meetings with Utilidata to review progress, track status of milestones, and address any deficiencies in project budget, schedule, or performance.

NREL will deliver the RT-OPF code packages to Utilidata. The other deliverables will be the PowerPoint slides that NREL presents in each meeting. Additionally, NREL will summarize the Q&A in each meeting and share with Utilidata. Upon completion of Task 3 of this JWS, Utilidata will return and/or delete all NREL RT-OPF code in its possession unless a separate license agreement is executed.

As planned, regular progress, status and budget meetings were held, with deliverables and milestones met. RT-OPF code packages were delivered to Utilidata and returned back to NREL upon task completion as agreed upon.

Final Task. CRADA Final Report

Preparation and submission in accordance with Article X.

This report encompasses the completion and deliverable of the Article X requirement for a CRADA Final Report.

<u>Subject Inventions Listing</u>:

None

<u>ROI #</u>:

None