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Validated Modeling of Distributed Energy Resources at Distribution Voltages

LDRD Project 38672

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Abstract

A significant barrier to the deployment of distributed energy resources (DER) onto the power grid is uncertainty on the part of utility engineers regarding impacts of DER on their distribution systems. Because of the many possible combinations of DER and local power system characteristics, these impacts can most effectively be studied by computer simulation. The goal of this LDRD project was to develop and experimentally validate models of transient and steady state source behavior for incorporation into utility distribution analysis tools. Development of these models had not been prioritized either by the distributed-generation industry or by the inverter industry.

A functioning model of a selected inverter-based DER was developed in collaboration with both the manufacturer and industrial power systems analysts. The model was written in the PSCAD simulation language, a variant of the ElectroMagnetic Transients Program (EMTP), a code that is widely used and accepted by utilities.

A stakeholder team was formed and a methodology was established to address the problem. A list of detailed DER/utility interaction concerns was developed and prioritized. The list indicated that the scope of the problem significantly exceeded resources available for this LDRD project. As this work progresses under separate funding, the model will be refined and experimentally validated. It will then be incorporated in utility distribution analysis tools and used to study a variety of DER issues. The key next step will be design of the validation experiments.

Problem Statement

Lack of validated models of distributed energy resources (DER) is a significant barrier to their deployment. Utilities are tasked with providing power of acceptable quality to their customers. Because of this, they are necessarily cautious about connection of generators that are not well understood or even under their control. At high aggregated power levels, such generation could affect fundamentally important areas such as system protection and stability.

To date, the impact of aggregated DER has been modeled primarily on transmission systems. However, sources that are presently being commercialized and those in the foreseeable future will operate at low voltage and connect via transformers to local distribution systems. The goal of this project was to develop and experimentally validate models of transient and steady state source behavior for incorporation into utility distribution analysis tools. Development of these models had not been prioritized either by the distributed-generation industry or by the inverter industry.

The project emphasized DER based on power-electronic inverters. Although the electrical behavior of rotating machines such as diesel generators has been well characterized, no utility-compatible models are available for power-electronic inverters. Inverters are the utility interface for microturbines, fuel cells, photovoltaic (PV) inverters, variable-frequency wind generators, and virtually any system using electrical energy storage.

This report will provide a summary of the project. Specific details may be obtained by contacting the author.

Approach

There are many different aspects to the problem of distributed resource interactions with utility distribution systems. In order to make progress it was critical to focus the activity. Key considerations were:

Utility involvement

It was felt that in order for the results of this work to be useful to utility engineers, it was important that they be involved and consulted for guidance by the project team. Salt River Project (SRP), a large utility based in Phoenix, provided the primary source of utility expertise. The team took advantage of various cooperative activities between Sandia and utilities to crosscheck the guidance from SRP.

Prioritization of Issues

There are a large number of concerns related to the operation of distributed generation with utility distribution feeders. Documenting these issues and prioritizing them were necessary precursor activities for this project.

DER Selection

The aspect of a distributed energy resource that is key to its interaction with the grid is its method of control. Information from the manufacturer on control algorithms and settings is necessary for accurate modeling. Cooperation by a manufacturer of inverter-based DER was a major factor in selection of the first source to be modeled.

Modeling Language

Criteria were developed for choosing among the various commercially-available circuit-simulation codes.

Tasks and Results

Document and Prioritize Grid/DER Interactions Issues

Grid/distributed energy resource (DER) interaction issues were documented and prioritized based on utility concerns. In order to tap existing industry expertise and to minimize initial research time, guidance was obtained from a white paper[1] documenting these issues. Doug Dawson, a power system protection expert who is widely respected in the utility community, wrote the paper. It lists nine high-penetration DER issues. The LDRD team prioritized the three that could be studied most productively at Sandia. The highest priority was assigned to the issue of anti-islanding, i.e., behavior of a source upon loss of utility. The Consortium for Electric Reliability Technology Solutions (CERTS), a partnership among industry, national laboratories, and universities, provided the funding to generate this report. The fact that the LDRD funding was able to leverage these additional funds illustrates one of the many areas to which this work is applicable.

The report, summary of research issues, and internal prioritization made by the LDRD team were sent to Salt River Project (SRP) for review and comment. SRP and Sandia were involved via a CRADA to study impacts of DER on the SRP distribution grid. A microturbine belonging to SRP was tested at Sandia in support of this CRADA. A meeting was held with the SRP distribution planning and protection engineers to discuss high-penetration issues. SRP independently confirmed the prioritization of the anti-islanding studies.

