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DUIT Phase I Final Report

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This report is dedicated to the memory of

Joe Iannucci

whose years of leadership paved the way to DUIT.

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final report for the Distributed Utility Integration Test (DUIT), 501-033-A-2, conducted by Distributed Utility Associates. The report is entitled DUIT Phase I. This project contributes to the Energy Systems Integration program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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ABSTRACT

The Distributed Utility Integration Test brought together manufacturers, utilities engineers and energy researchers to design and build a testing facility to measure and document the interaction of distributed energy resources in a realistic utility distribution system setting. The facility was designed to segregate testing in three bays, residential, single-phase units up to 5kW, commercial three phase inverters 45 and 100kW and industrial bay housing a synchronous generator of 250 kW. The facility was completed successfully and the testing began with single unit unintentional islanding tests. The team documented a detailed testing sequence from the unintentional islanding testing protocol and began with single unit unintentional islanding test. The single unit results validated the testing set-up and the methodologies employed. The multiple unit tests began the project testing at distribution voltage, 21kV and completed a sequence of homogenous testing of the single phase inverters and the small group testing.

KEYWORDS: distributed energy resources, distribution system, island, islanding

EXECUTIVE SUMMARY

Not enough is known about how distributed energy resources (DER) perform with regard to safety, health, economics, availability, and reliability—especially over time. Knowledge regarding the interconnection or interface of DER with a distribution grid or customer facility is also limited. Their operation must be interactive if the highest-value benefits are to be obtained and safety and reliability problems are to be avoided.

The increasing potential of distributed resources in emerging utility markets has focused attention on two critical issues: interconnection of distributed resources with the electric distribution system, and the unknown nature of potential interactions between multiple distributed devices. Interconnection is a critical issue because of the diversity of distributed technologies and the variability of interconnection standards and practices from state to state and utility to utility. The other critical issue is that the potential for interactions between distributed resources in close proximity within a distribution system is not known, simply because not enough operating experience has been gained to date.

DUIT Program

This Distributed Utility Integration Test (DUIT) is the next step in assuring the safe, reliable, secure and cost-effective inclusion of distributed resources into the electric systems of the future

By examining current and emerging technologies and operational concepts to properly integrate diverse distributed resources, this project gives new insights into grid support issues. The goal of the Distributed Utility Integration Test as funded by the California Energy Commission is to determine what impact large numbers of Distributed Energy Resources will have on the electrical distribution system

The goal of the Distributed Utility Integration Test as funded by the California Energy Commission is to determine what impact large numbers of Distributed Energy Resources will have on the electrical distribution system.

The specific goals of this phase of the DUIT project were to develop a testing facility to prove the feasibility of the integration of diverse distributed energy resources in a distribution system and provide a testing ground for observing and measuring the interactions between the distributed technologies on the distribution system. Achieving these goals requires a facility that can conduct full-scale implementation testing and demonstration of distributed energy resources in realistic utility installation.

Objectives

The Objectives of this phase of the DUIT project are to:

- Build a 480V testing facility that would be able to test commercially viable in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.
- Conduct the unintentional islanding tests for individual units, homogenous inverter groups and small groups of non-homogenous inverters

Approach

The general approach for accomplishing our project objectives consisted of:

1. Developing An Industry Team
2. Test Plan Prioritization and Detailed Design
3. Technology and Electrical Engineering Facility Preparation
4. Validate Test Design
5. Conduct Tests

Developing an Industry Team

We first began by developing and implementing a procurement process for vendors and suppliers of the distributed resource equipment to lend the appropriate amount of equipment to be tested based on its relevance to the California market.

Our teaming process then to brought to the table testing bodies and other industry experts to assist with the review of the test plan along with the DER vendors and utilities and other financing partners.

Test Plan Prioritization and Detailed Design

Working from the DUIT test protocols developed in 2001, we overlaid the prioritized protocols with the scheduling and availability of DER hardware, fuel needs, maintenance, and other operational factors and established an efficient optimal test plan schedule.

We then developed, a more detailed definition of order and precedence of the anti-islanding set of test, as well as how tests within the groups would take place. This prioritization process was open and solicited input from our industry team many of whom are members of the Rule 21 committee.

Technology and Electrical Engineering Facility Preparation

It was necessary to upgrade the PG&E testing facility to accommodate DUIT testing. This included a redesign and the interconnection of the selected DER This task also included hardware procurement necessary for performing the DUIT tests. Only that hardware to be used in the early phases of the testing was be procured at this time. The engineering effort necessary for this procurement and the construction of infrastructure equipment drawings are identified here in the body of this report. The upgrades affect not only the 480V testing effort but begin the preparation of the DUIT testing at distribution voltages, as shown in the 21kV drawing.

The facility plan was to design and install supporting infrastructure and DER to meet these minimum requirements.

- 3 DER sites or (bays), each consisting of one larger unit, or several smaller units
- Total combined generation up to 500kW

- Maximum single unit generation of 150kW
- Variable resistive, reactive, and capacitive loads at each DER location
- 480 V radial distribution
- Total simulated impedance of 30 miles, in 10 mile steps
- Design of 21kV distribution test facility for future use
- Data, Acquisition and control in coordination with the installation of the DER.

Validate Test Design

Validating the test design and set up is accomplished by conduction the basic unintentional islanding test and modeling the test set up. Modeling can allow subsequent test conditions to be repeated on the computer rather than having to actually setup and re-execute testing. The ability to extend the DUIT test results to these subsequent conditions minimizes actual testing while maximizing value of results. Furthermore, the models, as validated during testing, can available for use in extending test results to other "real world" projects which will likely have slightly modified configurations. For these reasons, it is important to develop and validate models as testing is being performed. Those tests that lend themselves to modeling for future applications are identified, models are developed, and when testing takes place, the simulation runs are compared with actual test data. The loop is closed when this data from test results are used to adjust or tune the models.

Conduct Tests

Conduct the tests as documented in the test plan.

Outcomes

This phase of the DUIT project objectives were accomplished by developing and industry team of advisors Technical Advisory Committee (TAC), developing a peer reviewed and prioritized detailed and sequenced test plan, upgrading the PG&E facility to accomplish the testing. When the facility was complete the team was able to validate all aspects of the test setup and then proceed with testing and analyzing results.

The DUIT team accomplished our objective of building a world class DER integration test facility that has given many tours to visitors from all over the United States and from more than eight countries from around the world. We also completed the single unit unintentional islanding tests at 480V. Then we went on to complete the homogenous and small group tests at 21kV. We had expected to complete much more of the unintentional islanding group of tests during this phase of the project but the testing took much longer than expected. However, the results were so unexpected and the learning was so rich that we are confident that the DUIT test results have had a significant impact on the industry in support of the interconnection standards.

Developing an Industry Team

We developed a technology and testing review team consisting of representatives of six DER vendors, who lent their DER equipment to the project for an extended period of time, all of the California Investor Owned Utilities and Sacramento Municipal Utility District, Underwriters laboratory and other interested parties. Accomplishing this effort enabled Distributed Utility Associates to build a team of vendors, that lent the appropriate amount of equipment to be tested based on its relevance to the California market. Results of this task are documented in contract deliverable 2.1.4 The Final Procurement Process Report.

Test Plan Prioritization and detailed design

A test plan was detailed out for Basic single unit unintentional islanding tests, as well as unintentional islanding tests multiple unit testing specifically for homogenous groups and small groups. Homogeneous Groups are groups of DER that contain the same technology and manufacturer. Small Groups are groups of DER consisting of different manufacturers within a given DER technology.

The review team was also responsible for the prioritization of the test plan.

Technology and Electrical Engineering Facility Preparation

Our team designed and built a 480V testing facility that has proved to be the best in the world for testing commercially viable DER in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.

It was necessary to upgrade the PG&E testing facility to accommodate DUIT testing. This included design and line diagrams for the interconnection of the selected DER The upgrades affect not only the 480V testing effort but begin the preparation of the DUIT testing at distribution voltages. The facility attributes are as follows:

- 3 DER sites, each consisting of one larger unit, or several smaller units
- Total combined generation up to 500kW
- Maximum single unit generation of 500kW
- Variable resistive, reactive, and capacitive loads at each DER location
- 480 V radial distribution
- Total simulated impedance of 30 miles, in 10 mile steps
- 21kV distribution testing capability for islanding tests and additional use in testing additional protocols

These attributes more than met the minimum required in this phase of the project.

Validate Test Design

Validating the test design and set-up was accomplished by conduction the basic unintentional islanding test and modeling the test set up. The Single-Unit Unintentional Islanding Test Results at the DUIT Test Facility validated the test design and setup. These tests were the first tests to be performed in a comprehensive suite of tests to evaluate the impacts of distributed resources in a realistic test environment.

Conduct Tests

We conducted the unintentional islanding tests for individual units and homogenous groups and some small groups of different types of single phase inverters. In particular the DUIT test illuminates: requirements and tests for safe and effective interconnection, interconnection equipment performance and functional characterization and installation test method design, development, test set up validation and documentation

For the single unit tests the manufacturers of the units that experienced islanding times in excess of 2.0 seconds were asked to provide details of the anti-islanding algorithm used in their units. Analysis of this information may enable design and/or calibration changes to eliminate the occurrence of islanding run-on.

In the results meeting of June 4th 2004, the utility reviewers strongly recommended that the project immediately move to distribution voltage level testing in our case 21kV. PG&E responded by bring the necessary equipment to the project in order to upgrade the voltage. This allowed the testing to proceed at a higher voltage than was ever expected in the first phase of testing.

Multiple-Unit Islanding tests derive from the Unintentional Islanding test for single phase units. The test procedure is the same as the tests conducted for Single-Unit except that the test is run through the distribution voltage islanding switch.

558 Islanding Tests were completed in the Multiple-Unit Test Phase. They included 15 test sequences, each containing 33%, 66% and 100% power ratings with ±5% variations in Q at 1% intervals.

Summary of Homogeneous Groups Islanding Test Results

254 Islanding tests were completed in the Homogeneous Testing Phase.

1 islanding test ran on for up to 2.327 seconds, exceeding the 2-second maximum limit.

The results reveal differences in trends between inverter types as deployment numbers increase. Two inverters improve trip times as more systems are installed in parallel. Conversely, one inverter type points toward longer trip times occurring in a narrower resonance zone. In one case, this yielded trip times in excess of two seconds.

Summary of Small Group Islanding Test Results

304 Islanding tests were completed in the Small Groups Testing Phase.

Inverter Type D did not run on when paralleled with device types F or E.

However, when device Types F and E were combined, there were 6 events exceeding the allowable 2-second limit. These occurred at different power levels, depending on the specific combination being tested. In one case, with ten units under test, the run-on time exceeded 1 minute.

Conclusions and Recommendations

Conclusions

The Distributed Utility Integration Test successfully brought together manufacturers, utilities engineers and energy researchers to design and build a testing facility to measure and document the interaction of distributed energy resources in a realistic utility distribution system setting.

The DUIT team accomplished our objective of building a world class DER integration test facility that has given many tours to visitors from all over the United States and from more than eight countries from around the world. We also completed the single unit unintentional islanding tests at 480V. We then went on to complete the homogenous and small group tests at 21kV. We had expected to complete much more of the unintentional islanding group of tests during this phase of the project but the testing took much longer than expected. However, the results were so unexpected and the learning was so important to the industry that we are confident that the DUIT test results have had a significant impact on the industry in support of the interconnection standards.

Our team designed and built a 480V testing facility that has proved to be the best in the world for testing commercially viable DER in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.

The facility was completed successfully and the testing began with single unit unintentional islanding tests. The single unit results validated the test set-up and the methodologies employed.

The results of the testing for basic unintentional islanding tests proved that it was necessary to continue efforts with a focus on unintentional islanding. This moved the team into the multiple unit tests. At the conclusion of the phase of the project it was determined by the CEC that it was necessary to continue funding and move forward with additional testing.

The multiple unit tests began the project testing at distribution voltage, 21kV and completed a sequence of homogenous testing of the single phase inverters and the small group testing. Various distributed resources underwent unintentional islanding tests according to industry standards, in a realistic distribution system test environment. The results again validated the test setup at the distribution voltage level and prepared for further and more involved phases of testing of unintentional islanding scenarios.

These islanding tests have brought together the distributed resources industry manufacturers, utilities and government entities to examine the distribution system grid impact of distributed resources and the test results are supporting the industry interconnection standards efforts and the quantification of the value of deploying distributed resources in the utility distribution system.

Recommendations

The first recommendation is specific to the results obtained from the single unit unintentional islanding tests. The Technical Advisory Committee (TAC) recommended

that the manufacturer of DER units provide details of the anti-islanding algorithm, if they are unable to comply with that request, then the device is to be subjected to islanding tests at the center and the limits of the manufacturer's specified input voltage window, plus a test at 5% load. This will increase the number of test voltages from one to four resulting in tests increasing from 33 to 132.

Discussions with Underwriters Laboratories regarding the results of the single unit unintentional islanding tests led to the conclusion that UL should consider revisions to UL1741, comprising more explicit language in the following areas:

- Definition/specification of what constitutes "balanced test conditions";
- Definition of linearity of the test load;
- Acceptable tolerances on pre-test voltage and frequency; and
- Accounting for parasitic losses (real and reactive) in the test load setup

Our industry TAC representing utilities, DER vendors, standards and testing bodies have all recommended that the DUIT project continue on its path of completing the unintentional islanding test plan and move on to the voltage regulation and stability test protocols. Under the 2005 contract with the California Energy Commission and with additional support of the United States Department of Energy we are currently completing this set of tests. It has also been recommended by the DUIT industry TAC to add to the body of research regarding distribution systems. Currently the DUIT efforts examine only those issues having to do with radial systems. It has become increasing important to examine the issues and testing needs for utility network systems.

Benefits to California

Through extensive collaboration the California Energy Commission has advanced the state of the art of distributed resources integration and strengthens its leadership role in distributed power.

- Regulators will be able to make more informed decisions regarding the adoption of IEEE 1547 or other proposed interconnection standards.
- Deeper DER penetration of the distribution system will be better understood and accepted by utilities.
- Utilities will be able to see firsthand the protection afforded by standards and better understand the remaining issues.
- Utilities/distribution companies will have more substantial proof and confidence in the use of DER for their own purposes.
- DER installations will be less likely to have excessive costs because of interconnection fears.
- Customers will have more surety that their DER will be interconnected safely, smoothly, and with minimum cost.
- Customers will be less likely to be adversely affected by their neighbor's DER.

- Manufacturers will be better able to anticipate the types of protection devices required for the most beneficial incorporation of DER into utility systems or at customer sites.
- Standards-setting bodies and rule 21 will feel more (or less) comfortable about aspects of the current standards, leading them to refine, reconsider, or expand subsequent versions.
- Stakeholders will consider the DUIT a good first in resolving some of their most important issues regarding the interconnection of distributed resources into the utility distribution system.

1.0 Introduction

The increasing potential of distributed resources in emerging utility markets has focused attention on two critical issues: interconnection of distributed resources with the electric distribution system, and the unknown nature of potential interactions between multiple distributed devices. Interconnection is a critical issue because of the diversity of distributed technologies and the variability of interconnection standards and practices from state to state and utility to utility. The other critical issue is that the potential for interactions between distributed resources in close proximity within a distribution system is not known, simply because not enough operating experience has been gained to date.

In general, not enough is known about how distributed energy resources (DER) might perform with regard to safety, health, economics, availability, and reliability—especially over time. Knowledge about the interconnection or interface of DER with a distribution grid or customer facility is also limited. Their operation must be interactive if the highest-value benefits are to be obtained and safety and reliability problems are to be avoided. Energy market players such as utilities and customers are traditionally risk-adverse and will defer decisions to install DER until performance is better known.

Without accurate and demonstrated performance knowledge, early adopters are more likely to encounter failures that will further discourage risk-adverse would-be adopters.

Policymakers such as lawmakers, regulators, and public-good funds managers need test information to develop, implement, and enforce policy decisions that result in improved laws, regulations, codes and standards, and technologies.

Even now, as the Institute of Electrical and Electronics Engineers (IEEE) P1547 committee has developing interconnection standards for distributed power, the issue of the allowable penetration level of DER on a feeder is controversial. Diverse opinions (but little data) abound. DER penetration levels may not even be as important as the types and numbers of technologies in a given locality.

Individual states and utilities have begun to evaluate whether these standards should be adopted in whole or in part. Utilities might still be circumspect about the applicability of these standards to their typical distribution conditions. Thus, an early integration test tailored to address state and utility concerns will lead to a more uniform national set of standards by reducing the difficulty of embracing the IEEE standards. This will help make policy more uniform at state and utility levels.

As this industry expands and the power system becomes more dependent on distributed power, the efficiency, grid and facility compatibility, and reliability of DER and up-to-date, appropriate rules and regulations become more pressing public issues.

As distributed power becomes more commonplace, its electrical interactions will become more important to understand and more challenging to manage. This testing program attempts to anticipate electrical interactions and discover the problems and benefits that will result from the extensive use of DER.

This Distributed Utility Integration Test (DUIT) is the next step in assuring the safe, reliable, secure and cost-effective inclusion of distributed resources into the electric systems of the future. Through extensive collaboration the California Energy Commission has advanced the state of the art of distributed resources integration and strengthened its leadership role in distributed power.

By examining current and emerging technologies and operational concepts to properly integrate diverse distributed resources, this project gives new insights into grid support issues. The goal of the Distributed Utility Integration Test as funded by the California Energy Commission is to determine what impact large numbers of Distributed Energy Resources will have on the electrical distribution system

DUIT Program Objectives

The overall objective of the Distributed Utility Integration Test (DUIT) Project is to perform comprehensive testing to evaluate the potential impacts of substantial penetration of distributed resources into the distribution system.

The DUIT Program is a thorough test of the feasibility and value of co-location and integration of multiple diverse distributed generation and storage technologies into the electric distribution system. Several distributed energy resource technologies are installed within electrical interaction proximity of each other to allow for their aggregate benefits and operational issues to become evident.

The units are instrumented to measure the potential electric distribution system advantages and challenges of substantial penetration (greater than 10% of local load) of distributed energy resources.

The project is meant to measure and analyze the interactions between units rather than prove the operation of any single innovative distributed generation technology and storage component; thus rental, lease or loan of "off-the-shelf" distributed generation and storage units is preferable from both test design and budgetary standpoints. The purchase of distributed generation and storage hardware is beyond the budget and scope of this project.

There are a total of eleven classes of tests to be performed at the DUIT Facility, in accordance with the *Distributed Utility Integration Test Project Plan* [National Renewable Energy Laboratory]:

1. Unintentional Islanding
2. Voltage Regulation
3. Power Quality
4. Reclosing Coordination
5. Sectionalizing
6. Fuse Coordination

7. Short Circuit Contribution

8. Capacitor Switching

9. Stability

10. Adjacent Feeder Faults

11. Intentional Islanding

The purpose of this phase of the project is to take elements from the complete turnkey DUIT plan which is optimized for a multi-year budget phased approach and to sub-divide this into two immediate key elements. These elements are the performance of high priority tests at low voltage and the modification of the distribution voltage facility at the proposed test site to accommodate multi-unit testing at 21kW and other future testing.

The tests are performed following the steps outlined below.

- Acquiring the necessary distributed generation sources for completion of the most immediate tests.
- Plan and organize tests based on Rule 21 committee input.
- Installation of DER technology and performance of qualification and acceptance testing of distributed generators at the DUIT site.
- Development, installation and verification of a Data Acquisition System (DAS) for low voltage testing.
- Identification of appropriate models for extending and validating test results.
- Performance of the low voltage tests and monitoring and analysis of results.
- Upgrading of the distribution voltage test area.
- Establishing of multiple test bays for accepting multiple distributed generators

1.1. Objectives

The Objectives of this phase of the DUIT project are to:

- Build a 480V testing facility that would be able to test commercially viable in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.
- Conduct the unintentional islanding tests for individual units, homogenous inverter groups and small groups of non-homogenous inverters

The first objective of this phase of the project was to develop a facility to prove the feasibility of the integration of diverse distributed energy resources in a distribution

system; and provide a testing ground for observing and measuring the interactions between the distributed technologies on the distribution system. Achieving our second objective, testing, requires a facility that can conduct full-scale implementation testing and demonstration of distributed energy resources in realistic utility installation.

In particular the DUIT test illuminates the following issues:

- Requirements and tests for safe and effective interconnection;
- Interconnection equipment performance and functional characterization and installation test method design, development, validation and documentation;
- Interconnection equipment/technology body of tests issues and procedures

This report documents the development of the facility and the initial testing, Unintentional Islanding: single-unit unintentional islanding tests, and multiple unit single phase inverter tests.

The testing results of this report document the Unintentional Islanding tests for single-unit (Test 6.1) and single phase multiple-unit (Test 6.2) from the Unintentional Islanding test plan CEC deliverable 2.24.

1.2. Overview and Background

The distributed utility concept involves the use of modular electric technologies that provide electric capacity or energy when and where they are needed within an electricity distribution system. Such technologies, collectively referred to as distributed energy resources or distributed resources, include both distributed energy resources (DER) and distributed storage. DER may be either interconnected with a large grid or isolated from the grid, but their locational value is high enough that their distributed value is important to their economics and operation. Modular electric technologies (e.g., photovoltaics [PV], fuel cells, microturbines, cogeneration, or small battery storage systems) are common examples of DER and have historically been sized to maximize local advantages, usually from the customer perspective. This has led to matching DER to local loads and dispatching for substantial customer benefits. Dispatch and control by the utility, for the utility's benefit, has, for the most part, not been a major consideration in the design of these systems.

Utilities can use modular electric technologies to delay, reduce, or eliminate the need for additional generation, transmission, and distribution infrastructure and to avoid some expenses while firming up voltage and local reliability. If the DER can serve the load effectively, the utility avoids incurring costs associated with its traditional "central generation and wires" solution.

Customers can apply the Distributed Utility concept two ways: to manage their bills and reliability by augmenting their service with DER or to provide power completely independent of the grid (either by choice or out of necessity). If the customer system is grid-connected, interconnection procedures and contractual relationships with the utility must be addressed.

Although the Distributed Utility concept makes economic sense for the vertically integrated utility of the present, how will the envisioned electric utility industry restructuring affect opportunities for distributed generation or storage and targeted demand management? The potential benefits of using DER include reduced capital expenditures for generation, transmission, and distribution equipment; increased component life; reduced line losses; improved reliability and power quality; and expanded customer service. The development of an accepted methodology for evaluating these benefits is only beginning, but considerable work has been done in this area over the past 10 years.

The benefits of applying the Distributed Utility concept—whatever they are in a given instance—can be internalized by vertically integrated utilities as part of their regulated business practices. A utility's generation, transmission, and distribution planners and operators can determine just the right place and time to install DER for maximum advantage.

DER is in its infancy as a utility solution for cost reduction, improved use of T&D resources, and enhanced system reliability (e.g., ancillary services such as operating reserves and voltage support). Nevertheless, end-use customers have been using on-site power in various forms for many years to achieve benefits such as improved reliability (standby/emergency power), reduced demand charges (peak shaving, interruptible rates, power factor improvement), and reduced energy costs (cogeneration, prime power in areas with high electric rates or no electric service). Traditional technologies such as reciprocating engines and steam and gas turbines have outstanding track records of providing end-use customers with these and other benefits. Emerging technologies such as microturbines, fuel cells, PV, and energy storage systems hold promise to provide customers with these same benefits and other desirable enhancements (e.g., improved power quality and uninterruptible supply) at higher efficiencies and reduced emissions.

What is missing from the customer side of the equation is proof that traditional and emerging technologies can work together seamlessly to provide the desired mixture of benefits. What is missing from the utility side of the equation is proof that any of these technologies can be used as reliable DER to improve system operation and lower the cost of electric service for all customers. Questions that must be answered before either utilities or customers will widely adopt DER as a means of achieving these benefits include:

- Will there be significant systems integration and interoperability problems when installing and using different kinds of equipment from different manufacturers (e.g., conflicting modes of operation, inability to "load share" between multiple units, inability to communicate with units for maintenance and tracking purposes)?
- Can "islanded" operation as a "microgrid" be automated to best use the features and characteristics of different DER technologies to serve base load, intermediate load, and peak load requirements at a facility?

- How will multiple DER technologies at a facility interact with the grid when interconnected, and can these resources be managed safely and cost effectively with other utility resources?
- Can DER be integrated cost effectively into other utility systems such as substation automation, distribution automation, and customer billing systems?
- What benefits, if any, do DER provide with regard to voltage regulation, power factor improvement, or other ancillary services?
- Do we need DER standards for issues such as metering and billing, protective relays for safe interconnection with the grid, emissions and other permitting requirements, communication protocols for proper fault recovery and system coordination, and management?
- Will there be adverse interactions among different types and brands of DER technologies that could actually create power quality problems rather than alleviate them (e.g., harmonics from inverters)?
- What economic and reliability benefits can the utility really expect to achieve with automated dispatch capabilities?
- Can DER participate cost effectively bidding procedures for generation supply or customer load on an aggregated basis?
- Is there a DER technology demonstration project available in the public domain to help utilities, manufacturers, and customers make informed decisions with regard to the claims surrounding DER?

1.3. Benefits to California

The realization of conceived benefits is another expected result from the DUIT program. The economic benefits of location and dispatchability as well as ancillary benefits will be validated through demonstration.

The list of potential results illustrates the types of issues that will be resolved, raised, or illuminated by the DUIT. The effect of having these technical answers will differ depending on the stakeholder.

- Regulators will be able to make more informed decisions regarding the adoption of IEEE 1547 or other proposed interconnection standards.
- Deeper DER penetration of the distribution system will be better understood and accepted by utilities.
- Utilities will be able to see firsthand the protection afforded by standards and better understand the remaining issues.
- Utilities/distribution companies will have more substantial proof and confidence in the use of DER for their own purposes.
- ISOs, regional transmission organizations, generation companies, transmitting utilities, and energy brokers will have more confidence in the operation and benefits of grid-connected DER.

- DER installations will be less likely to have excessive costs because of interconnection fears.
- Customers will have more surety that their DER will be interconnected safely, smoothly, and with minimum cost.
- Customers will be less likely to be adversely affected by their neighbor's DER.
- Manufacturers will be better able to anticipate the types of protection devices required for the most beneficial incorporation of DER into utility systems or at customer sites.
- Standards-setting bodies such as IEEE will feel more (or less) comfortable about aspects of the current standards, leading them to refine, reconsider, or expand subsequent versions.
- Some stakeholders will consider the DUIT as a good first step but still inadequate to resolve some of their most important issues.

1.4. Report Organization

This report is organized as follows:

Section 1.0 Introduction

Section 1.0 provides the background and discusses the issues regarding the need for testing DER for distribution system grid impacts. It provides a discussion of the history and the overall goals for the DUIT program as well as the objectives of the first phase of the California Energy Commission sponsored DUIT project.

Section 2.0 Project Approach

Section 2.0 presents the approach and methodology by laying out the steps involved in developing the teaming and partnership activities, the development of the test plan, and provides an overview of the test facility, details of the various aspects of the design of the DUIT facility and as well as specifications regarding the equipment utilized. Layout drawings of the testing site are also provided in this section.

Section 3.0 Project Outcomes

This section documents the results of the industry teaming efforts, the test plan, the completed facility and the test validation. This section also details test results for the various phases of testing, organizing the data into graphs and tables.

Section 4.0 Conclusions and Recommendations

Appendix A Basic Anti-Islanding Test

Appendix B Anti-Islanding with Multiple DER Types

Appendix C Anti-Islanding with Reduced Undervoltage and Underfrequency Trip settings

Appendix D DUIT Data Acquisition System (DAS) Architecture

2.0 Project Approach

The general approach for accomplishing our project objectives consisted of

- Developing An Industry Team
- Developing A Detailed Test Plan For Unintentional Islanding
- Test Plan Prioritization and Detailed Design
- Validating Test Design
- Conducting Tests

2.1. Developing an Industry Team

We first began by developing and implementing a procurement process for vendors and suppliers of the distributed resource equipment to lend the appropriate amount of equipment to be tested based on its relevance to the California market.

Our teaming process then to brought to the table testing bodies and other industry experts to assist with the review of the test plan along with the DER vendors and utilities.

In considering a broad range of DER available for testing, there were two principal requirements which were considered. First, the DER to be used needed to be compatible with obtaining the highest maximum value from the testing proposed under this program. In meeting this requirement, the DER should be diverse and representative of commercial hardware currently installed within the state of California. Once the diversity, commercial viability, and portfolio of DER was considered, it was determined desirable to obtain as much DER equipment as possible under borrow or donation terms from the vendors or other interested third parties. This approach is taken for three reasons: 1) because ownership of equipment is not necessary to meet the project's goals and objectives, 2) this approach should minimize system engineering and procurement costs and 3) vendor support and project buy-in. The DER technology developers are eager to include their systems in a world-class, groundbreaking project like DUIT as they have a keen interest in resolving the exact interconnection issues identified by this testing. To date DUA has secured approximately $250,000 worth of DER equipment on a no cost basis to the project.

2.1.1. Selected DER

The MGTF facility is divided into three different bay areas which are shown in the drawings facility chapter. The photographs in Figure 1, Figure 2, Figure 3, and Figure 4 show the respective DER. Bay 1 contains 34 residential scale photovoltaic inverters and is to be representative of a radial feeder within a subdivision or housing tract. Bay 2 contains two larger three-phase inverters and is representative of a commercial building installation. Finally, Bay 3 contains the rotating DER consisting of a diesel generator set and a rotating induction generator and motor load. The sum total of all connected DER in the three bays is 515 kW. There is a diverse combination of DER technologies as well as a wide diversity of electrical kW ratings of the generation devices.

Figure 1 STS and Beacon Inverters

Figure 2 Xantrex and SMA Inverters

Figure 3 Layout of Equipment in Bay 2

Figure 4 Cummins Diesel – Bay 3

2.1.2. Coordination of DER/Test Schedule

When this task was initiated, it was assumed that DER equipment would be cycling in and out of the test facility on a regular basis. If this had been true, then the need to carefully coordinate test schedules with DER schedules would be apparent. However, the arrangements made with all vendors permits the project to have the DER at the outset of the testing and for all DER to remain available at the site until after the testing is completed. The fact that this equipment is available through the entire testing duration of CEC DUIT Phase 1, eliminated the availability constraint and provides greater flexibility in the scheduling of the test phase of the program.

2.1.3. Inverter Based Prime Movers (Photovoltaics and Power Supplies)

The inverter based DER is being driven by two principal sources of power. First, PG&E has contributed the use of approximately 13.5 kW of roof mounted photovoltaics (PV). This commitment is in addition to the currently documented costshare. These modules are mounted on the Technical and Ecological Services main building roof and have been wired via over/under ground conductors to the testing area. DUA is in the process of negotiating additional PV from other vendors, however, this additional PV will not be required, or available for the initial CEC DUIT Phase 1 testing. The PV is supplemented by the purchase of a number of power supplies. The power supplies are broken into two categories: high voltage, low current, and low voltage, high current. The high voltage, low current supplies are used in Bay 1 and are used to provide power to five SMA inverters. The other five inverters are supplied power from the PG&E provided PV panels. Having five inverters with each prime mover will allow testing and confirmation of how well the power supplies emulate the PV panels for islanding tests and will allow us to determine which of the prime movers represents the worst case. The seven low voltage, high current supplies are all connected together to make up a single large 42 kW power supply. This power supply then provides power to the low voltage Xantrex inverters. The Xantrex inverter is designed to operate off of a battery source and it does not peak power track. For these reasons, no PV is initially connected to the Xantrex inverters. The power supplies were purchased from the Programmable Power Group at Xantrex.

2.1.4. DER Cut-Sheets

Cut-sheets for all of the DER devices to be used in the tests are provided in the Final Procurement report. The cut-sheets provide the important application information about each of the DER. For example, mounting dimensions and air flow requirements are identified in the cut-sheets. DER specifications are included in most of the cut-sheets. Where programming of the DER is required, the methods and approaches to programming are also included.

Transformers, impedance's, the control system network and data acquisition networks are also shown in the drawings

2.2. Test Plan Prioritization and Detailed Design

Introduction

Working from the DUIT test protocols developed in 2001, we overlaid the prioritized protocols with the scheduling and availability of DER hardware, fuel needs, maintenance, and other operational factors and established an efficient optimal test plan schedule.

We then developed, a more detailed definition of order and precedence of the anti-islanding set of test, as well as how tests within the groups would take place. This prioritization process was open and solicited input from our industry team many of whom are members of the Rule 21 committee. The results of this task are thoroughly documented in the contract deliverable, 2.2.5 Final Test Plan.

Background

The existing distribution system was engineered to distribute electric power from a single source, the distribution substation, to various customer loads in the most cost-efficient manner. It was designed to provide power between zero load and the maximum projected load to all customers on analysis particular distribution circuit at voltages and frequencies within allowable ranges.

The test plan outlining the most efficient sequence to be used in the implementation of the unintentional islanding subset of DUIT tests. This version of the test plan was submitted to selected members of the distributed generation community within the state of California for review and comment. This group included representation from utilities, manufacturers, and integrators and installers. As a result of the feedback obtained from the review process, a modified final plan was developed and submitted. The complied comments from the reviewers were submitted as deliverable 2.2 #3 to the Energy Commission.

The draft test sequence proposed in this document is the result of a substantial earlier prioritization and review efforts under Department of Energy Contract # NREL –AAD-0-30605-05. The test protocols developed under that contract were developed by a group consisting of utility protection engineers, DER manufacturers, and DER integrators and installers. After a draft version of the protocols was developed, the protocols were circulated among a larger group of DER community, both within the state of California as well as nationally. The feedback provided on the draft set of protocols, together with the prioritization offered, then factored into the final protocols and the proposed sequence presented here. The test protocols developed under the DOE contract remain the property of Distributed Utility Associates.

In reviewing this draft test plan, it is important to read the Draft Facilities Hardware Report (Deliverable 2.6), to understand the layout of the DER within the facility as well as the facilities' capabilities. Also the Draft DER Test List and Draft Procurement Process Report (both Deliverables under 2.1) should be read for a description of the type of DER to be used as well as the timing and availability of this equipment.

The proposed subset of tests to be performed under this contract deal with the issue of unintentional islanding. In earlier prioritization efforts this topic has always appeared at the top of priority lists. In the state of California this issue has been the most contentious between vendors, installers, and utilities and has led to the disconnection of DER devices and the inability of certain sites to have DER installed. The following background section discusses many of the major anti-islanding topics surrounding the interconnection of DER into utility distribution systems.

2.2.1. History of the Unintentional Islanding Issue

Area Electric Power Source (EPS) operators have tremendous liability serving the customers in their service areas. The payouts that the Area EPS operator makes to cover customer equipment damaged by momentary sags and surges can be staggering. The problem is bad enough when the utility has control over the generation equipment providing the power. The thought of customer-owned generation operating a portion of the Area EPS without utility control keeps utility protection engineers awake at night.

Many of the problems utilities encounter result from small generators connected inappropriately and illegally to a customer's electric service panel without disconnecting from the Area EPS. Intended to power the customer's loads in an outage, these generators are not designed to operate in parallel with other generation nor power significant portions of the utility grid. They have caused damage to other customers' equipment (primarily due to undervoltage), are usually damaged catastrophically when the utility returns (lack of synchronization), and have injured and killed unsuspecting utility lineworkers.

Testing and theoretical analyses have shown that under extremely well balanced load and generation conditions, loss of utility, such as by opening a sectionalizing switch, will not necessarily lead to immediate system instability. Sandia National Laboratory (SNL) has shown that inverters using only under/over frequency and under/over voltage tripping can maintain a stable island with a load to generation ratio between 80 percent and 120 percent.

If the DER is not tripping off, then the frequency and voltage must be within specifications. The frequency and voltage windows that the DER is allowed to operate in (59.3 to 60.5 Hz, 106 – 132 VAC) are substantially wider than the utility is normally required to maintain (59.97 to 60.02 Hz, 114 to 126 VAC). The wide windows let the DER ride through disturbances and utility problem situations. Should islanded DER operate loads for an extended period at either extreme of voltage, other customers' equipment could be damaged, and the deep-pocketed Area EPS would most likely be held responsible.

The next question is: how likely are such "ideal" balanced island conditions likely to occur and remain stable for any significant period of time? Begovic, Ropp, et. al. looked at the probability of an island occurring, relying only on voltage and frequency trip points. This paper notes that all techniques of detecting islanding can be fooled and defines the term Non-Detect Zone (NDZ) to describe the conditions, specific to each detection method, that cause it to fail to detect. Having a non-detect zone does not mean

the method is inadequate, as the NDZ may be well outside reasonable operating conditions or it may require multiple unique (unlikely) situations to occur simultaneously.

In fact, much of the debate surrounding islanding has to do with the probability of the required conditions occurring. It is generally agreed that the probability need not be zero for a method to be effective, but the debate continues over what is an acceptable level of probability, and what the probability is of any specific situation or set of conditions occurring.

Various techniques have been developed to detect and prevent the formation of an unintentional island. The vast majority of potential islands are unstable and quickly fall outside of standard voltage or frequency limits. Simple detection techniques developed in the 1980s, such as frequency shift, were able to reduce the islanding window, or non-detect zone, significantly. Advanced techniques, now standard on commercially available products, have squeezed the non-detect zone even further such that the NDZ exists only for unrealistic grid conditions.

2.2.2. Islanding Detection Methods

The most effective method for detecting an island condition is for the utility to provide a signal telling the DER it's okay (or, more commonly, it's not okay) to parallel. For 100 kW and larger DER systems, the use of such a signal—typically called transfer trip—may be an economically justifiable anti-islanding technique. However, depending on the implementation, it is not always flawless, and it is not economical for smaller systems. For this reason among others, there has been substantial activity in developing active and passive[1]islanding detection methods for small inverters for photovoltaic systems. Beginning in the early 1980s, PV inverter manufacturers began developing and implementing anti-islanding techniques. At the time, the most effective techniques were those that attempted to destabilize the grid, most commonly trying to push the frequency up or down. With utility generation sources present, the inverter is unable to affect the line frequency; however, when the utility sources go away, the inverters can shove the island frequency out of tolerance and trip off. This approach, commonly used in the U. S. and other places, can potentially be defeated by rotating loads or DERs on the same line or by a balanced number of DERs trying to push in opposite directions. For example, when the utility goes away, a motor load tends to spin down, reducing

[1] The terms active and passive islanding detection have a variety of interpretations. Often, they are used to differentiate between techniques that try to actively affect a change in one or more Area EPS parameters, such as frequency push, and those that passively measure grid parameters such as under/over frequency. Alternatively, they are used to distinguish between methods that control the inverter output and those that don't. The impedance methods, where the inverter output is changed as a way of measuring—but not affecting—grid impedance would be considered passive under the first definition, and active under the second. Another interpretation might be that passive methods attempt to detect the island condition, while active methods attempt to inhibit the formation of an island.

frequency; while an under-loaded rotating generator will tend to speed up. Either of these could tend to balance out a simple frequency push method. In addition, if the push is uncoordinated, half of the DERs could be pushing up and the other half pushing down, thus again stabilizing the island.

A method currently favored in parts of Europe is based on measuring the impedance of the Area EPS. By injecting a current pulse and measuring the voltage response, the impedance of the Area EPS grid can be measured. Typically, the grid impedance changes when the utility disconnects from the island. Thus, when the impedance drops below a predetermined value or when it changes by more than a certain amount, the unit initiates a disconnect. This technique is very sensitive to loss of utility but has a few drawbacks. The act of injecting a current pulse is a form of distortion. If this pulse is of high enough magnitude and performed frequently enough, it will have an adverse impact on harmonics. The solution to this is to keep the current pulse small and relatively infrequent, e.g., once a second. Infrequent measurements slow the detection.

There is also a potential interference problem at high penetration levels leading to nuisance tripping. If two units are close enough and inject the pulse at about the same time, there will be a reduction in the perceived impedance (twice the current should result in a doubling of the voltage change), which could lead to a trip. Nonetheless, there are several small inverters that have effectively implemented this technique and some empirical data suggests there is little interference between units.

As a result of the1997 Sandia Anti-Islanding working group, discussed below, two detection methods were developed. These methods are similar to techniques developed by Toshiba, and before them, American Power Conversion. Essentially, the Sandia Frequency Shift and Sandia Voltage Shift attempt to push the frequency or voltage first in one direction, then the other. If the parameter in question appears to be affected, the unit continues to push again in the same direction, successively harder each time. Together, these methods tend to be much more effective at detecting island conditions and do so much more quickly. These methods may also be subject to self-interference if an aggregate of units is attempting to push in one direction while a nearly equal aggregate of units is pushing in the other. Incorporating a small random offset in the rate at which each unit attempts to push should reduce this possibility. There is also a concern that large DERs on weak Area EPS line segments trying to push the utility frequency or voltage around may actually do so, even with the utility present.

Along with these two detection methods, a more precise procedure for evaluating islanding detection techniques was described based solely on passive resistive/inductive/capacitive elements. Most notably, the pass/fail criterion was defined in terms of circuit resonance, or Q. The test is felt to eliminate the need for rotating loads, which are very difficult to define and implement in a replicable way. Also, the circuit Q is related to power factor—a parameter of significance to Area EPS engineers. The selected Q of 2.5 is equivalent to a circuit with a power factor of about 0.37, which is poorer than would be reasonably expected on an operating or islanded Area EPS line segment. This test procedure has been adopted and documented in IEEE 929, UL 1741, and is being considered for IEEE P1547 as well as internationally by the International Electrotechnical Commission (IEC) Technical Committee 82.