The choice of anti-islanding as the initial focus of the work was consistent with feedback from other utilities. The project team has access to utility engineers via a number of different contacts. Department 6218 has had extensive interactions with utility engineers, most notably through Ward Bower's work on various domestic and international codes and standards committees and through John Stevens' chairmanship of IEEE 929-2000 and his ongoing participation in a variety of projects involving installations of utility-interconnected photovoltaic systems. Energy Storage Department 2525 has assisted in the development of large utility-interactive inverters incorporating battery storage to improve the power quality during periods of grid fluctuations. A number of these systems have been commercially deployed in cooperation with various utilities. The issue of islanding has been a recurrent theme through all these activities.

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[1] Dawson, Douglas C., "DR Penetration Issues: A Report on the Effects of Higher Distributed Resource Penetration on Utility Interconnection with Recommendations for Areas to be Studied," Report for Sandia National Laboratories, (limited distribution), March 2002.

Select One or More DER to Model

DER power electronic inverters were reviewed, and the Xantrex PV 20208 inverter was selected as the first DER to be modeled. This 20 kW grid-tied photovoltaic inverter, shown in Figure 1 is a mature, commercially available product. One had been installed and was generating power at the Distributed Energy Technologies Lab (DETL) operated at Sandia. A factor in the selection of this inverter was the excellent working relationship that has developed between Xantrex and Sandia staff. Xantrex expressed a high degree of interest in supporting the project. A small contract was placed to help defray the cost of Xantrex engineering time. Xantrex cost-shared the effort, and provided detailed circuit and controls information for the model.

Other distributed energy resources that were considered for the modeling effort included the Capstone Model 330 microturbine, Advanced Energy Multi-mode PV/storage inverter, Xantrex Trace Engineering SW5548 PV/storage inverter, and the Ingersoll-Rand microturbine. All these sources resided at the DETL, and their manufacturers expressed interest in the project. As this work progresses, it will be highly desirable to develop models of a wide variety of DER.

Figure 1. Xantrex PV20208 Grid-Tied PV Inverter

Review and Select DER Simulation Language

PSCAD was selected as the simulation language. A primary reason for this selection was that PSCAD is a variant of the ElectroMagnetic Transients Program (EMTP) that is widely used and accepted by utilities. Other simulation languages considered included MatLab Simulink and PSPICE. These showed expected agreement with PSCAD but did not offer as much flexibility in the circuit topology or run as efficiently. A major power systems analysis contractor, Electrotek Concepts, was engaged to collaborate in the development of the model. A goal of the project is to incorporate the new DER models into software tools that are presently used by utilities for distribution system planning. Electrotek's experience and insight into this area was felt to be relevant.

Develop DER Model with and without Storage

The operation of the PV 20208 inverter was simulated using PSCAD. Features that were incorporated into the model included semiconductor switch firing controls, the modulation scheme used to generate a sinusoidal output waveform, voltage and current regulation, and voltage shifting for detection of islanding. The power electronic switch matrix and a portion of the control logic are shown in Figures 2 and 3. Waveforms of a typical simulation of steady-state inverter operation are shown in Figure 4.