The use of a motor load in the test circuit is considered necessary by some. The inertia provided by a motor is a characteristic not found in passive RLC circuits. This inertia may impact methods that attempt to destabilize the island. However, the non-linear current required by the motor is not easy for some inverters to provide, thus their presence may enhance the DER's ability to detect an island.

2.2.3. Technologies Used In The Anti-Islanding Tests

Because of the large number of technologies and quantities of DER's used in this project, it is necessary to define different groups which will be used in anti-islanding testing.

These groups are defined as follows:

- Homogeneous Groups are groups of DER that contain the same technology and manufacturer. For example, a homogeneous group of SMA inverters could include as few as one inverter or as many as ten of the SMA single phase inverters.
- Small Groups are groups of DER consisting of different manufacturers within a given DER technology. An example of a small group would be 3 Xantrex PV inverters operating in a test together with 3 SMA PV inverters. The small group could also include three phase PV inverters as well. The quantity and makeup of DER's on this project allow for small groups of PV inverters only. At a future date, it should be possible to construct a small group of diesel gensets, or microturbines.
- Progression is a term used to combine different numbers of DER within a technology and/or combine different technologies. Progression in this test plan is used to describe the following,
- 20 single phase inverters,
- Plus 2 three phase inverters,
- Plus a 300 kW diesel genset.

2.2.4. Unintentional Islanding Tests

Tests in this section are intended to address issues and concerns related to unintentional islanding. While specific anti-islanding tests are prescribed in IEEE P1547, IEEE 929, and UL 1741, these tests are principally DER device related. There remain concerns that possible shortcomings exist in current anti-islanding approaches when an aggregation of DER devices are applied to a local area EPS. The tests in this section will deal directly with these concerns.

Islanding detection schemes can be devised to exploit test conditions, and tests can be devised to favor one detection method over another. Any islanding detection scheme can be foiled with a test specifically designed to do so. The proper approach is to define a test procedure that reflects extreme, yet realistic conditions that might occur during an island.

The tests in this section are intended to evaluate the limits of detection for various detection methods and how those limits may affect the proper operation of the Area EPS.

Note that many of the issues related to the integration of DER into the Area EPS are related to islanding.

The order of the progression is selected based primarily on increasing generation capacity.

A list of the tests and the sequence in the unintentional islanding test plan is listed below.

Table 1 Unintentional Islanding Test Plan

Unintentional Islanding Test Plan	Test Description and Sequence
6.1	Basic Islanding Test Individual unit testing
6.2	Islanding with Multiple DRs Homogeneous Groups Small Groups Progressions
6.3	Non-Linear Loads, Anti-islanding Tests Individual Units
6.4	Islanding with Dynamic Load :Generation Ratios Individual Units
6.5	Anti-islanding with Rotating Loads Individual Units
6.6	Harmonic Content due to Anti-islanding Schemes Individual Units
6.7	Voltage/Frequency Trip Settings Individual Units Homogeneous Groups Small Groups Progressions

2.2.5. Islanding Issues To Be Addressed

The following provides a list of known issues and concerns related to islanding. DUIT testing will address these issues.

- Number of devices – Large numbers of small units tripping independently can act as a stabilizing factor in the formation of an island. Islands are usually more stable when the load to generation ratio is equal to or slightly greater than 1.0. When this ratio is less than 1.0, a few DER units tripping off will move the island into a more stable condition.
- The inertia of rotating electrical machines combined with their tendency to, under loss of load, spin down (rotating loads) or spin up (rotating generators) can confound some active islanding detection schemes, tending to stabilize the island.
- Types of load - Motors, transformers, and other devices can require complex current waveforms that improve the ability some DER to detect an island condition. May depend on device design (motor type, transformer design, magnetization current, etc.)

- High penetration of DER with active anti-islanding (i.e., frequency push) may cause power quality problems or force the Area EPS to be unstable or to shift voltage unnecessarily.
- High penetration of DER with active anti-islanding (even some passive) may interact to cause nuisance tripping.
- Some anti-islanding techniques may be incompatible. Interaction of different techniques may cause non-detect or nuisance tripping (one "bad" unit causes all the neighbors to trip or not detect)
- The size of the island (number and magnitude of load and DER) may make detection easier or more difficult. Does the size of the island make an islandable load-to-generation match more or less likely?
- Autonomous voltage support schemes (active VAR compensation) may enhance or impede islanding detection
- Scalability – Will the results from multiple small DER and small load equate to larger DER and larger loads? Are there voltage-related issues?
- Penetration – are there techniques that are more applicable to low penetration? Are there different issues at high penetration than at low penetration?
- 1-phase vs. 3 phase. Compare single phase DER to three-phase, and combinations of both.
- DER type – do slow-response DER island more easily or is it more difficult

2.2.5.1. Type Test

The testing completed and documented for this report in test 6.1 Basic Unintentional Islanding and 6.2 Multiple Unit testing of single-phase inverters.

Samples of each model of DER will be tested individually at each of the following conditions:

Q = 0, 0.5, 1, 1.8, 2.5

P = 50%, 100%

PLoad/PGen = 0.8, 0.9, 1, 1.1, 1.2

Other Q's and power levels may be performed as necessary or desired. PV simulator and PV array will be compared repeating the test on one sample of each model using one then the other source. This test will need to be done under stable clear sky conditions, and care will need to be take to ensure that the simulator output is reasonably close to that of the array, in both voltage and current.

Measure the clearing time for each test, defined as the time between when the utility disconnect is opened to the time when the DER ceases to energize the utility. This latter

condition will be met when the output current of the device drops to less than 3% of its output just prior to utility disconnect.

2.2.6. Homogeneous Groups

Using the same Q and power levels as in Test 1 (load to generation = 1), multiple units of the same model will be tested as a group. The small single phase inverters will be tested in groups of 2 (any 2), 5 (original 2 plus any other 3) and all 10. This test will address the potential interaction of multiple units operating in close proximity.

2.2.7. Small Group

Using the same Q and power levels as in Test 1 (load to gen ratio = 1), 3 units (any 3) of each of the small single phase inverters will be tested as a group of 9 units total we will increment, for example 1 of each type 2 of each type all 9

2.2.8. Progression

Using the same Q and power levels as in Test 1 (load to gen ratio = 1), perform an islanding test with

a. 20 Single Phase Units

b. Plus The 2 Three Phase Xantrex Inverters

c. Plus 75 kW Inductive Machine

d. Plus 300 kW Cummins

This order is based primarily on increasing generation capacity and the availability of DER equipment.

2.2.9. Synchronous Generator with Small Inverters

This test is intended to determine the impact of a large synchronous generator without anti-islanding (AI) detection on the stability of the island. The three possible outcomes are 1), the units with AI detect the loss of utility and shut down and the synchronous generator is swamped by the load; 2) the units with AI detect the loss of utility and shut down but the synchronous generator remains operating; 3) the units with AI are unable to detect the loss of utility.

Defeat the anti-islanding function on the Cummins 250kW diesel genset. Operate all 30 single-phase inverters at full power. Operate the diesel at 25%, 50%, 100% and 200% of the aggregate output of the small inverters. Set the real load to the combined output of all units and the Q to 0, 0.5, 1, and 2.5.

The monitoring and control system shall:

- Control The Utility Disconnect Switch(Es),
- Collect Pre And Post Trigger Data,

- Control The Load Setting (Though The Setting Value Will Be Entered By The Operator)
- Measure Current Of Each Device (Load Component, Der, Disconnect) And Voltages On Both Sides Of The Disconnect. Other Voltages May Be Necessary Depending On Wiring Losses.
- Current And Voltage Measurements Will Be Band-Pass Filtered To Capture Roughly 58-62 Hz Data.
- Display "Real-Time" Commanded And Actual Real Power, Capacitive Vars, And Inductive Vars (Fundamental Values)

2.3. Technology and Electrical Engineering Facility Preparation

It was necessary to upgrade the PG&E testing facility to accommodate DUIT testing.

2.3.1. Detailed Facility Description

The following is a detailed description of the final design and construction of the PG&E facility where DUIT testing is performed. This Final Report uses engineering drawings, bills of material, and photographs of the PG&E site to convey the upgraded facility plan.

This report identifies the modifications made to the PG&E testing facility, including the Modular Generation Test Facility (MGTF) building, in order to conduct the testing specified in the Final Test Plan. The modifications identified include those needed to upgrade the facility to distribution voltages for DUIT testing. The facility more than meets the testing minimums as described in the Scope of Work:

- Three (3) distributed energy resource (DER) installation sites, consisting of one larger unit or several smaller units;
- Total combined DER generation capacity up to 500 kW;
- Maximum single unit generation of 150 kW;
- Variable resistive, reactive, and capacitive loads at each DER site;
- 480-volt radial distribution;
- Total simulated impedance of 30 miles in 10-mile steps.

The impedance required is not represented on the drawing and was not used for the tests documented in this report.

An overview of the facility is shown in Figure 5. The key buildings and resources are also identified in the figure. For purposes of the DUIT test, the key areas include the Modular Generation Test Facility (MGTF) and the high current yard. The facility was modified to accept DER, load banks, PV, and 21 kV distribution transformers for the proposed DUIT testing. Key elements of the facility include the following:

- Existing MGTF showing the location of three testing bays and respective load banks. The bays are used to indicate physical location of the DER and electrical interconnection methods. The contents and electrical connection of

each bay, as shown in the overview are documented in greater detail below in Figure 6, Figure 7, Figure 7 and Figure 9.

- Fenced-off high current yard and distribution transformer arrangement. The distribution voltage transformers are shown adjacent to the MGTF and are located in a controlled, fenced area. A second drawing, Figure 10, shows details of the distribution transformer arrangement. A photograph of the transformers and bus are shown in Figure 14 and the rigid bus structure which the transformers are connected to is also shown in Figure 15. The transformers are arranged and identified according to the bay to which they supply power.
- Location of the load banks for the three bays. The load banks are physically separate from, but electrically connected to, the DERs in the respective bays. The load banks are located within the MGTF as shown on the overview drawing.
- The PG&E-supplied photovoltaic array is shown as mounted on the main building in the drawing. The array is to be wired through over- and underground conduit to the MGTF. The photovoltaic array is approximately 500 ft. from the MGTF. The PV array will be used in bay 1 to supply power to residential scale PV inverters.

2.3.2. Test Bay Layouts

The three bays within the MGTF are identified as Bay 1, Bay 2, and Bay 3 in Figures 2-5 respectively. The bay drawings are one-line diagrams showing the DER, loads, and power sources to be used in each of the bays. The bay drawings also reflect the data acquisition system (DAS) and test management control system networks (documented in "DUIT Test System Architecture – Data Acquisition System"). The DAS network is identified as the National Instruments DAS hardware network, and the test management control system is identified as the Personal Computer network. The number of DAS channels is identified on the drawings by the italicized v(t) and i(t). The total connected, rated kW of all three bays is 485 kW.

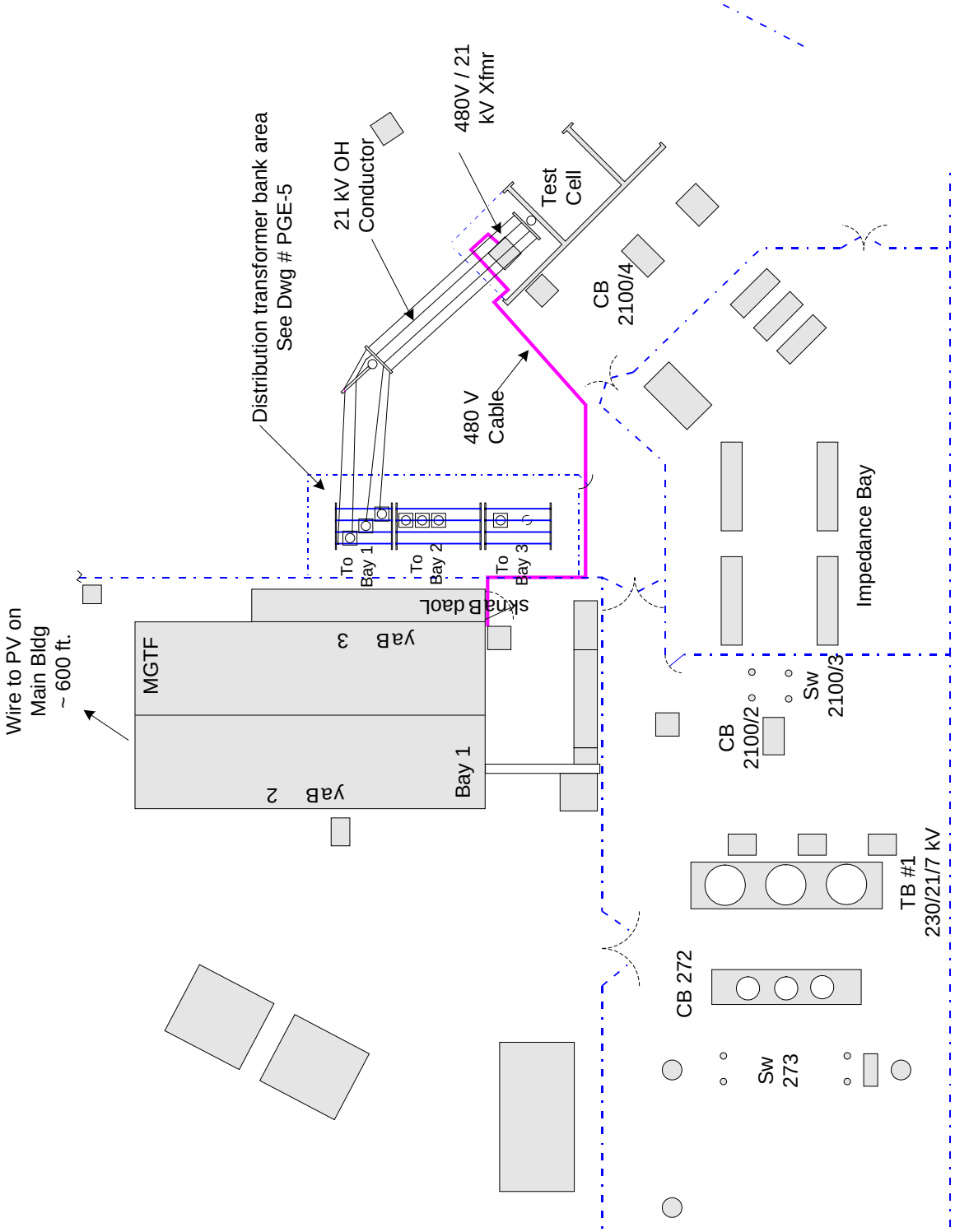

Figure 5 Distributed Utility Integration Test Facility

Bay 1 is shown in Figure 6 and Figure 7. This bay contains thirty residential scale inverters which operate in grid tie mode only. The bay consists of 10 Xantrex inverters and the 10 SMA inverters. These inverters have been donated by the companies for purposes of this test.

Bay 2 is shown in Figure 8. This bay contains larger, commercial scale DER consisting of two Xantrex inverters interconnected to the utility. The DC power source for these two inverters is the existing PG&E photovoltaic simulator system. This is a DC power supply which follows a preprogrammed I/V curve similar to a photovoltaic array. The inverters are lent by Xantrex and the PV simulator is supplied by PG&E.

Bay 3 is shown in Figure 9 of this report. This bay contains the rotating DER equipment. This includes a 250 kW diesel generator set. Two additional distribution level transformers are shown in this bay for future interconnection.

2.3.3. Test Bay Component Systems

2.3.3.1. DAS and Control System

Also shown on the Bay drawings are two local area networks. One network which connects the National Instruments hardware from the data acquisition system (DAS). The DAS system is represented as the "National Instruments Network." And the other which connects the test management control hardware and coordinates the test control system.

2.3.3.2. PV Simulators (Power Supplies)

The photovoltaic simulators shown in the Bay 1 drawing are DC power supplies. The convention for anti-islanding testing has been to use power supplies in a controlled way as opposed to using actual PV. The power supplies represent a more extreme test than PV because the power available from actual PV can vary quite dynamically with changing cloud cover and atmospheric conditions. The power supply readily allows for a balanced, stabilized load to be established with relative ease. Both U/L 1741 and IEEE 929 require the use of power supplies for purposes of islanding tests. It is the plan of the DUIT test to use these power supplies to determine quantitative differences between the testing as it is currently being performed and how the same systems would perform with actual PV. The power supplies used for this purpose in the Bay 2 drawing already exist and are supplied by PG&E.

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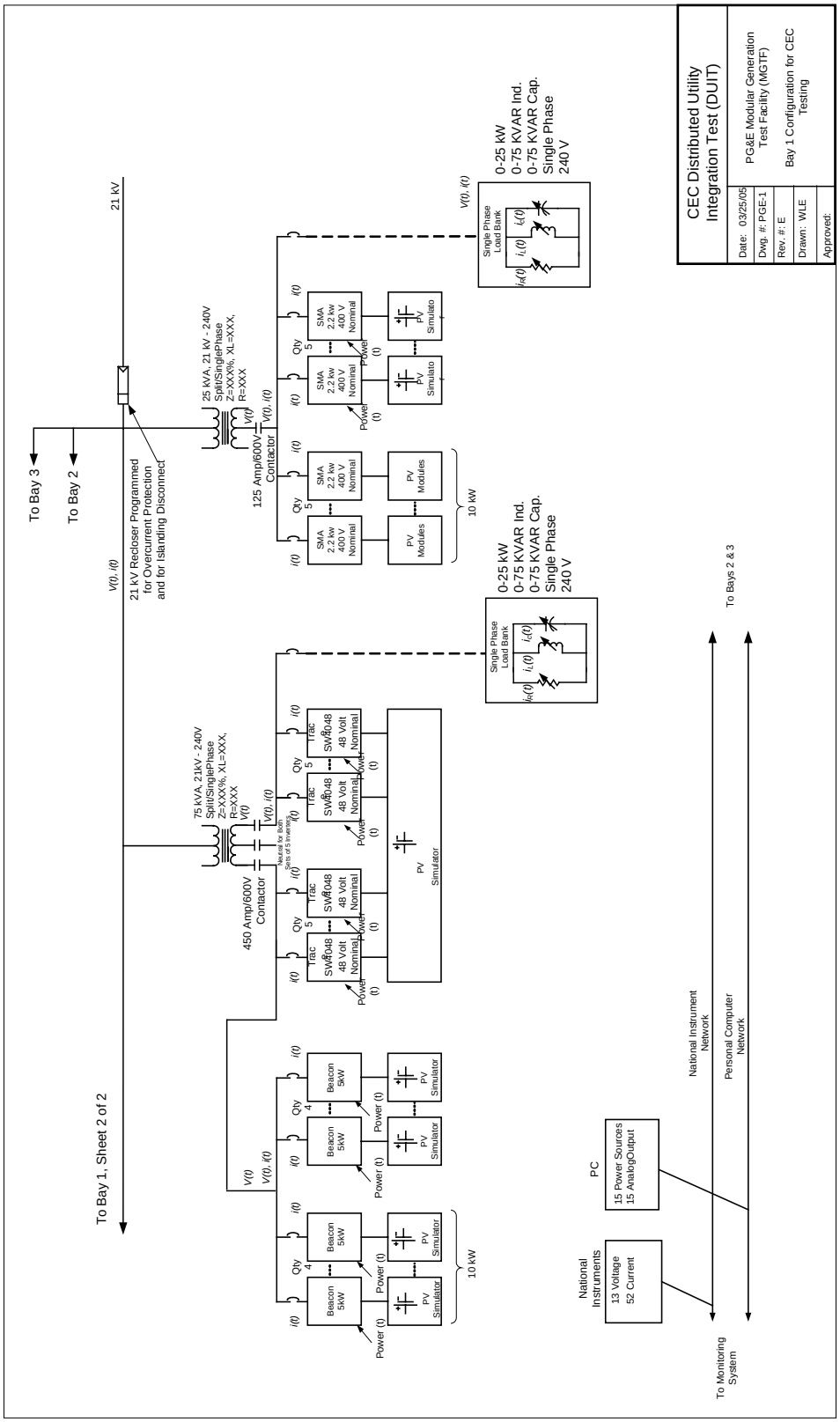