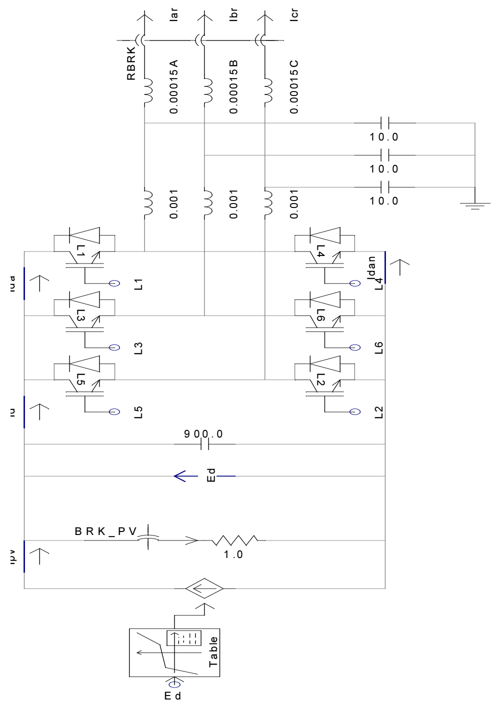

Figure 2. Power electronic switch matrix

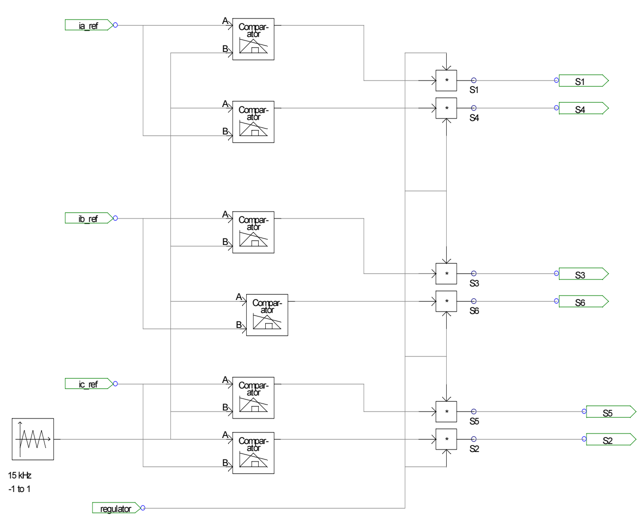

Figure 3. Control logic block diagram

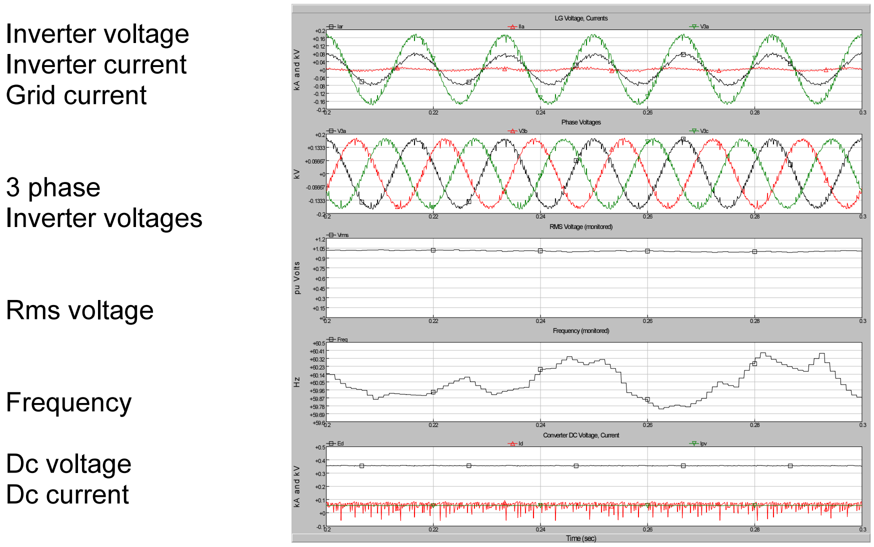

Figure 4. Steady-state waveforms of PV 20208 simulation

Develop Test Protocols

DETL has documented anti-islanding test protocols that were developed for IEEE 929, "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems." These protocols have been used extensively and incorporated into UL 1741, used by Underwriters Laboratory for certification testing. As shown in Figure 5, the test circuit consists of an RLC load tuned for resonance at a frequency of 60 Hz. Active detection and control methods are required to detect loss of utility with this configuration. Passive methods such as verifying that grid voltage and frequency are within limits are not adequate.