Figure 6 DUIT Bay 1, XFMR 1&2 Configuration for CEC TestilNG

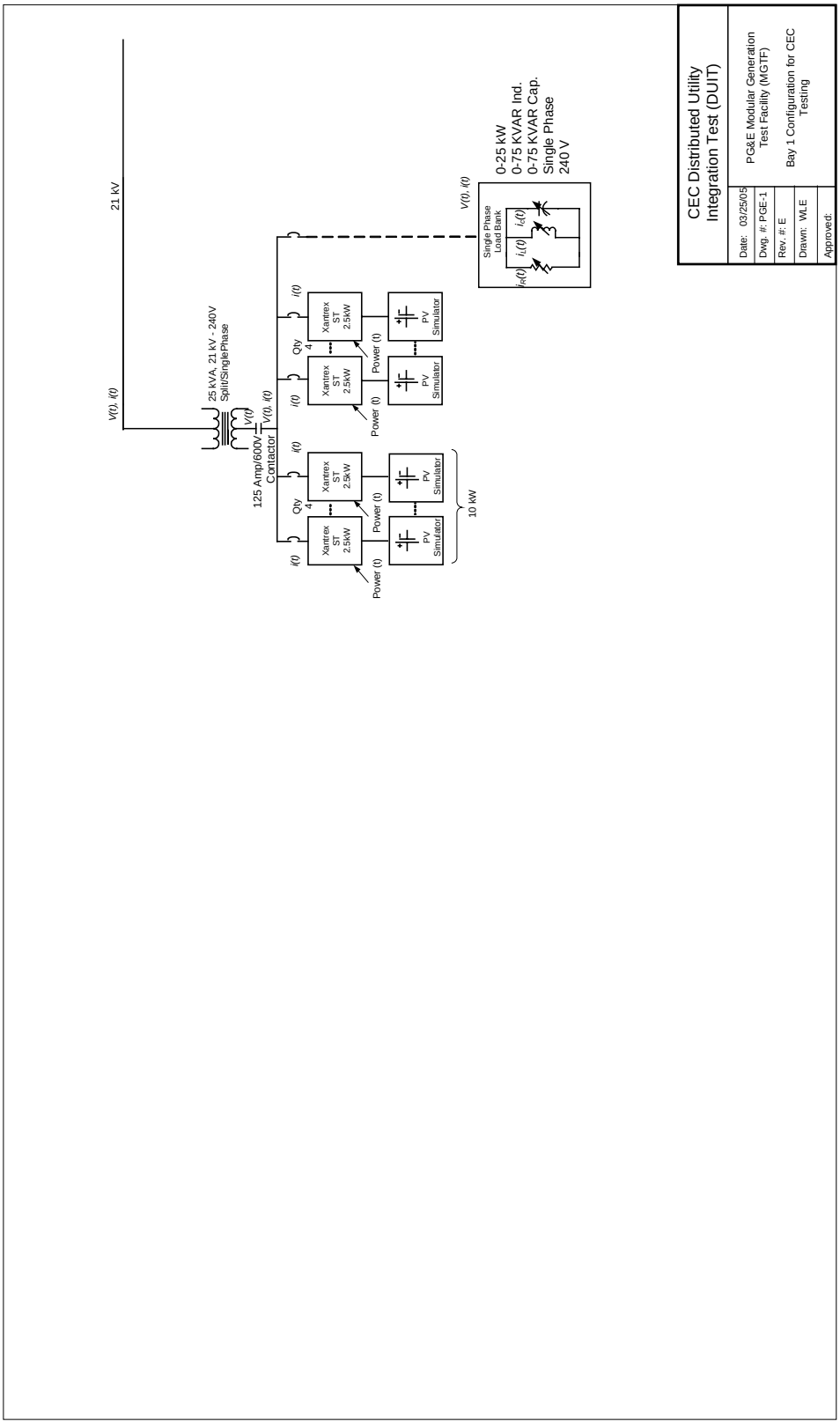

Figure 7 DUIT Bay 1, XFMR 3 Config. for CEC Testing

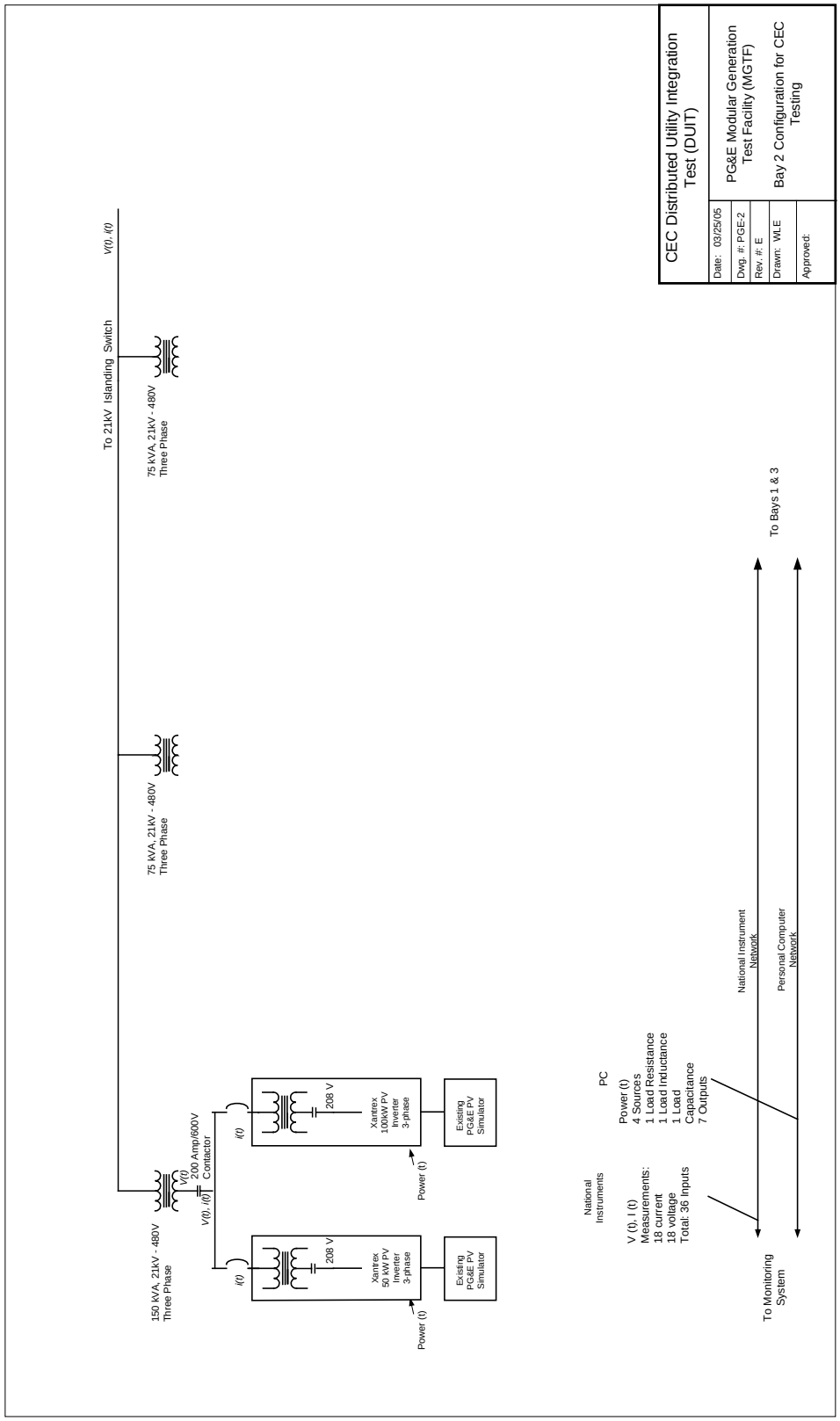

Figure 8: DUIT Bay 2 Configuration for CEC Testing

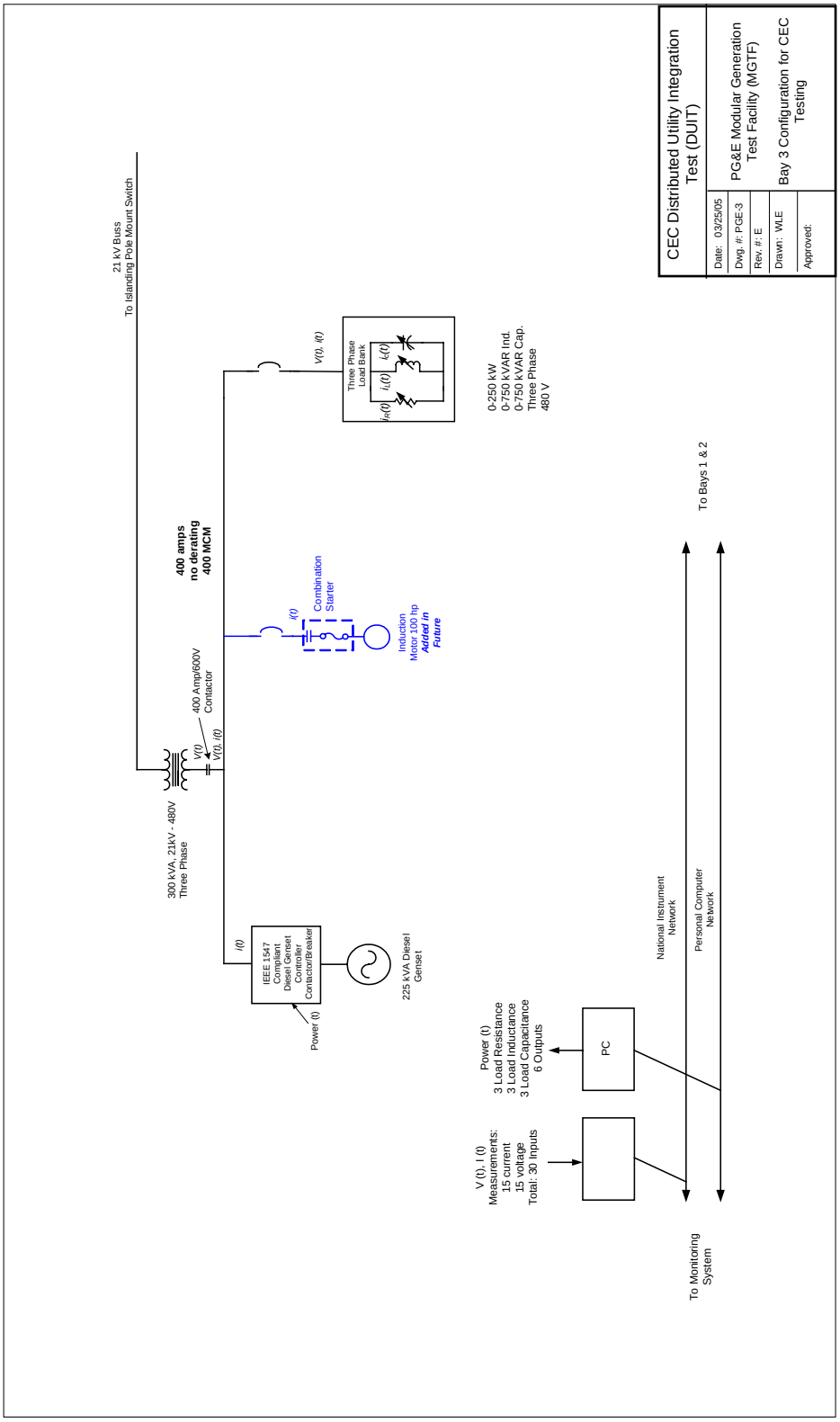

Figure 9: DUIT Bay 3 Configuration for CEC Testing

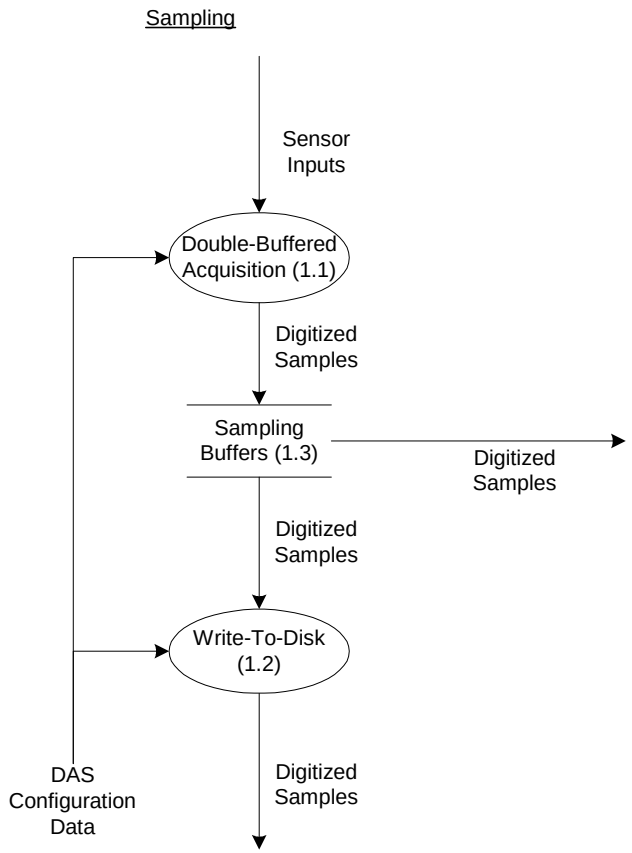

Figure 10 Sampling Functions Detail

2.3.4. Load Banks

The DUIT test facility includes a total of five different load banks. There are three 20 kW, 70 kvar (Q = 3), single phase load banks in bay 1. These load banks are all identical and are being fabricated by a third party vendor. The load banks represent a cost share by PG&E. A large load bank rated 250 kW, 750 kvar (Q=3) is electrically interconnected in bay 3. This load is in part existing and is currently being supplemented to meet DUIT requirements by PG&E. Lastly, there is a smaller, portable load bank (Figure 11) that is to be used for type testing of individual inverters and DER. This load bank is rated 5 kW, 15 kvar, single phase, 240 VAC. All load banks were constructed by PG&E.

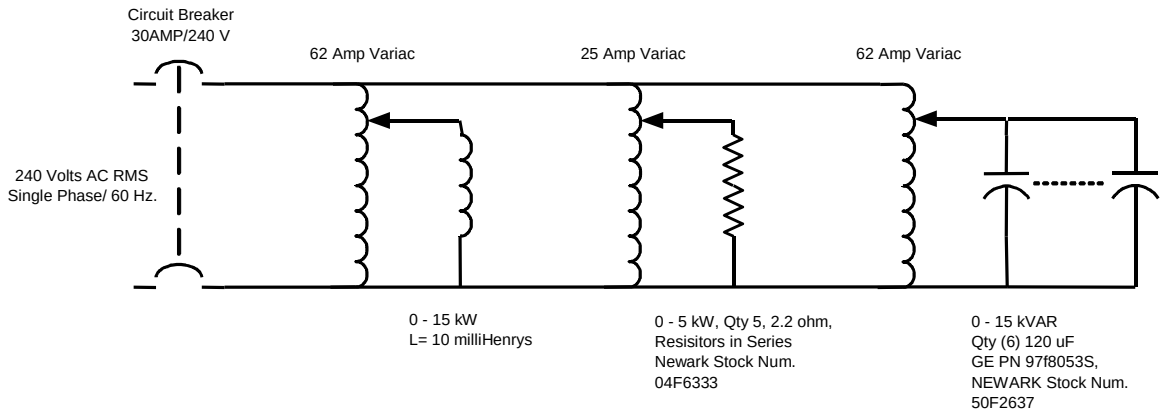

Figure 11 240 Volt Type Testing load Bank

2.3.5. Existing Photovoltaic Array

A picture of the existing photovoltaic array is shown in Figure 12. The array is rated 13.5 kW peak rated power and resides on the roof of the TES main building. The conductors run from the array to the MGTF total approximately 600 feet in length. This is done through over/under ground conduit and the conductor sizing is oversized at 4/0 to compensate for the relatively long conductor run. The PV array was manufactured by Siemens and has been mounted and in place for approximately 10 years. The array is currently wired for split, bipolar high voltage connection to an Omnion inverter. The array will be rewired so as to interface with the SMA inverters provided for the test. This requires configuring the array for unipolar, grounded negative connection.

Figure 12 Photovoltaic (PV) Array

2.3.6. DAS and Control System

Also shown on the Bay drawings are two local area networks. One network connects the National Instruments hardware to the data acquisition system (DAS). The DAS is represented as the "National Instruments Network." The second network connects the test management control hardware and coordinates the test control system.

2.3.7. Transformer Nameplate Data

There are seven pole mounted transformers used in the three bays of the test facility. These transformers are part of the PG&E cost share and are taken from revolving stock. The nameplates provide all of the technical data required for the development of the test plan and for the modeling phase of the project. Additionally, single phase, three phase, delta vs. wye connections and other technical data is identified on the nameplate for the transformers. The transformers are located in the transformer section of the high current yard, adjacent to the MGTF as shown in Figure 14. The arrangement and wiring of the transformers to the distribution bus can be seen in Figure 14 and Figure 15.

Figure 13 Distribution Transformers

Figure 14 Distribution Transformer Wiring

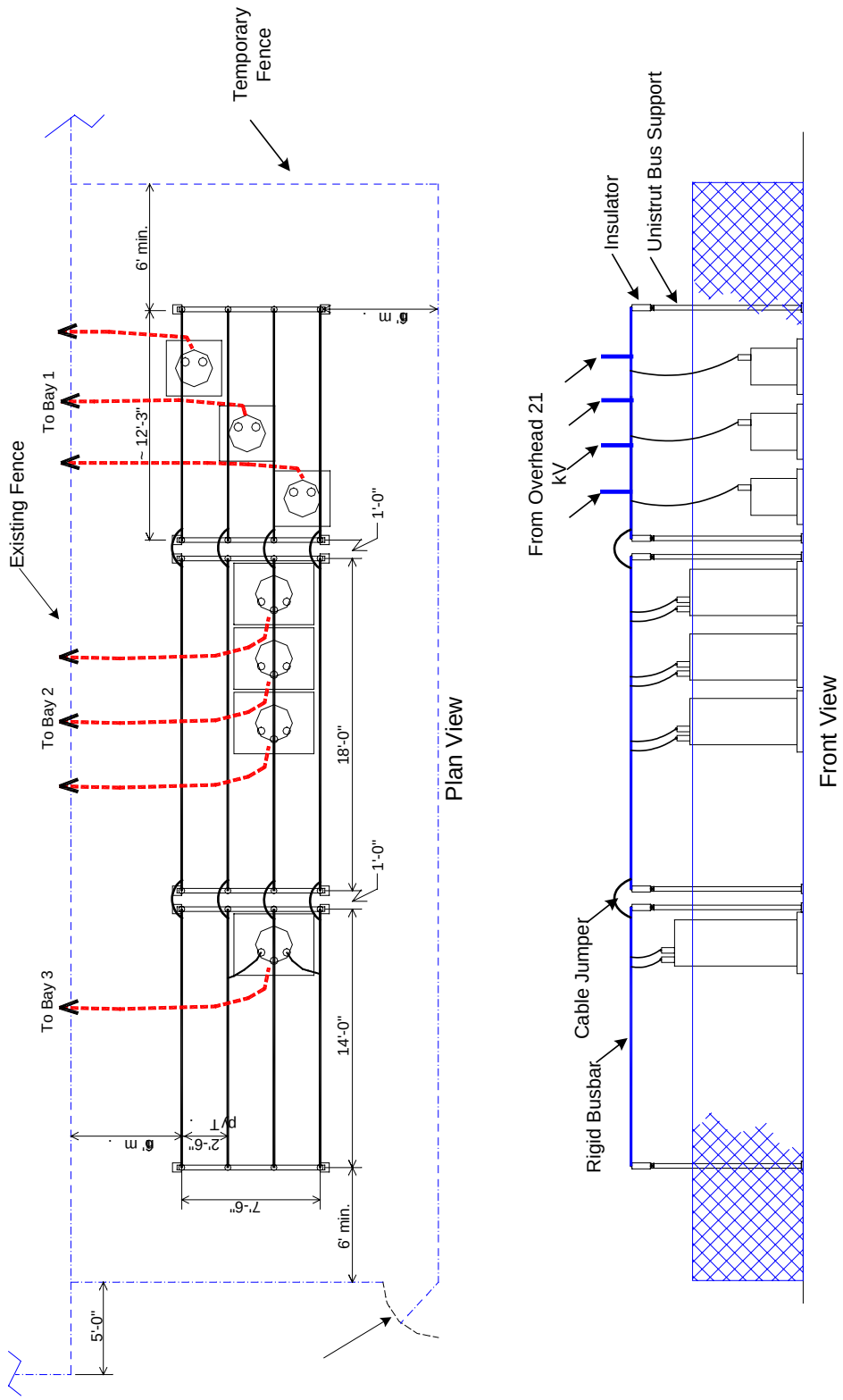

Figure 15 Distribution Transformer Layout

2.4. Validate Test Design

Validating the test design and set up is accomplished by conduction the basic unintentional islanding test and modeling the test set up. Modeling can allow subsequent test conditions to be repeated on the computer rather than having to actually setup and re-execute testing. The ability to extend the DUIT test results to these subsequent conditions minimizes actual testing while maximizing value of results. Furthermore, the models, as validated during testing, can available for use in extending test results to other "real world" projects which will likely have slightly modified configurations. For these reasons, it is important to develop and validate models as testing is being performed. Those tests that lend themselves to modeling for future applications are identified, models are developed, and when testing takes place, the simulation runs are compared with actual test data. The loop is closed when this data from test results are used to adjust or tune the models.

2.5. Conduct Tests

Conduct the tests as documented in the test plan

3.0 Outcomes

This phase of the DUIT project objectives were accomplished by developing and industry team of advisors, developing a peer reviewed and prioritized detailed and sequenced test plan, upgrading the PG&E facility to accomplish the testing.