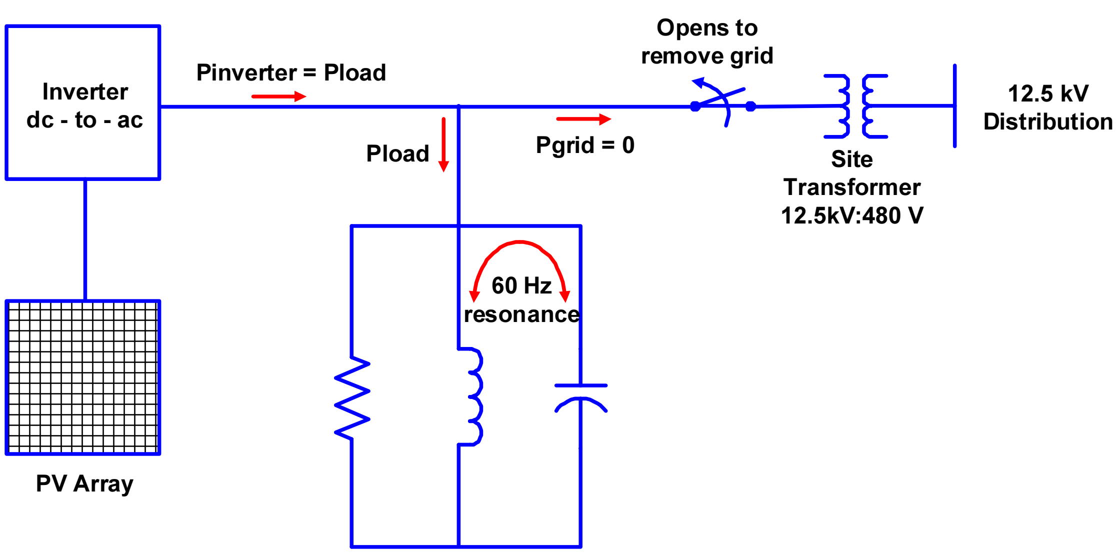

Figure 5. Anti-islanding test configuration

Perform Validation Testing

Tests were conducted at DETL to compare the results of the computer simulations to measurements of actual hardware behavior. There was reasonable agreement in such areas as current wave shape and harmonic distortion. However, much more detailed work remains to be done. There were insufficient resources available to resolve observed differences to the level of detail desired.

Review and Select One or More Distribution Analysis Tools

Distribution planning tools were surveyed. Information was obtained from a study performed by New Mexico State University (NMSU) in 1993 for Pacific Gas and Electric. The not-unexpected finding of the survey was that there is no single code that is universally used and accepted by utilities for this purpose. SRP uses power flow programs developed by Power Technologies Inc. (PTI) and General Electric (GE). Electrotek has developed a code called “DistCo Suite” that is specifically designed for distribution planning. However, many aspects of distribution planning are presently performed manually or using “in-house” analysis techniques. Because many of the existing tools are being revised, more research is required, including a possible update of the NMSU survey.

Simulate DETL Distribution System

The inverter was connected to the DETL distribution system as shown in Figure 6. With assistance from Electrotek, a model of this configuration was developed in PSCAD.