The DUIT team accomplished our objective of building a world class DER integration test facility that has given many tours to visitors from all over the United States and from more than eight countries from around the world. We also completed the single unit unintentional islanding tests at 480V. Then we went on to complete the homogenous and small group tests at 21kV. We had expected to complete much more of the unintentional islanding group of tests during this phase of the project but the testing took much longer than expected. However, the results were so unexpected and the learning was so rich that we are confident that the DUIT test results have had a significant impact on the industry in support of the interconnection standards.

3.1. Developing an Industry Team

We developed a technology and testing review team consisting of representatives of six DER vendors, who lent their DER equipment to the project for an extended period of time, all of the California Investor Owned Utilities and Sacramento Municipal Utility District, Underwriters laboratory and other interested parties. Accomplishing this effort enabled Distributed Utility Associates to build a team of vendors, that lent the appropriate amount of equipment to be tested based on its relevance to the California market. Results of this task are documented in contract deliverable 2.1.4 The Final Procurement Process Report.

DUIT Sponsors and Participants

DUIT is a public-private collaboration among DER technology companies, government agencies and utilities. These organizations are contributing equipment, expertise and financing.

Sponsors and Participants:

Beacon Power	NREL
California Energy Commission	Pacific Gas & Electric Co.
Capstone Turbines	Sacramento Municipal Utility District
Caterpillar	Salt River Project
Consolidated Edison	San Francisco Public Utility Commission
Cummins Power Generation	SMA America
Distributed Utility Associates	Solar Turbines
ENCORP	Texas Public Utility Commission
Endecon Engineering	US Department of Energy
EPRI	Underwriters Laboratory
Exelon	Xantrex
	ZBB

Below in Table 2 *is the list of DER equipment, the companies that supplied the equipment and its' term of availability.*

Table 2 DER Equipment and Availability

DER Prime Mover	Supplier	Quantity	Terms	Arrival Date	Duration
4.0 kW PV	Xantrex	10	Loan	12/02	Indefinite
2.5 kW PV	Xantrex	10	Loan	12/02	Indefinite
2.5 kW PV	SMA	10	"	12/02	Indefinite
5.0 kW PV	Beacon	6	"		
100 kW PV	Xantrex	1	"	12/02	Indefinite
45 kW PV	Xantrex	1	"	12/02	Indefinite
250 kW Diesel Genset	Cummins	1	"	03/03	Minimum of 12 Months

Note: All DER units except diesel genset have been U/L type test certified.

3.2. Test Plan Prioritization and Detailed Design

Terms of the DER Equipment

Distributed Utility Associates (DUA) has been successful in borrowing all of the DER equipment required for the initial DUIT testing. Vendors and third parties have been very responsive and have willingly provided equipment for purposes of this test. The inverters from SMA and Xantrex are loaned for an "indefinite" amount of time. In Bay 2, the commercial scale inverters are also supplied by Xantrex and they also have an indefinite loan duration. In Bay 3, the diesel generator set is to be supplied by Cummins. The loan duration of this equipment is also open ended, however, time frames of 1 to 2 years have been discussed. DUA considers this equipment to be available for a minimum of at least one-year.

3.3. Technology and Electrical Engineering Facility Preparation

Test Plan Prioritization And Detailed Design

A test plan was detailed out for Basic single unit unintentional islanding tests, as well as unintentional islanding tests multiple unit testing specifically for homogenous groups and small groups. Homogeneous Groups are groups of DER that contain the same technology and manufacturer. Small Groups are groups of DER consisting of different manufacturers within a given DER technology.

The review team was also responsible for the prioritization of the test plan.

Table 3 Unintentional Islanding Test Plan

Unintentional Islanding Test Plan	Test Description and Sequence
6.1	Basic Islanding Test Individual unit testing
6.2	Islanding with Multiple DRs Homogeneous Groups Small Groups Progressions
6.4	Islanding with Dynamic Load :Generation Ratios Individual Units
6.5	Anti-islanding with Rotating Loads Individual Units
6.6	Harmonic Content due to Anti-islanding Schemes Individual Units
6.7	Voltage/Frequency Trip Settings Individual Units Homogeneous Groups Small Groups Progressions

3.3.1. Technology and Electrical Engineering Facility Preparation

Our team designed and built a 480V testing facility that has proved to be the best in the world for testing commercially viable DER in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.

It was necessary to upgrade the PG&E testing facility to accommodate DUIT testing. This included design and line diagrams for the interconnection of the selected DER The upgrades affect not only the 480V testing effort but begin the preparation of the DUIT testing at distribution voltages. The facility attributes are as follows:

- 3 DER test bays each consisting of one larger unit, or several smaller units
- Total combined generation up to 500kW
- Maximum single unit generation of 500kW
- Variable resistive, reactive, and capacitive loads at each DER location
- 480 V radial distribution
- Total simulated impedance of 30 miles, in 10 mile steps
- 21kV distribution testing capability for islanding tests and additional use in testing additional protocols
- State of the DAS and control system

These attributes more than met the minimum required in this phase of the project.

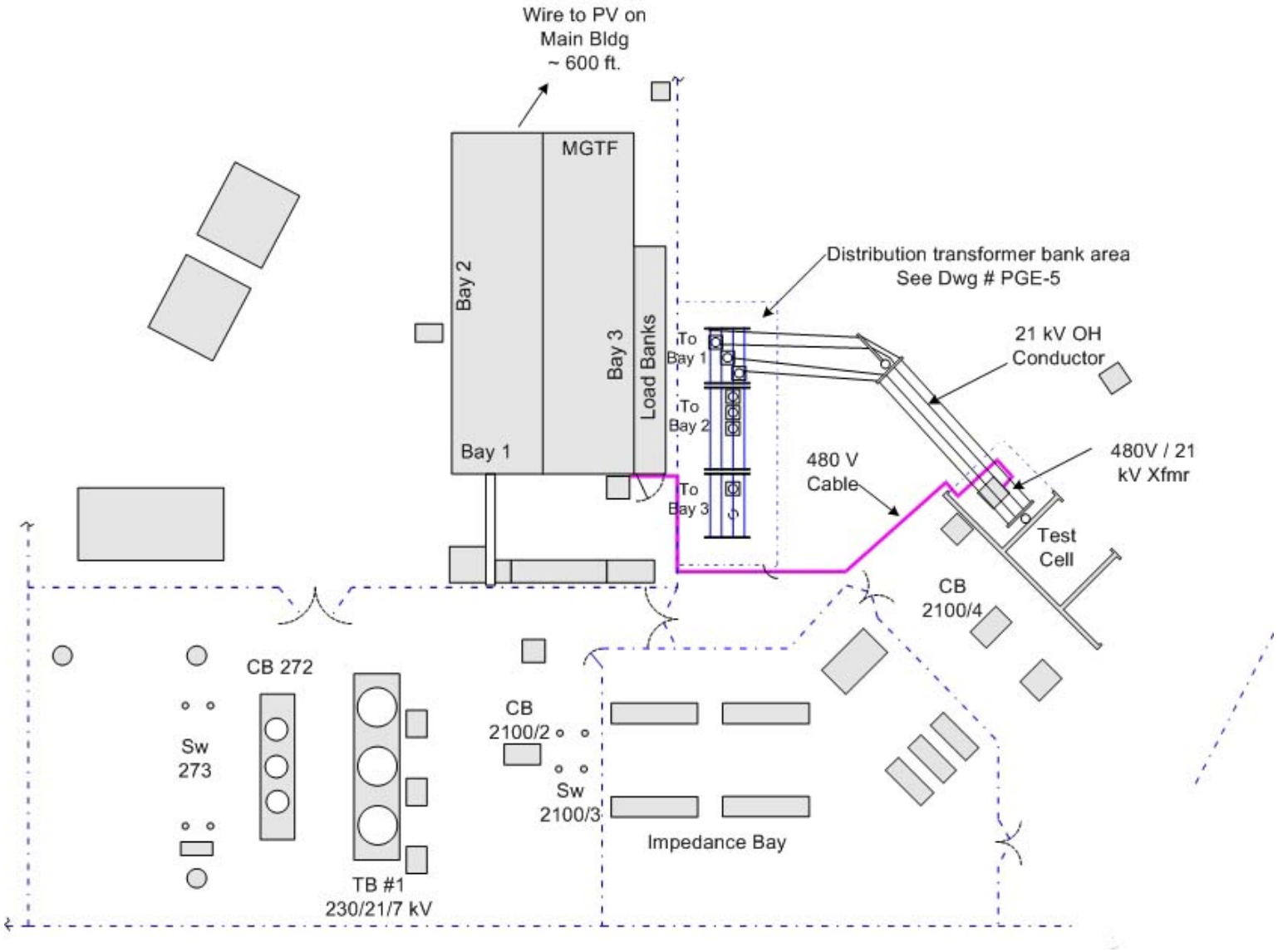

Figure 16 DUIT Layout

3.4. Validate Test Design

Validating the test design and set was accomplished by conduction the basic unintentional islanding test and modeling the test set up. The Single-Unit Unintentional Islanding Test Results at the DUIT Test Facility validated the test design and setup. These tests were the first tests to be performed in a comprehensive suite of tests to evaluate the impacts of distributed resources in a realistic test environment.

3.4.1. Single-Unit Unintentional Islanding Test Results at the DUIT Test Facility

These tests are the first tests to be performed in a comprehensive suite of tests to evaluate the impacts of distributed resources in a realistic test environment.

3.4.2. Overview

UL 1741 and IEEE 1547 require that grid-connected DERs operating while connected to a load with a Q factor of 2.5 be able to disconnect themselves from the utility in 2.0 seconds or less after an islanding situation occurs. The DUIT single-unit islanding test is designed to determine the ability of a DER to meet this requirement. Each islanding test is performed at a specified DER loading level (25, 50, or 100%).

Because of possible measurement error in the data acquisition system, the possibility exists that the load circuit for a given test could be detuned slightly from a nominal value of 60 Hz. To eliminate the possibility that this potential error could result in erroneous results, tests are performed over a range of +5% of the capacitive load, in 1% steps; this ensures that test results bracket the estimated DAS error range. There are therefore a total of eleven individual tests in each test sequence. The variac-based load control allows precise tuning of the reactive load in 1% increments as called out in the test plan.

Figure 17 summarizes typical results for an unintentional islanding test run sequence, for an inverter-based DER. Each data point represents the time to shutdown of the DER after the islanding switch is opened. The 0% point represents the first, “baseline,” case, in which the real and reactive power of the load on the DER result in a Q factor of 2.5, and the inductive and capacitive loads are equal. Test points to the right represent variations on this baseline case: the capacitive load exceeds the inductive by the indicated percent. Conversely, points to the left of the 0% point represent decrements of capacitive reactance.

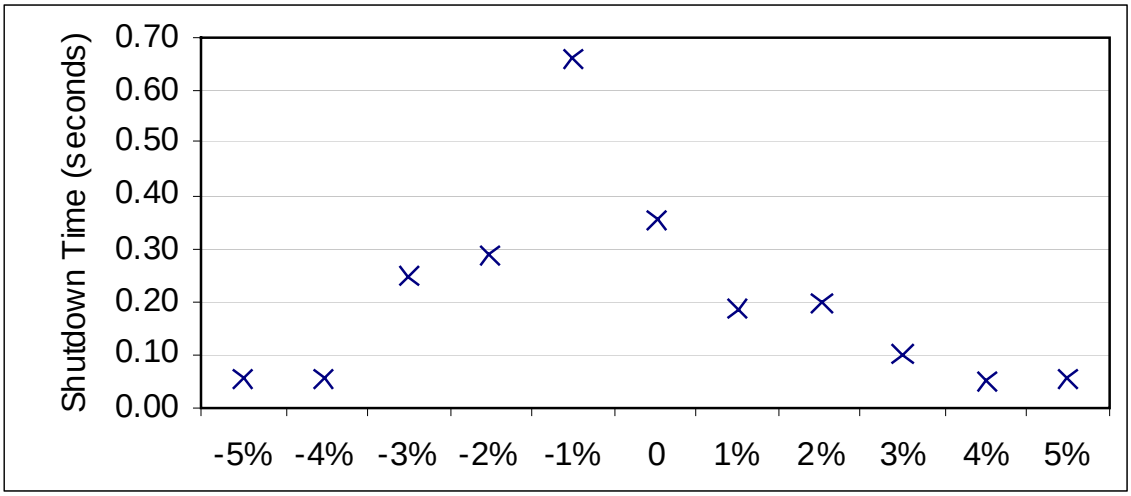

Figure 17 Single Unit Islanding Test - Typical Results Summary

3.4.3. Summary of Single-Unit Islanding Test Results

For devices A and B from Table 4 (Bay 2 Commercial) DERs, the median trip times ranged from 0.10 to 0.20 seconds. For device C in Table 5 (Bay 3 Industrial) DERs, the median trip time was 0.99 sec, with observed time > 3 sec. in one case. (It should be noted that this DER was equipped with external anti-islanding controls that have not yet been NRTL-certified to UL 1741.)

For devices D-G, Table 6 (Bay 1 Residential) DERs, the median trip times ranged from 0.06 to 0.34 seconds. Two devices each had trip times > 2 seconds: one at 3.31 sec in one test, the other at 2.22 sec in one test. Supplemental testing of Bay 1 units revealed run-on times > 30 seconds for some load conditions.

Table 4 Single Unit Islanding Test Results, Bay 2, Initial Testing

Device	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	# of Trip Times > 2 seconds	Longest Trip Time (sec)
A	0.12	0.10	0.05	0 of 33	0.39
B	0.26	0.20	0.23	0 of 33	1.16

Table 5 Single Unit Islanding Test Results, Bay 3, Initial Testing

Device	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	# of Trip Times > 2 seconds	Longest Trip Time* (sec)
C	1.27	0.99	0.66	5 of 40	3.33

*This device includes external anti-islanding controls that have not yet been NRTL-certified to UL 1741.

Table 6 Single Unit Islanding Test Results, Bay 1, Initial Testing

Device	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	# of Trip Times > 2 seconds	Longest Trip Time* (sec)
D	0.34	0.34	0.08	0 of 66	0.55
E	0.27	0.09	0.48	1 of 66	3.31
F	0.14	0.06	0.23	0 of 66	1.16
G	0.20	0.08	0.35	1 of 66	2.22

*Observation of trip times > 2 seconds was impetus for supplemental testing.

3.4.4. Supplemental Testing – Bay 1

Supplemental testing was performed in an effort to determine the causes of the islanding times in excess of 2.0 seconds that resulted from the initial tests. The results, by device, are as follows:

3.4.4.1. Device E

The longest run-on in initial testing occurred at rated power, with the inverter operating in power limiting mode.

Supplemental testing with the device at its power limit and DC input voltage near minimum of operating range resulted in some trip times exceeding 10 seconds with a well-tuned load.

3.4.4.2. Device F

When power levels were decreased from 27% to 24% of device rating (outside of current UL 1741 test requirements), run-ons in excess of 30 seconds were observed.

3.4.4.3. Device G

Power limiting in initial testing was achieved through changing inverter set points, consistent with UL methods.

Supplemental testing was performed by lowering input voltage to effect DC current limiting for achieving partial load points (not consistent with current UL 1741 test requirements); some run-on times in excess of 30 seconds were observed with well-tuned load.

3.4.4.4. Islanding Impacts Analysis

To further address the controversial issue of unintentional islanding, DUA initiated a study under the modeling task of this Contract, with the assistance of the National Renewable Energy Laboratory, which assigns a probability to the necessary conditions for an unintentional islanding event to occur on a real-world distribution system feeder. The analysis focuses on physical conditions such as real and reactive load to generation matching, the probability of a utility disconnect event, effects of load diversity, and short term time domain requirements, as well as other factors, all of which are required to sustain an island. The only other known studies of this type were performed by the International Energy Agency (IEA) and KEMA in the Netherlands. This study builds upon this earlier analysis and applies appropriate assumptions for US and California distribution systems and for commercially viable DER technologies.

This modeling effort followed the results of the single unit unintentional islanding test in order to put the test results in perspective.

This analysis was limited to single phase inverters in a radial distribution system Conservation limits on the physical requirements for islanding were determining for reasonable assumptions of DER penetration and operational situations in common distribution systems. See Final Modeling Review Report, contract deliverable 2.10.2.

The issue of islanding has been cause for much concern since it is physically possible for some distributed energy resources (DER) to continue to operate unintentionally when isolated from the grid, forming an “island” with the connected loads. Such a situation is a potential safety hazard, and utility radial distribution systems are not intended to operate in such an uncontrolled and isolated manner.

An unintentional island may be defined as a combination of distributed resources and loads in the distribution system, isolated from utility generation and control, stable for two seconds or more, and with more than one customer involved. Since the real and reactive power provided by the DER must closely match that consumed by the loads, power balance and export from some of the individual customer sites must be allowed and is, in fact, required for such an island to occur.

Though the scope of this analysis is limited to radial distribution systems and inverter-based DER, similar analysis could be applied to other technologies and distribution system designs. The inverters in this analysis are assumed not to have any active anti-islanding function included.

This assumption results is a very conservative estimate of the likelihood of islanding for these devices on distribution systems.

The analytical approach utilized divides the physical islanding requirements into tractable, statistically independent phenomena and estimate the likelihood of each physical requirement being met. All conditions are statistically independent. The composite likelihood is the product of the individual probabilities. The four separate factors are:

1. Real power balance within the tolerance specified by a "non-detection zone" (NDZ),
2. Reactive power balance within the tolerance specified by a second NDZ, or, equivalently, load inductance and capacitance with a resonant frequency near 60 Hz,
3. The occurrence of a switching event in the proper location, and
4. Stability of these conditions for at least two seconds.

All four factors must be satisfied for an island to exist, and the likelihood of each is estimated as a function of the DER penetration of the distribution system and export of power to the grid. The analysis does not take the place of site-specific situations. General situations are analyzed to gain insight about the more functional importance of guarding against island situations.

The intent of this analysis was to bound the probability of unintentional islanding in distribution systems, making simplifying assumptions and providing ranges of likelihoods where needed. Conservative assumptions (those tending towards maximizing the probability of islanding) were incorporated. For many of the physical factors, a broad range of probabilities are provided. Some of the physical factors are easier to estimate by examining the spatial domain while others are best looked at in terms of the loads, not their locations. Simultaneous optimization of the spatial and load level perspectives is not presented, though such simultaneous analysis would not yield substantially different results. Analysis is also limited to the probability that unintentional islanding can occur but does not look at the additional probability of any detrimental consequences of such an occurrence.

3.4.4.5. Summary of Islanding Probabilities

Collecting the probabilities of each of the physical factors required for islanding:

1. Static P,Q balance:
    - 0.001 to 0.01 per event (High penetration)
    - 1E-10 to 1E-8 per event (Low penetration)

2. Resonant frequency:
    - 1E-5 to 1E-2 per event
3. Fault event probability events/ year:
    - 0.15 to 0.3 events/year on any feeder
4. Time domain stability:
    - per event

The combined probability is then is:

- High penetration case: 1.5E-10 to 3E-6 islands per feeder per year
- Low penetration case: 1.5E-17 to 3E-12 islands per feeder per year

Since there are approximately 10,000 feeders in California and currently there is low penetration of distributed resources on distribution systems, stable islands will form no more than once in 30 million years on some feeders in the state.

On a known high-density feeder, such an islanding event can be expected every 300,000 years at the upper end of the probability range.

While probability ranges shown are large, nonetheless the results should be of use to those studying the impacts of inverter-based DER islands on the power systems of the future. Further, the results are conservation in that a Q_f of 2.5 has been assumed, which corresponds to an uncorrected power factor of 0.37, something that would rarely be seen on a loaded distribution feeder line section. Smaller assumed values for Q_f reduce the probability of a stable island forming.

3.4.4.6. Conduct Additional Tests

We conducted the unintentional islanding tests for individual units and homogenous groups. In particular the DUIT test illuminates: requirements and tests for safe and effective interconnection, interconnection equipment performance and functional characterization and installation test method design, development, test set up validation and documentation

For the single unit tests the manufacturers of the units that experienced islanding times in excess of 2.0 seconds were asked to provide details of the anti-islanding algorithm used in their units. Analysis of this information may enable design and/or calibration changes to eliminate the occurrence of islanding run-on.

In the results meeting of June 4th 2004, the utility reviewers strongly recommended that the project immediately move to distribution voltage level testing in our case 21kV. PG&E responded by bring the necessary equipment to the project in order to upgrade the voltage. This allowed the testing to proceed at a higher voltage than was ever expected in the first phase of testing.

Multiple-Unit Islanding tests derive from the Unintentional Islanding test for single phase units. The test procedure is the same as the tests conducted for Single-Unit except that the test is run through the distribution voltage islanding switch.

558 Islanding Tests were completed in the Multiple-Unit Test Phase. They included 15 test sequences, each containing 33%, 66% and 100% power ratings with ±5% variations in Q at 1% intervals.

3.4.4.7. Multiple-Unit Islanding Test Results

Multiple-Unit Islanding tests derive from the Unintentional Islanding test 6.2 for single phase units. The test procedure is the same as the tests conducted under 6.1 for Single-Unit.

561 Islanding Tests were completed in the Multiple-Unit Test Phase. They included 15 test sequences, each containing 33%, 66% and 100% power ratings with ±5% variations in Q at 1% intervals.

3.4.4.8. Homogeneous Groups Islanding Test Results

There were 254 Islanding tests completed in the Homogeneous Testing Phase.

One islanding test ran on for up to 2.327 seconds, exceeding the 2-second maximum limit.

The results reveal differences in trends between inverter types as deployment numbers increase. Two inverters improve trip times as more systems are installed in parallel. Conversely, one inverter type points toward longer trip times occurring in a narrower resonance zone. In one case, this yielded trip times in excess of two seconds.

Data displayed in Table 7 through Table 13incorporate testing at 33%, 66%, and 100% power levels.

3.4.4.9. Device D

The graphic below is representative of the Device type D, highlighting consistent performance between units and a longer shutdown time at the resonance point.

There were no trip times in excess of 2 seconds. Trip times appeared independent of power level. Trip times and consistency improved with increased number of units.

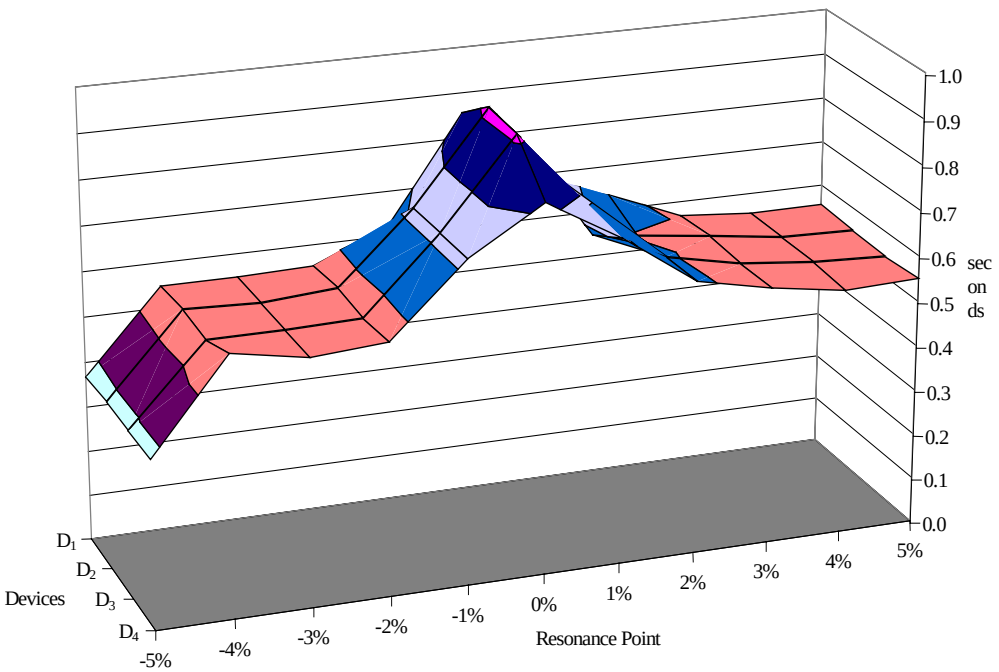

Figure 18 Islanding Response of 4 Type D Inverters at 100% Power

Table 7 Sequence #1: Homogeneous Groups – Type D

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.628	0.561	0.206	1.065	37	0
D_2	0.622	0.561	0.202	1.065	37	0

Table 8 Sequence #2: Homogeneous Groups – Type D

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.581	0.566	0.082	0.819	33	0
D_2	0.586	0.559	0.092	0.913	33	0
D_3	0.589	0.566	0.096	0.919	33	0
D_4	0.580	0.561	0.085	0.857	33	0

3.4.4.10. Device Type F

Inverter Type F demonstrated a high level of consistency and short islanding times that were independent of power level.

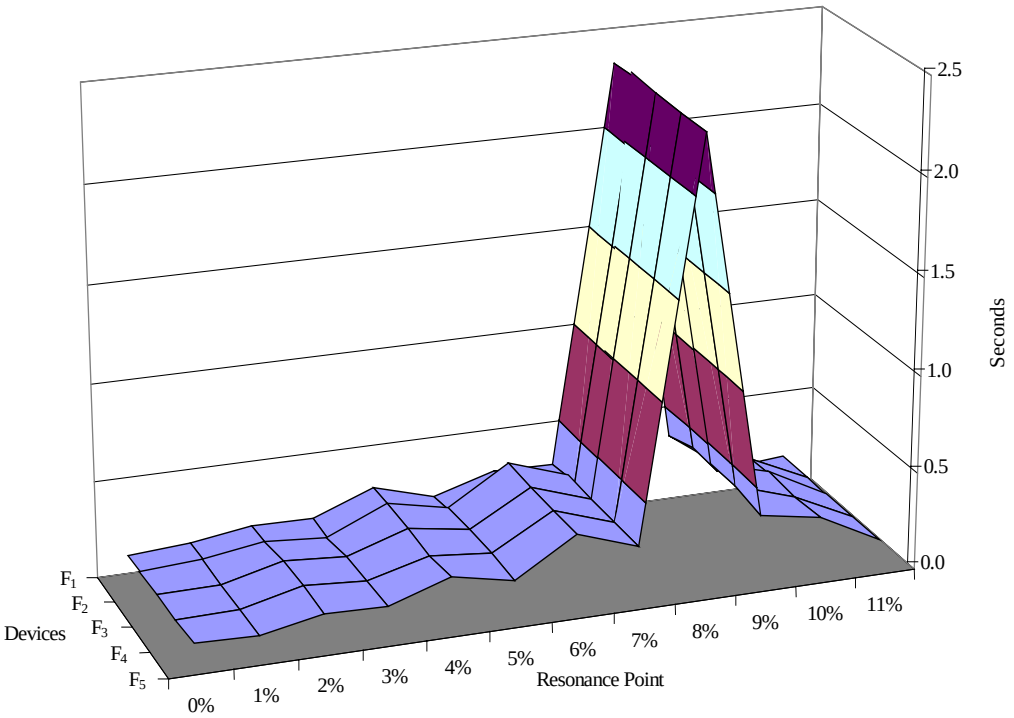

Figure 19 Islanding Response of 5 Device Type F Inverters at 100% Power

Increasing the number of units in parallel had the affect of *narrowing and raising* the resonance zone, to the point of exceeding the 2-second limit. This is shown in Figure 20.

Table 9 Sequence #3: Homogeneous Groups – Type F

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
F_1	0.178	0.075	0.289	1.397	74	0
F_4	0.178	0.080	0.286	1.360	74	0

Table 10 Sequence #4: Homogeneous Groups – Type F

Device	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
F_1	0.335	0.169	0.464	2.307	34	1
F_2	0.326	0.174	0.477	2.305	34	1
F_3	0.328	0.162	0.485	2.313	33	1
F_4	0.332	0.149	0.489	2.327	33	1
F_5	0.328	0.151	0.483	2.320	34	1

3.4.4.11. Inverter Type E

Inverter Type E had the shortest trip times – both on and off the resonance point. The resonance zone appeared lower and wider compared with the other inverter types.

Trip times remained consistently faster than the other inverters, however they did increase at lower power levels.

Trip times and consistency appeared to be independent of the number of units.

There were no trip times in excess of 2 seconds.

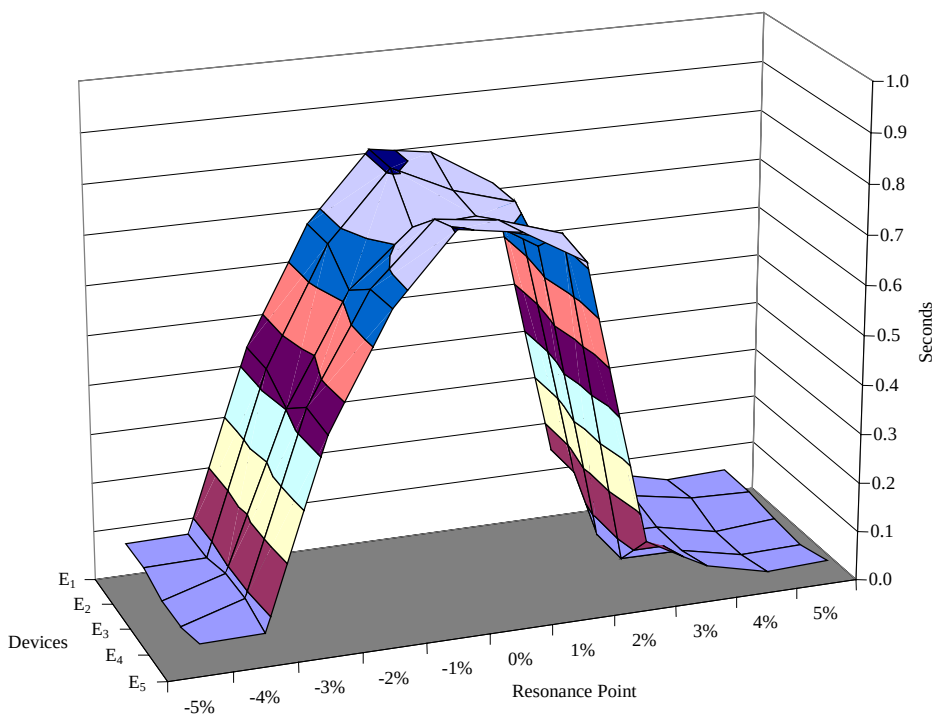

Figure 20 Islanding Response of 5 Type G or E Inverters at 100% Power

Table 11 Sequence #5: Homogeneous Groups – Type E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
E_1	0.301	0.129	0.278	0.902	33	0
E_2	0.306	0.128	0.288	0.949	33	0

Table 12 Sequence #6: Homogeneous Groups – Type E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
E_1	0.140	0.065	0.171	0.739	43	0
E_2	0.144	0.068	0.173	0.786	43	0
E_3	0.135	0.065	0.167	0.745	43	0
E_4	0.142	0.068	0.171	0.765	43	0
E_5	0.148	0.068	0.170	0.765	43	0

Table 13 Multiple Unit Test Results Summary

Device Type	Result
2 E	No run-ons in excess of one second
5 E	No run-ons in excess of one second
2 F	No run-ons in excess of 1.5 seconds
5 F	Longest run-ons approx. two seconds, independent of power level
2 G	No run-ons in excess of 1.5 seconds
5 G	No run-ons in excess of 1.5 seconds
2 D	No run-on in excess of one second, Except near 60 Hz resonance point, trip times are very consistent (600 ms)
4 D	No run-on in excess of one second, Except near 60 Hz resonance point, trip times are very consistent (600 ms)

3.4.5. Small Groups Islanding Test Results

304 Islanding tests were completed in the Small Groups Testing Phase.

Inverter Type D did not run on when paralleled with device types F or E.

However, when device Types F and E were combined, there were 6 events exceeding the allowable 2-second limit. These occurred at different power levels, depending on the specific combination being tested. In one case, with ten units under test, the run-on time exceeded 1 minute.

Data displayed in the Table 14 through Table 23 incorporates testing at 33%, 66%, and 100% power levels.

3.4.5.1. Inverter Device Types D & F

The combination of inverter types D and F yielded no run-on conditions with up to seven devices running in parallel. Furthermore, the longest trip-times did reduce as more devices were connected in parallel.

Figure 21 shows the uniform shutdown times of all of the devices, independent of technology and control algorithms.

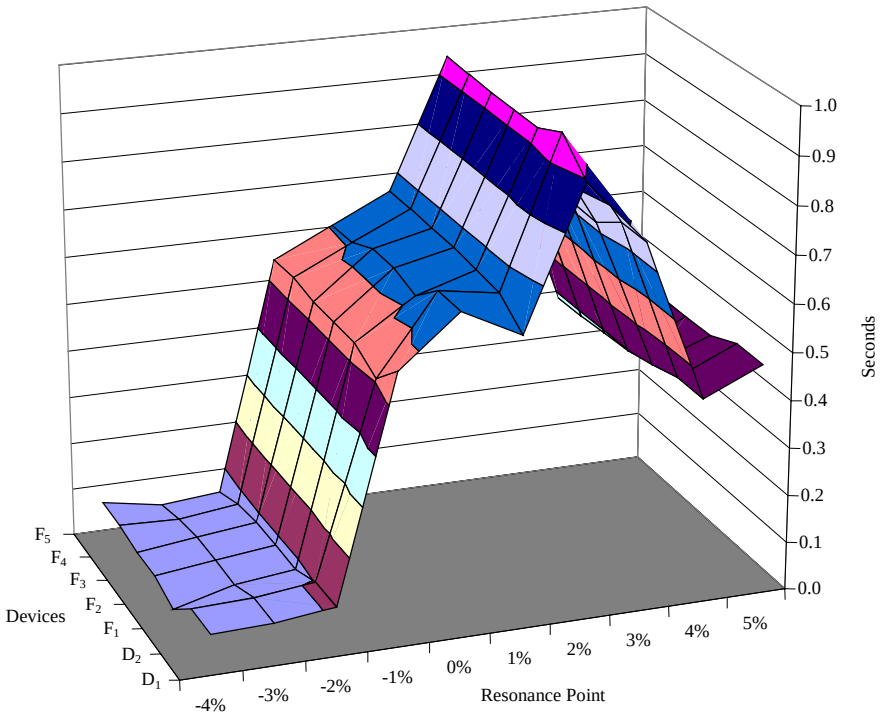

Figure 21 Islanding Response of 2 Type D & 5 Type F Inverters at 66% Power

Table 14 Sequence #7: Small Groups – Types D & F

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.588	0.578	0.273	1.581	36	0
D_2	0.590	0.578	0.269	1.516	36	0
F_1	0.533	0.535	0.293	1.543	36	0
F_4	0.527	0.520	0.295	1.554	36	0

Table 15 Sequence #8: Small Groups – Types D & F

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.437	0.526	0.248	0.896	32	0
D_2	0.437	0.515	0.251	0.957	32	0
F_1	0.409	0.498	0.257	0.930	32	0
F_2	0.410	0.498	0.258	0.930	32	0
F_3	0.413	0.497	0.259	0.930	32	0
F_4	0.407	0.512	0.248	0.933	32	0
F_5	0.414	0.500	0.259	0.937	32	0

Table 16 Sequence #9: Small Groups – Types D & F

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.255	0.087	0.284	0.996	34	0
F_1	0.187	0.043	0.265	0.968	34	0
F_2	0.221	0.044	0.290	0.968	34	0
F_3	0.226	0.044	0.295	0.968	34	0
F_4	0.213	0.066	0.280	0.976	34	0
F_5	0.231	0.064	0.290	0.976	34	0

3.4.5.2. Inverter Types D & E

The combination of inverter Types D and E also yielded no run-on conditions with up to seven devices running in parallel.

Increasing the number of units reduced the mean trip time and did not appear to impact the maximum trip-times, which remained the lowest of all the device combinations.

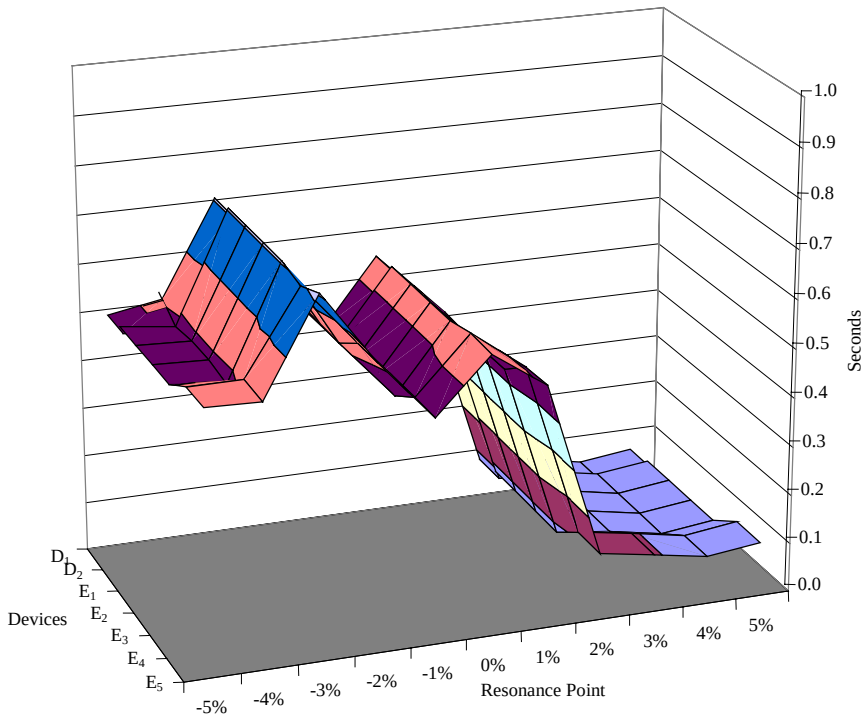

Figure 22 Islanding Response of 2 Type D & 5 Type E Inverters at 66% Power

Table 17 Sequence #10: Small Groups – Types D & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.497	0.549	0.178	0.868	33	0
D_2	0.495	0.548	0.180	0.871	33	0
E_1	0.456	0.498	0.205	0.814	33	0
E_2	0.453	0.501	0.206	0.829	33	0

Table 18 Sequence #11: Small Groups – Types D & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
D_1	0.359	0.444	0.219	0.778	33	0
D_2	0.363	0.444	0.223	0.823	33	0
E_1	0.322	0.423	0.239	0.843	33	0
E_2	0.321	0.407	0.238	0.843	33	0
E_3	0.325	0.405	0.232	0.840	33	0
E_4	0.324	0.419	0.236	0.840	33	0
E_5	0.327	0.407	0.233	0.846	33	0

3.4.5.3. Inverter Types F & E

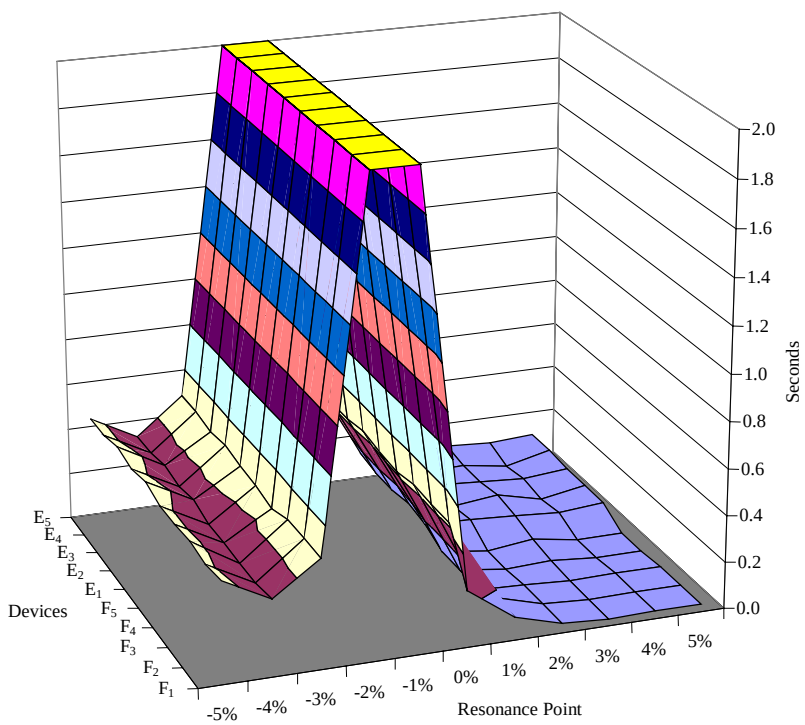

Figure 22 Islanding Response of 5 Type F & 5 Type E Inverters at 66% Power

This combination of devices yielded 6 run-on conditions, one exceeding 1 minute in length. While median trip times remained relatively stable throughout the tests, there appeared to be some direct correlation between the number of units operating in parallel and increased mean trip times and maximum trip times, as well as standard deviation.