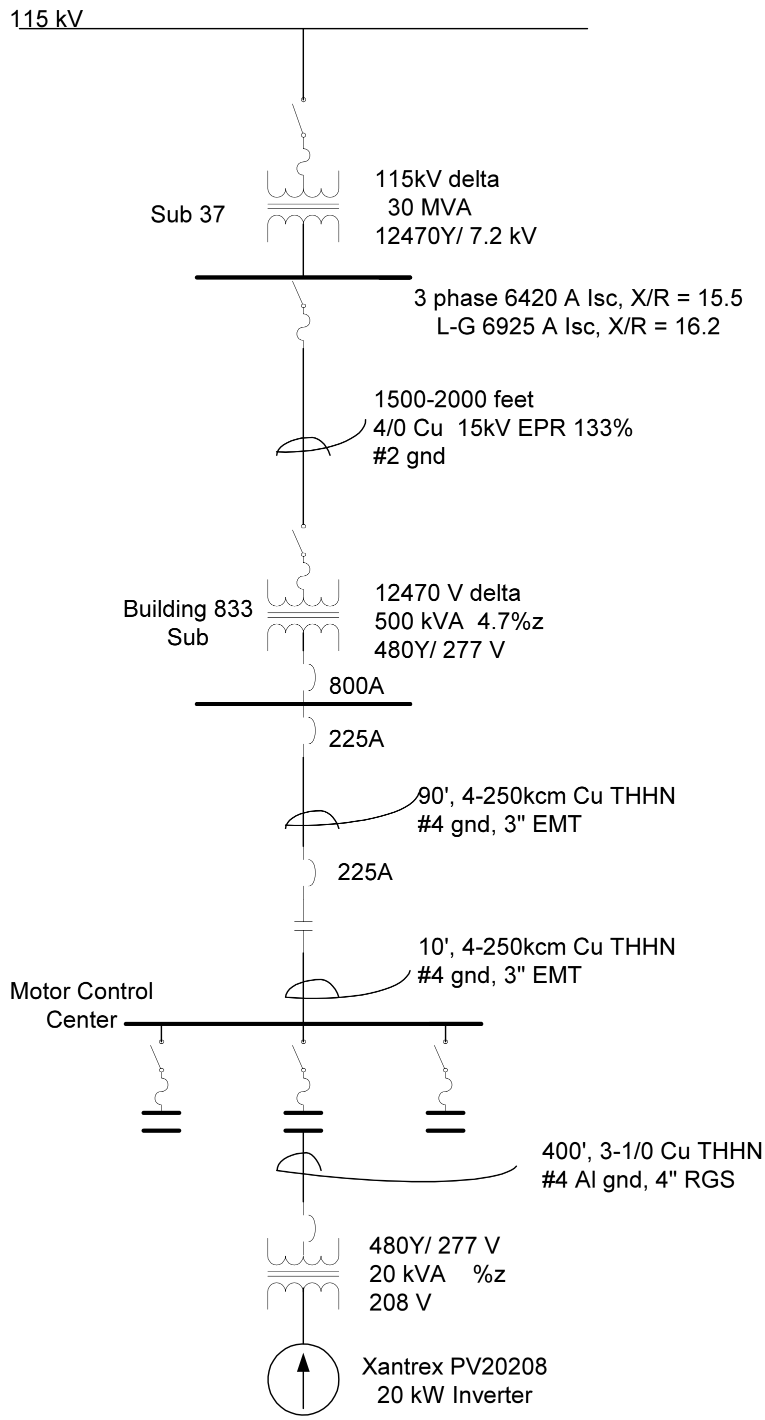

Figure 6. One-line diagram of PV 20208 connection to DETL grid

The impedance of the distribution transformer used to step the site voltage from 12,470 V to 480 V dominates the characteristics of the ac circuit to which the inverter is connected. Because the characteristics of the local distribution transformer have a significant impact on the anti-islanding behavior of grid-tied DER, an effort was made to analytically and experimentally characterize distribution transformers. Four representative transformers were obtained from Public Service Company of New Mexico (PNM) for this purpose. DETL and PNM were involved in a CRADA with the goal of evaluating the performance of two new microturbines that were being installed by PNM in the Santa Fe service area. This CRADA laid the groundwork for extended cooperation in other areas of DER such as these transformer characterizations. Figure 7 shows some of these transformers and a typical magnetizing current waveform. These measurements indicated that high-quality, low-loss transformers purchased by utilities require nonlinear magnetizing current that is an order of magnitude lower than that required by laboratory-type dry transformers. This information was valuable to Underwriters Laboratories, the California Energy Commission, and the PV user community in ongoing efforts to quantify islanding conditions.

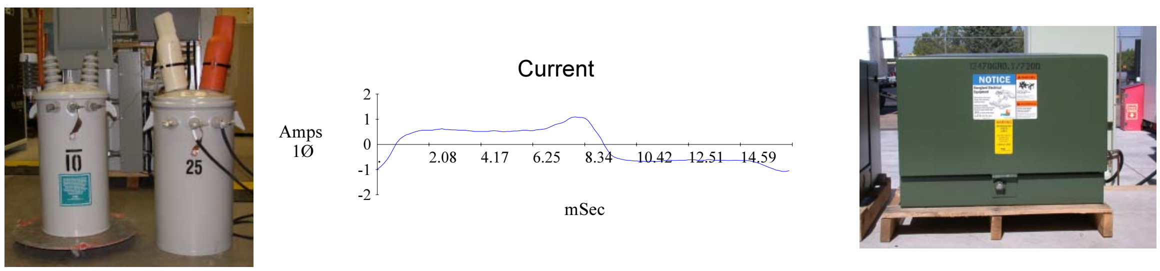

Figure 7. Utility distribution transformers and typical magnetizing current

Conclusions

Distributed energy resources can have a variety of impacts on the operation of the utility distribution system to which they are connected. Developing a laboratory-validated tool to predict these effects is a task requiring resources an order of magnitude greater than those available for the present project. Nevertheless, a useful beginning was made. Specific impacts on the distribution system were documented. Utility engineers, power system modelers, DER manufacturers, university researchers, and staff from other national laboratories expressed interest, and many actively participated in the project. Consensus among these stakeholders was that the issue is critically important and that the ability to simulate DER interactions and impacts with confidence will remove significant barriers to DER deployment.

A functioning inverter simulation model was developed using PSCAD, a variant of EMTP, a code widely accepted by utilities. In its present state, this model is useful as a tool for understanding and providing training on the operation of power electronics. It will be further refined for a variety of customers including the DOE Office of Solar Technologies, the California Energy Commission, and utilities such as SRP.

The next step in developing this tool is the definition of detailed laboratory model-validation tests. This step is being taken in collaboration with South Dakota State University, which is funded by the National Science Foundation for related inverter-reliability activities.

Work done under this LDRD project will be extended by incoming new staff in collaboration with outside stakeholders, including those identified in this project. The ability to confidently model utility-connected power electronics is useful for a variety of customers of Sandia's Center 6200.

In summary, the following items were accomplished under this LDRD project.

1. Identified problem, formed team, developed methodology
2. Obtained stakeholder input confirming importance of the problem
3. Developed list of detailed issues indicating scope of problem exceeded resources available
4. Built a useful model
5. Identified critical next step and began working on it
6. Started a new capability within Sandia's Center 6200 for multiple customers.

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