Table 19 Sequence #12: Small Groups – Types F & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
F_1	0.073	0.074	0.047	0.283	35	0
F_2	0.074	0.076	0.048	0.288	35	0
E_3	0.044	0.040	0.019	0.096	35	0
E_2	0.056	0.042	0.051	0.261	35	0

Table 20 Sequence #13: Small Groups – Types F & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
F_1	0.685	0.080	1.889	>60	33	3
F_2	0.691	0.080	1.887	>60	33	3
F_3	0.692	0.074	1.891	>60	33	3
F_4	0.684	0.061	1.892	>60	33	3
F_5	0.680	0.061	1.893	>60	33	3
E_1	0.719	0.104	1.881	>60	33	3
E_2	0.719	0.108	1.881	>60	33	3
E_3	0.719	0.103	1.882	>60	33	3
E_4	0.718	0.104	1.882	>60	33	3
E_5	0.722	0.107	1.881	>60	33	3

Table 21 Sequence #14: Small Groups – Types F & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
F_1	0.279	0.046	0.905	4.670	33	2
E_1	0.318	0.099	0.910	4.758	33	2
E_2	0.319	0.102	0.907	4.743	33	2
E_3	0.316	0.091	0.908	4.743	33	2
E_4	0.318	0.099	0.907	4.743	33	2
E_5	0.315	0.093	0.900	4.701	33	2

Table 22 Sequence #15: Small Groups – Types F & E

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
E_1	0.470	0.151	1.089	6.295	35	1
E_2	0.466	0.151	1.089	6.295	35	1
E_3	0.465	0.154	1.090	6.295	35	1
E_4	0.468	0.151	1.089	6.295	35	1
E_5	0.468	0.152	1.089	6.295	35	1

Table 23 Small Group Result Summary

Device Types and Combinations	Result
2 D with 2 E	No run ons
2 D with 5 E	No run ons
4 D with 5 E	No run ons
2 D with 2 F	No run ons
2 D with 5 F	No run ons
4 D with 5 F	No run ons
2 E with 2 F	Several run-ons in excess of 2 seconds, Run-ons occurred only at 100% inverter power
5 E with 5 F	Several run-ons in excess of 2 seconds (one continuous) Shutdown times longer at lower power levels

3.4.6. Summary of Initial Testing with an Inverter and a Diesel Engine Generator

33 Islanding tests were completed using a 250kW Diesel Engine Generator and an Inverter of Type D.

While the diesel engine generator averaged a 1.4-second trip time, it exceeded the 2-second limit on 11 occasions. The maximum trip time was 3.594 seconds.

As with the previous tests, the Type D inverter device did not run on in parallel with the diesel engine generator. Instead, it consistently shut down within less than 0.7 seconds

of the islanding event. In addition, there was no pronounced device resonance point to be seen at any of the three power levels.

Data displayed in Table 24 below incorporates testing at 33%, 66%, and 100% power levels.

Table 24 Sequence #16: Diesel Engine Generator w. Small Groups – Type D

Device Type	Mean Trip Time (sec)	Median Trip Time (sec)	Standard Deviation (sec)	Longest Trip Time (sec)	Number of Tests	# of Trip Times > 2 seconds
C	0.562	0.577	0.076	0.697	33	0
DEG	1.432	1.339	0.979	3.594	33	11

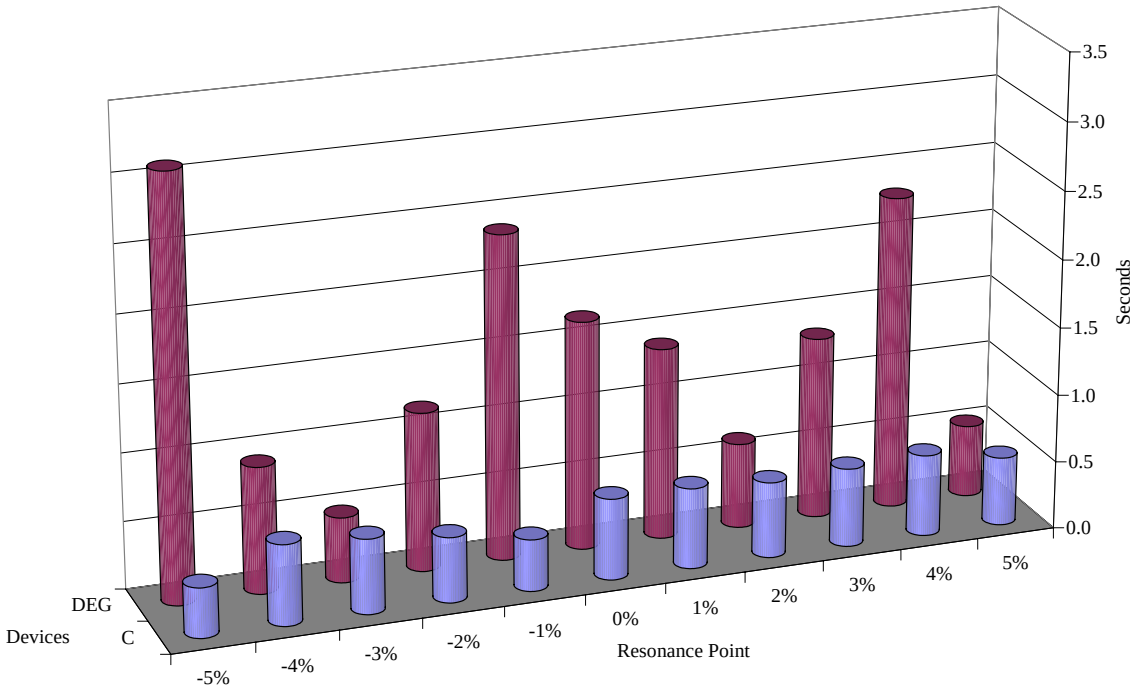

Figure 23 Islanding Response of 1 Type D Inverter & 250kW Diesel Engine Generator at 66% Power

4.0 Conclusions and Recommendations

4.1. Conclusions

The Distributed Utility Integration Test successfully brought together manufacturers, utilities engineers and energy researchers to design and build a testing facility to measure and document the interaction of distributed energy resources in a realistic utility distribution system setting.

Our team designed and built a 480V testing facility that has proved to be the best in the world for testing commercially viable DER in a realistic utility distribution system setting and begin planning for a full scale distribution voltage test.

The facility was completed successfully and the testing began with single unit unintentional islanding tests. The single unit results validated the test set-up and the methodologies employed.

The DUIT team accomplished our objective of building a world class DER integration test facility that has given many tours to visitors from all over the United States and from more than eight countries from around the world. We also completed the single unit unintentional islanding tests at 480V. Then we went on to complete the homogenous and small group tests at 21kV. We had expected to complete much more of the unintentional islanding group of tests during this phase of the project but the testing took much longer than expected. However, the results were so unexpected and the learning was so rich that we are confident that the DUIT test results have had a significant impact on the industry in support of the interconnection standards.

The multiple unit tests began the project testing at distribution voltage, 21kV and completed a sequence of homogenous testing of the single phase inverters and the small group testing. Various distributed resources underwent unintentional islanding tests according to industry standards, in a realistic distribution system test environment. The results again validated the test setup at the distribution voltage level and prepared for further and more involved phases of testing of unintentional islanding scenarios.

These islanding tests have brought together the distributed resources industry manufacturers, utilities and government entities to examine the distribution system grid impact of distributed resources and the test results are supporting the industry interconnection standards efforts and the quantification of the value of deploying distributed resources in the utility distribution system.

The results of the testing for basic unintentional islanding tests proved that it was necessary to continue efforts with a focus on unintentional islanding. This moved the team into the multiple unit tests. At the conclusion of the phase of the project it was determined by the CEC that it was necessary to continue funding and move forward with additional testing.

4.2. Recommendations

The first recommendation is specific to the results obtained from the single unit unintentional islanding tests. The Technical Advisory Committee (TAC) recommended that the manufacturer provide details of the anti-islanding algorithm, if they are unable to comply with that request, then the device is to be subjected to islanding tests at the center and the limits of the manufacturer's specified input voltage window, plus a test at 5% load. This will increase the number of test voltages from one to four resulting in tests increasing from 33 to 132.

Discussions with Underwriters Laboratories regarding the results of the single unit unintentional islanding tests led to the conclusion that UL should consider revisions to UL1741, comprising more explicit language in the following areas:

- Definition/specification of what constitutes "balanced test conditions";
- Definition of linearity of the test load;
- Acceptable tolerances on pre-test voltage and frequency; and
- Accounting for parasitic losses (real and reactive) in the test load setup

Our industry TAC representing utilities, DER vendors, standards and testing bodies have all recommended that the DUIT project continue on its path of completing the unintentional islanding test plan and move on to the voltage regulation and stability test protocols. Under the 2005 contract with the California Energy Commission and with additional support of the United States Department of Energy we are currently completing this set of tests. It has also been recommended by the DUIT industry TAC to add to the body of research regarding distribution systems. Currently the DUIT efforts examine only those issues having to do with radial systems. It has become increasing important to examine the issues and testing needs for utility network systems.

4.2.1. Islanding Analysis Recommendations

Further research into any of the four physical factors quantified in the islanding analysis is warranted and would lead to narrower ranges of islanding probabilities, but is unlikely to raise the upper bound. Non-inverter based systems (e.g., rotating machines) will have different results.

4.2.2. Multiple Unit Testing Recommendations

Islanding with multiple DERs Test 6.2 concluded following homogenous groups of single phase inverters, small groups of single phase inverters, and one test of a residential single phase unit and the Bay 3 generator.

The full range of testing for unintentional islanding includes six more suites of test configurations. The recommendations of the team are to proceed according to the

sequence, and as detailed in the DUIT Anti-Islanding Test Description and Sequence in the Test Plan commercial-sized units in Bays 2 and 3 and the rotating machine in Bay 3 are operated and tested simultaneously).

At the conclusion of test sequence 6.2, a Progress Review Meeting will be held at which the project Technical Advisory Committee will review the results and re-prioritize Tests 6.3 – 6.7. The committee consists of representatives from manufacturers, utilities and the California Energy Commission and the National Renewable Energy Laboratory.

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Distributed Utility Associates (DUA) Web site: www.dua1.com/DUIT.

GLOSSARY

List of Acronyms and Abbreviations

CEC	California Energy Commission
DAS	Data Acquisition System
DEG	Distributed Energy Generator
DER	Distributed Energy Resource
DOE	Department of Energy
DUA	Distributed Utility Associates
DUIT	Distributed Utility Integration Test
DUT	Device Under Tests
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
EPS	Electric Power System
Kvar	Kilovolt-ampere-reactive
MGTF	Modular Generation Test Facility
NI-DAS	National Instruments Data Acquisition System
NDZ	Non-Detect Zone
NREL	National Renewable Energy Laboratory
RTO	Regional Transmission Organizations
SNL	Sandia National Laboratories
PG&E	Pacific Gas and Electric Company
PIER	Public Interest Energy Research
PV	Photovoltaic
UL	Underwriter's Laboratory

APPENDIX A: BASIC ANTI-ISLANDING TEST

BASIC ANTI-ISLANDING TEST

This is first in a series of tests dealing with the validity of anti-islanding techniques when there are multiple DERs in the island.

The test described here is the basic anti-islanding test procedure defined in IEEE 929 and UL 1741. Subsequent procedures in this section will use this procedure with modifications or additions to evaluate various aspects of the procedure or different DER/Area EPS scenarios.

Governing IEEE 1547 Sections, CA Rule 21, Other documents:

IEEE 1547:	§4.2.1, 4.4.1, 5.1.8, Annex A.5
CA Rule 21:	§D.1.i, D.3.d.1), J.3.d
UL 1741:	§46.3
IEEE 929:	Annex A

Test Objectives:

Determine the amount of time it takes the DER under test to detect the loss of Area EPS from a stable, balanced island, and to cease energizing the grid ("trip"). The load within the island is designed to be highly resonant with the DER unit to simulate an extreme condition.

Key Testing Parameters

The key test parameter is the time required for the DER on the island to trip ("cease energizing" the line). This definition is related to current output from the DER, as there may be a significant delay between the reduction of current below a threshold level and the mechanical opening of a disconnecting device.

Expected Results:

This test will quantify the amount of time required for the DER to trip once an islanding condition exists.

1.0 Test Procedure:

This test was developed from the procedure described in IEEE 929 Annex A. That document was defined for inverter-based photovoltaic (PV) systems, so modifications were incorporated to accommodate other types of DER.

Unless otherwise specified, measurement error for all parameters, except frequency, in the following test procedures shall be less than 1%. Measurement error for frequency shall be less than or equal to 0.05 Hertz (Hz).

For this procedure, a utility source implies a source capable of maintaining an island within the recommended voltage and frequency windows. An engine-generator with voltage and frequency control and with no anti-islanding protection is considered a simulated utility source for the purpose of this test.[i] However, because of the uncertainty associated with the need to sink both real and reactive power from the DER, this test may be performed most conveniently with an actual utility connection, rather than a simulated utility. This test should be conducted with voltage and frequency near the middle of their operating ranges. Voltage should be at least 3% inside the most restrictive voltage trip limits. Frequency should be at least 0.25 Hz inside the most restrictive frequency trip limits. (Note that frequency and voltage variation are not required for this testing.)

This test procedure is based on having the quality factor, Q, of the islanded circuit (including load and generator) set equal to 2.5.

$$Q = (1/P)\sqrt{P_{qL} \quad \text{x} \quad P_{qC}}$$

Where:

Q is quality factor
R is effective load resistance
L is effective load inductance
C is effective load capacitance (including shunt capacitors)
P is real power
P_{qL} is inductive load
P_{qC} is capacitive load.

Note also that, in the resonant case:

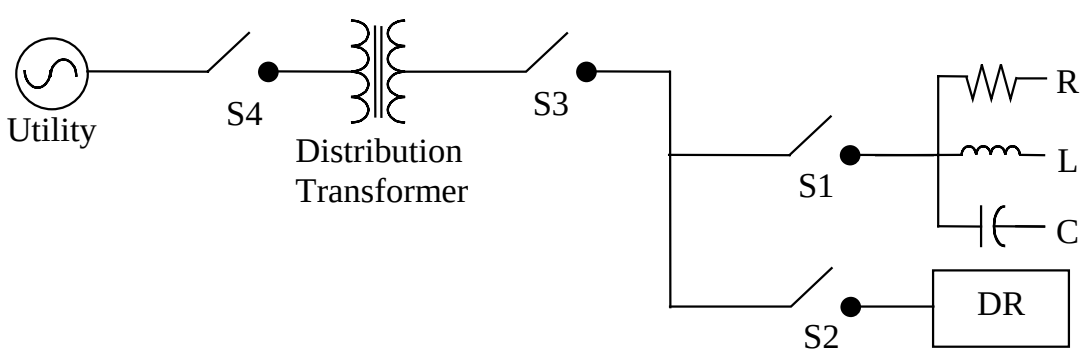
$$P_{qL} = P_{qC} = P_q$$

Therefore, in the resonant case:

$$Q = P_q/P$$

These formulas apply to DER with unity-power-factor output.
This test procedure is designed to be universally applicable to both unity-power-factor DER and non-unity-power-factor DER. With unity-power-factor DER, the second step below, where Pq-DERDER is measured, will result in a value of Pq-DER that is zero, simplifying the remainder of the procedure. For DER where Pq-DER is not zero, the test is complicated by the presence of reactive power in the DER.
Harmonic currents by the utility to the capacitor and the DER further complicate the situation by making it appear that current is flowing when the 60 Hz component of current has been zeroed. Thus, it is important, when adjusting inductive and capacitive reactance, to use instruments that can read only the 60 Hz components of current and power.
The sequence of the steps below is suggested for several reasons. The inductance is measured first because that measurement is low in harmonics. The capacitance is added second so that the voltage is stable when the resistance is added. The resistive parallel load is then added and adjusted. Note that this resistance will be in addition to the resistance that will be part of the inductive load.

Figure 1: Anti-Islanding Test Circuit



This test procedure assumes that a non-unity-power-factor DER will be sourcing, not sinking, reactive power. The procedure refers to a circuit that is configured as shown in Figure 1 Details of this circuit may be changed to suit the specific hardware available to the tester. For example, it may be convenient to replace switch S1 with individual switches on each leg of the RLC load. For each DER/load power combination, the following procedure is suggested to achieve the proper generation-to-load complex power balance. In the following description, the utility disconnect switch may be either S3 or S4. Normally, the utility disconnect switch on the secondary side of the distribution transformer, S3, is used for this purpose. This switch removes the distribution transformer from the island circuit (a more difficult requirement). In some cases, it may be desirable or necessary to include the transformer. In those cases, the primary side disconnect, S4, may be used.

Sequence of steps:

1) Determine DER test output power, P_{DER}, that will be used.
2) Operate the DER at PDER and measure DER reactive power output, $_{Pq\text{-}DER}$. The utility disconnect switch should be closed. With no local load connected (that is, S1 is open so that the RLC load is not connected at this time), and the DER connected to the utility (S2 is closed), turn the DER on and operate it at the output determined in step a. Measure real and reactive power flow at the measurement point. The real power should equal PDER. The reactive power measured in this step is designated $P_{q\text{-}DER}$.
3) Turn off the DER and open S2.
4) Adjust the RLC circuit to have Q = 2.5 as follows:
    a. Determine the amount of inductive reactance required in the resonant RLC circuit using the relation $P_{qL} = 2.5\ P_{DER}$.
    b. Connect an inductor as the first element of the RLC circuit and adjusting the inductance to P_{qL}.
    c. Connect a capacitor in parallel with the inductor. Adjust the capacitive reactance so that $P_{qC} + P_{qL} = -\ P_{q\text{-}DER}$.
    d. Connect a resistor that results in the power consumed by the RLC circuit equaling P_{DER}.
5) Connect the RLC load configured in step 4d to the DER by closing S1. Close S2 and turn the DER on, making certain that the power output is as determined in step 4a.
    (Note: The purpose of the procedure up to this point is to zero out the 60 Hz components of real and reactive power, or to zero out the 60 Hz component of current flow, at the utility disconnect switch. System resonances will typically generate harmonic currents in the test circuit. These harmonic currents will typically make it impossible to zero out a measurement of continuous power or RMS current flow at the disconnect switch. Because of test equipment measurement error and some impact from harmonic currents, it is necessary to make small adjustments in the test circuit to achieve worst case islanding behavior. Step g is performed to make these small adjustments.)
6) Open the utility-disconnect switch to initiate the test.
7) After each successful test, adjust one parameter by approximately 1.0% per test, within a total range of ±5% of the operating point determined in step d) above.

The parameter that is adjusted may be load inductance, L, or load capacitance, C. After each adjustment, perform an island test is run and record the time to trip.

8) For three-phase DER, the test should be run with the utility disconnect occurring in all combinations of one, two, and three phases.
9) For three-phase DER the test should be done initially with the load determined as described above, individually for each phase. Optionally, the test can then be repeated with an imbalance in real power of 5 – 10 percent in various arrangements (i.e., reduce Phase A and B by 5%, increase C by 10%).

This test should be performed with the following ratios of real load to DER output, where both values are given as a percent of DER full output rating:

Table 1: Real Load to DER Output Ratios

Real Load	DER Output
25%	25%
50%	50%
100%	100%
125%	100%

The actual tripping time for each test shall be recorded.

2.0 Requirements

2.1 Data Acquisition Requirements:

Table 2: Data Acquisition Requirements

Parameter	Units	Range (Nom.)	Accuracy	Sampling Rate	Recording Rate
Island Contactor Status (i.e., aux. contact closure)	DC Volts	0-10	5%	600 Hz	600 Hz
Island Contactor Utility-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
Island Contactor Island-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
DER Output Current (1/DER)	AC Amps	0-FS	1%	600 Hz	600 Hz
DER Output Voltage, DER side of DER contactor, if accessible	AC Volts	0-480	1%	600 Hz	600 Hz

2.2 Control Requirements:

The basic test is supposed to evaluate autonomous operation of the different DER sources with no control interconnection between them. There are no special control system requirements; however, variations of this basic procedure may include some control strategies or equipment.

2.3 Facility Requirements:

The test facility will need adjustable resistive, inductive, and capacitive loads with sufficient capacity and resolution to meet the impedance and step size requirements of a particular test.

2.4 DER Requirements:

This basic test may be performed on a single DER or on multiple units. Subsequent test procedures will have their own specific requirements.

2.5 Other Requirements:

2.6 Modeling Requirements:

None

APPENDIX B: ANTI-ISLANDING WITH MULTIPLE DER TYPES

ANTI-ISLANDING WITH MULTIPLE DER TYPES

Governing IEEE 1547 Sections, CA Rule 21, Other documents:

IEEE 1547:	§4.2.1, 4.4.1, 5.1.8, Annex A.5
CA Rule 21:	§D.1.i, D.3.d.1), J.3.d
UL 1741:	§46.3
IEEE 929:	Annex A

1.0 Test Objectives:

Perform the basic anti-islanding test individually on 3 to 5 DERs. At least two of the DERs should be inverter-based, at least one should be a synchronous machine, and at least one should be an induction machine. The largest DER unit should not be more than twice the size (rated output) of the smallest. All DERs should have some form of anti-islanding detection (or reverse-power or under-power detection, in which case the related RLC load will have to be on the DER side of the under-power measurement point).

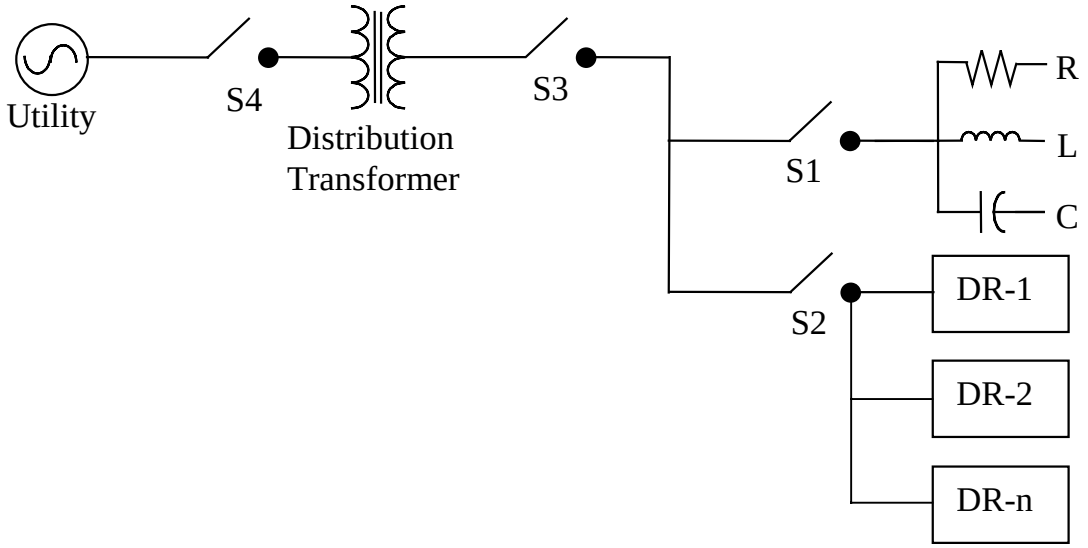
1.1 Key Testing Parameters

The key test parameter is the time required for the DERs on the island to trip ("cease energizing" the line). This definition is related to current output from the DER, as there may be a significant delay between the reduction of current below a threshold level and the mechanical opening of a disconnecting device.

1.2 Expected Results:

This test will quantify the amount of time required for the DER to trip once an islanding condition exists.

Figure 1: Anti-Islanding Test Circuit with Multiple DERs



2.0 Test Procedure:

Same as for Test 2.1, with multiple DERs.

2.1 Data Acquisition Requirements:

Table 1: Data Acquisition Requirements with Multiple DERs

Parameter	Units	Range (Nom.)	Accuracy	Sampling Rate	Recording Rate
Island Contactor Status (i.e., aux. contact closure)	DC Volts	0-10	5%	600 Hz	600 Hz
Island Contactor Utility-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
Island Contactor Island-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
DER Output Current (1/DER)	AC Amps	0-FS	1%	600 Hz	600 Hz
DER Output Voltage, DER side of DER contactor, if accessible	AC Volts	0-480	1%	600 Hz	600 Hz

3.0 Requirements:

3.1 Control Requirements:

The basic test is supposed to evaluate autonomous operation of the different DER sources with no control interconnection between them. There are no special control system requirements; however, variations of this basic procedure may include some control strategies or equipment.

3.2 Facility Requirements:

The test facility will need adjustable resistive, inductive, and capacitive loads with sufficient capacity and resolution to meet the impedance and step size requirements of a particular test.

3.3 DER Requirements:

This basic test may be performed on a single DER or on multiple units. Subsequent test procedures will have their own specific requirements.

3.4 Other Requirements:

None.

3.5 Modeling Requirements:

None

APPENDIX C: ANTI-ISLANDING WITH REDUCED UNDERVOLTAGE AND UNDERFREQUENCY TRIP SETTINGS

ANTI-ISLANDING WITH REDUCED UNDERVOLTAGE AND UNDERFREQUENCY TRIP SETTINGS

There are several circumstances where loss of generation may exacerbate an existing problem. The undervoltage setting limits the ability of the DER to ride through voltage sags caused by, for example, a fault on an adjacent feeder. One reason for the current setting is as a precaution against islanding: the narrower the operating window, the less likely that islanding will occur. While there may be other reasons for these settings (e.g., to enhance fault detection) determining the impact of these settings on the DER's ability to detect an island may help to determine new or alternative set points.

Under this test, the undervoltage and underfrequency settings will be adjusted down in 5 Volt and 0.1 Hz increments, respectively, and the impact on the cease to energize time will be evaluated.

These tests were conducted in conjunction with the 6.1 tests and the supplemental testing.

Governing IEEE 1547 Sections, CA Rule 21, Other documents:

IEEE 1547:	§4.2.1, 4.4.1, 5.1.8, Annex A.5
CA Rule 21:	§D.1.i, D.3.d.1), J.3.d
UL 1741:	§46.3
IEEE 929:	Annex A

1.0 Test Objectives:

The objective of this test is to characterize device performance by performing the anti-islanding test (Test 2.1) with sequentially reduced settings for undervoltage and underfrequency settings.

1.1 Key Testing Parameters

The key test parameter is the time required for the DERs on the island to trip ("cease energizing" the line). This definition is related to current output from the DER, as there may be a significant delay between the reduction of current below a threshold level and the mechanical opening of a disconnecting device.

1.2 Expected Results:

This test will quantify the amount of time required for the DER to trip once an islanding condition exists.

2.0 Test Procedure:

Same as for Test 2.1, with single and multiple DERs, with the additional variables of sequentially reducing the undervoltage and underfrequency settings in steps of 5 Volts and 0.1 Hz, respectively.

2.1 Data Acquisition Requirements:

Table 1: Data Acquisition Requirements w. Reduced Under-Voltage and -Frequency Trip Settings

Parameter	Units	Range (Nom.)	Accuracy	Sampling Rate	Recording Rate
Island Contactor Status (i.e., aux. contact closure)	DC Volts	0-10	5%	600 Hz	600 Hz
Island Contactor Utility-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
Island Contactor Island-Side Voltage	AC Volts	0-480	1%	600 Hz	600 Hz
DER Output Current (1/DER)	AC Amps	0-FS	1%	600 Hz	600 Hz
DER Output Voltage, DER side of DER contactor, if accessible	AC Volts	0-480	1%	600 Hz	600 Hz

3.0 Control Requirements:

3.1 Control Requirements:

The basic test is supposed to evaluate autonomous operation of the different DER sources with no control interconnection between them. There are no special control system requirements; however, variations of this basic procedure may include some control strategies or equipment.

3.2 Facility Requirements:

The test facility will need adjustable resistive, inductive, and capacitive loads with sufficient capacity and resolution to meet the impedance and step size requirements of a particular test.

3.3 DER Requirements:

This basic test may be performed on a single DER or on multiple units. Subsequent test procedures will have their own specific requirements.

3.4 Other Requirements:

None.

3.5 Modeling Requirements:

None.

APPENDIX D: DUIT DATA ACQUISITION SYSTEM (DAS) ARCHITECTURE

DUIT DATA ACQUISITION SYSTEM (DAS) ARCHITECTURE

1.0 Overview of Software and Hardware for Data Acquisition and Test Control

The DUIT Data Acquisition and Control System (also called simply "the data acquisition system," or DAS) is intended to facilitate the various testing regimes and control and monitoring needs contemplated by the overall DUIT test plan. Monitoring (data acquisition) will be provided by the equipment and software described in this document. A portion of the control function is also accomplished with this hardware and software – primarily control that is related to test equipment and loads. Direct control of distributed resources (DER) is discussed in the companion documentation "DUIT Test System Architecture – DER Control."

1.1 Functional Requirements

The hardware and software are configured to provide the following functions:

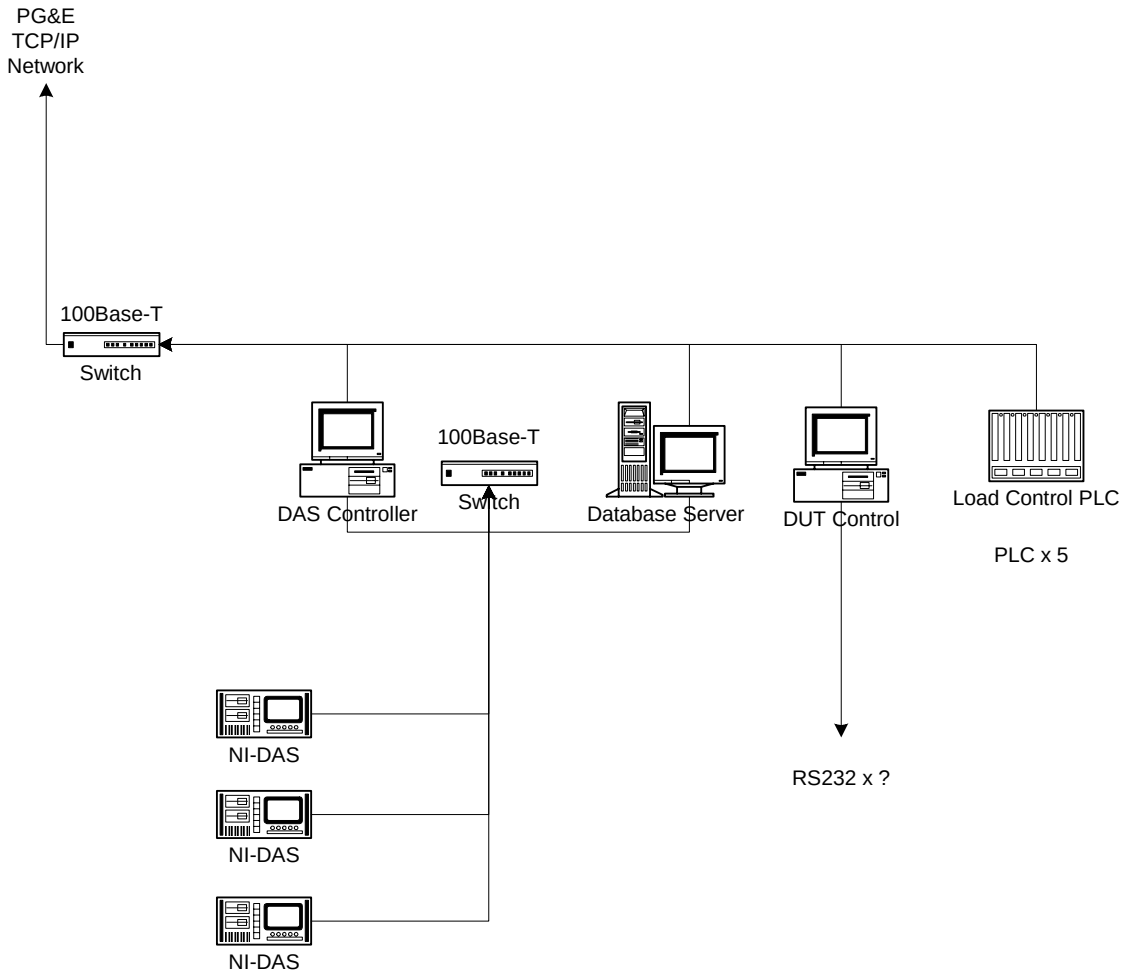
1) Devices under test (DUTs) will include inverter-based equipment as well as induction and synchronous generator equipment. The DAS hardware is capable of collecting sampled data from both three-phase and single-phase power flows into and out of these devices.
2) High-speed sampling rate is at least 6 kHz; higher rates may be required for some test situations. Data recording starts on operator command, and stops after an operator-specified duration.
3) Data display equivalent to a digital multi-meter based on sampled inputs is included on a full-time basis, whether high-speed recording is occurring or not. Single and three-phase power readings, including power readings that exclude harmonic content, are supplied. Root-mean-square voltage and current readings for AC measurement points are also standard. The update rate for all data displays is a minimum of 0.5 Hz.
4) Control of DUTs will be performed through manufacturer-supplied software/hardware interfaces; software-based control that can be located on computing hardware in the central control room will be preferred, where possible. Complete integration and automation of DUT control into the DAS architecture is not contemplated in this phase of development.
5) Control of DC power supplies and photovoltaic simulators is performed through a software user interface located in the central control room.

The following sections discuss hardware, key system functions, and data definitions. Following those sections, a discussion of the development plan is included, in which successively detailed partial implementations of the final product are described.

1.2 DAS Hardware Architecture

The DAS hardware architecture is illustrated in Figure 3. A complete specification of all the data channels in the DUIT DAS Architecture can be found in the companion documentation "DUIT Test Facility Hardware Report."

Figure 1: DAS Hardware Architecture



The major elements of DAS hardware architecture are described as follows:

1.2.1. DAS Controller

This computer is the console from which data collection will be performed. Additional functions, such as remote control of the Load Control Programmable Logic Controller (PLC) (see below), will also run on this computer.

1.2.2. National Instrument Data Acquisition System (NI-DAS)

These blocks are the National Instruments data sampling systems. Multiple units are expected to be required in order to provide enough processing power to meet the full-time metering requirements, and to allow co-location in the test bays to minimize sensor signal wiring length.

The NI-DAS units may be networked directly to the DAS Controller via a 100BaseT switch to minimize the effects of general network traffic load on DAS communications, if required.

1.2.3. Database Server

The database server provides central SQL database storage and backup capability. Both raw ("high-speed") and DUT/DAS configuration data (power contactor configuration, DUT operational parameters, and DAS channel configuration) are stored on this server. Post-test data analyses will retrieve these data as required.

1.2.4. DUT Control

These computers will be used to control the operation of the DER units. The architecture and operation of this system is further described in the companion document "DUIT Test System Architecture – DER Control."

1.2.5. Load Control PLC

One or more Ethernet-accessible PLC devices will be used to control loads, i.e., to select the operating points of the resistive, inductive and capacitive load components. Note that the PLC controller will be set up to control multiple loads at multiple test bays. The devices will be remotely controllable via ActiveX software interfaces on the DAS Controller computer.

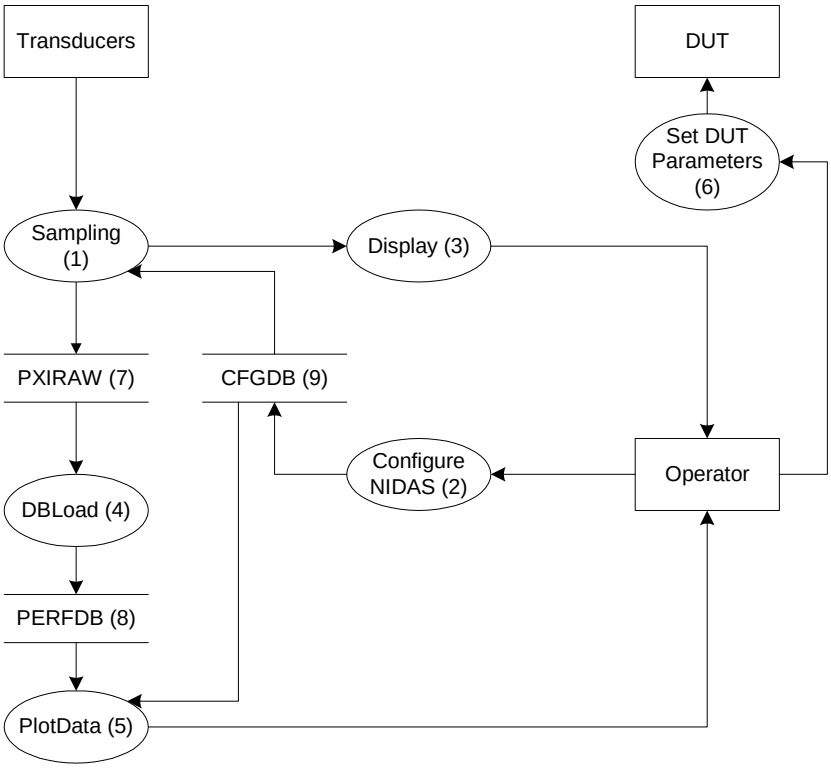
1.3 DAS Software Architecture[i]

The DAS software architecture implements the functions shown in Figure 4.
Functional Requirements

1.3.1. 1. Data Sampling

Data sampling must proceed continually while the DAS is operational to allow full time operation of the display function. Recording of the data to local storage need only occur during the test, as commanded by the operator. Please refer to Figure 5 for details of the data sampling process.
1.1 Double-Buffered Acquisition
This function continuously samples data at high speed, and writes it into one of two buffers, signaling the display and write-to-disk functions when a buffer is full and the other buffer is being filled.
1.2 Write-To-Disk
This function writes sampling buffers to disk when they are filled. The data are transferred as raw samples for high throughput.
1.3 Sampling Buffers
The sampling buffers are a pair of memory buffers representing between 0.5 and 1 second worth of data each, such that the summary display can be updated at approximately 1-second intervals.

Figure 2: Top Level DAS Software Functional Requirements



1.3.2. 2. NI-DAS Configuration

Configuring the NI-DAS prepares the necessary relationships to map the sensor inputs to "reading" columns in the DAS Control Display. These data are stored in the database for easy access and later reference.

1.3.3. 3. Display

A subset of the sampled data must be analyzed to produce the meter data to be displayed on the DAS Controller. To reduce communication bandwidth requirements, the computation of RMS values and average power values is performed on the NI-DAS, and transferred to the DAS Controller for display. Since different tests will require different data points to be monitored, the points to be monitored must be specified by the DAS Controller before it retrieves the data. Figure 2 illustrates this process.

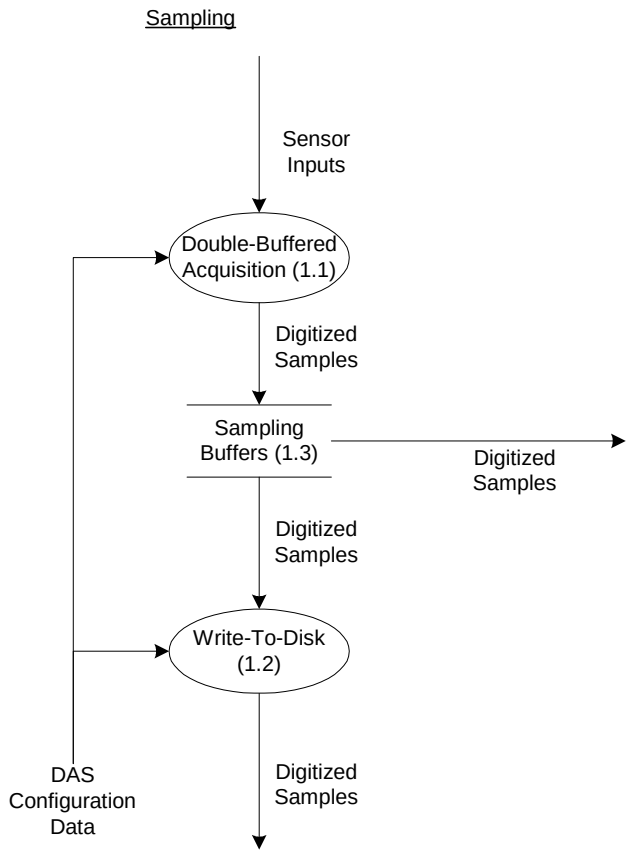
3.1 Display Data Reduction

This function accepts as input the digitized data samples from the sampling buffers, and processes some or all of that data into reading values suitable for display.

3.2 Network Data Responder

This function handles networked requests for "real-time" data, supplying the contents of the Display Data Source Buffer when requested. This function operates asynchronously from the Display Data Reduction function, so access contention must be handled in reading and writing data to the NI-DAS Display Data Buffer.

Figure 3: Sampling Functions Detail



3.3 Test Data Display
This function polls NI-DAS Reduced Data from the corresponding Network Data Responders and displays selected values for the test that is under way, including such presentation techniques as digital displays, meters and strip chart graphs.
3.4 NI-DAS Display Data Buffer
This buffer holds the most recent set of reduced data values from a particular NI-DAS; these data are intended for on-the-fly user display.

1.3.4. Contactor

Contactors may initially be in open or closed states as required by the test configuration, and/or opened or closed as part of the conduct of the test. In the former case, recording the states of the contactors at the beginning of the test should be sufficient. In the latter case, high-speed recording of the status of the wetting voltage on a secondary contact will be needed to identify the times of contactor state changes.

1.4 DAS Development Plan

The development will proceed in phases; each phase will produce a new version of the overall system software. Each phase will be developed in fractional version increments. Additional hardware and software complexity will be added in each phase. Note that the version numbers describe the system version number (i.e., the aggregate of all software and hardware components necessary to provide the functionality described). This is an

important distinction, as several software components will be developed throughout this effort, and each of these will have its own internal version number.

1.4.1. Version 1 – Localized-Source Testing

This system version will support islanding testing of co-located generator units with a minimum of auxiliary capabilities. A single NI-DAS unit will be configured and controlled as a stand-alone data collection workstation so as to support this minimal functionality. A separate database computer will be configured to store the data, and ad-hoc database queries will be used to extract data for analysis in spreadsheets. Configuration data for the test will be either hard-coded or read from local files on the NI-DAS. Figure 3 describes the development steps, and notes the focus on NI-DAS development, central DAS Controller development (Central), or database management system development.