POWER QUALITY AND THE CONTROL OF DG ON DISTRIBUTION SYSTEMS

JEFF SMITH and ROGER DUGAN
Electrotek Concepts, Inc
Knoxville, TN USA 37923

D. TOM RIZY and ABDI ZALTASH
Oak Ridge National Laboratory
Oak Ridge, TN USA 37831

Abstract: Recent research has provided additional data on power quality and control issues for distributed energy resources (DER) interconnected with utility distribution systems. Two power quality issues are examined in this paper: harmonics and voltage regulation. The harmonics issue sparked much of the initial research into DER interconnection. This has been largely resolved with modern inverters. Voltage regulation is looming as a larger issue and is frequently the most limiting issue with respect to how much DER capacity can be accommodated without changes to the utility system. Increased control and communications and an expanded role for distribution automation will be required to manage large amounts of widely dispersed DER.

***Keywords*--Harmonics, Power Quality, Distributed Generation, Distributed Energy Resource (DER), Distribution System**

I. Introduction

While adjustable-speed drives and sensitive computer loads have been the center of attention for much of the power quality research in recent years, there has always been a close tie between distributed energy resources (DER) and power quality. It is interesting to note that the foundation for a substantial amount of the power quality analysis technology in use today can be traced to a Phoenix, Arizona real estate developer (John F. Long) who proposed to install hundreds of rooftop photovoltaic solar systems around 1980. Subsequent measurements of the prototype inverter system revealed high harmonic content [1]. This led to a series of studies and reports that were some of the first to describe how to perform harmonics analysis on utility distribution systems [2 - 4]. This extended earlier work that had been previously supported by EPRI [5].

In parallel, there was an effort to study the protection of DER interconnected with the utility distribution system [6]. While the primary interest was in prevention of DER islanding and prevention of interference with utility fault clearing practices, computer tools and personnel were shared between the two projects. Analysis technologies for distributed generation and power quality evolved together.

Once again, interest in the two issues has converged. Technology advances into new DER, including turbines, microturbines, fuel cells, and reciprocating engines, and the opening of the electric power markets has thrust DER into the spotlight yet again and many who were working solely in power quality are finding there is much overlap in the two areas. In this paper, we will examine two of the several power quality issues related to DER interconnection. First, we will revisit the harmonics issue for which much has changed. Then we will examine voltage regulation, which is surfacing as one of more difficult and limiting power quality issues. Finally, we will cover certain advantages of, as well as present technical barriers associated with, DER control.

II. Harmonics

The most commonly recognized source of harmonic distortion attributed to DER is that from inverters. However, it has been found that the impact from this technology is not as significant as initially expected, and other, more unlikely sources such as synchronous machines can also produce harmonic distortion that can be problematic.

The thyristor-based, line-commutated inverters used by small DER in the early 1980's quickly developed a reputation for being undesirable on the power system. Many distribution engineers still associate DER with harmonic distortion. These earlier type of inverters produce harmonic currents in similar proportion to loads such as adjustable-speed drives with traditional thyristor-based converters. Besides contributing to the distortion on the feeders, one fear was that this type of distributed generation would produce a significant amount of power at the harmonic frequencies. However, such power does little more than heat up wires.

Much has changed. The industry has converted to pulse-width modulated (PWM) switching inverters that produce a much lower harmonic current content than earlier line-commutated, thyristor-based inverters. We will first look at inverter technology and then examine some potential issues associated with rotating machines.

A. Inverters

To achieve better control and to avoid problems of producing high levels of harmonics, the inverter technology has changed to switched, pulse-width modulated (PWM) technologies. This has resulted in a more "friendly" interface to the electric power system.

In IEEE Std. 519-1992 [7], generators are limited to the most restrictive values in the tables on the allowable amount of harmonic current injection. While generator inverters are not necessarily any worse than power converters used in loads, the developers of the standard allocated all the capacity in the system to loads, leaving very little for generators. Fortunately, the shift to PWM switching technology has made it easier for inverters to meet the standard.

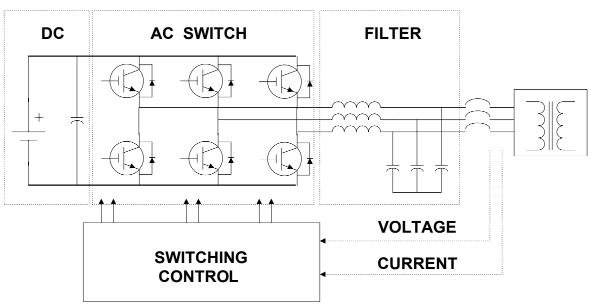

Figure 1. Simplified Schematic Diagram of a Modern Switching Inverter

Figure 1 shows the basic components of a utility interactive inverter that meets the requirements of IEEE Std 929-2000. [8] Direct current is supplied on the left side of the diagram either from a conversion technology that produces dc directly or from the rectification of ac generator output. Variations of this type of inverter are commonly employed on fuel cells, microturbines, photovoltaic solar, and some wind turbines.

The dc voltage is switched at a very high rate with an insulated gate bipolar transistor (IGBT) switch to create a sinusoid voltage or current at the power frequency. The switching frequency is typically on the order of 50 to 100 times the power frequency. The filter on the output attenuates these high frequency components to a degree that they are usually considered negligible. However, resonant conditions on the power system can sometimes make these high frequencies noticeable. The largest low-order harmonic current (usually, the 5th) is generally less than 3% and the others are often negligible. The total harmonic distortion (THD) limit is 5%, based on the requirements of IEEE Std 519-1992. There are reports of inverters exceeding these limits under specific conditions, including the example here, but the harmonic issue with inverters is certainly much less of a concern than with the older technologies.

Tables 1A and 1B show the total harmonic distortion (THD) recently measured at the terminals of a 3-Phase 30kW microturbine at ORNL's CHP Integration Test Facility in Oak Ridge, Tennessee [9]. The microturbine is connected to the grid through a wye-delta transformer with the delta on the grid side. The dominant voltage harmonics are the fifth and seventh at ~3% and ~0.3%, respectively, of the nominal phase voltage rating based on the initial conditions when the microturbine reaches full power. However, additional measurements are necessary to determine what level of background voltage and current distortion is preexisting on the system and how the harmonic distortion varies with unit startup and shutdown. Table 1B shows harmonic THD at the microturbine. The average of the sample measurements for current THD were slightly higher than the 5% limit.

TABLE 1A. TOTAL HARMONIC VOLTAGE DISTORTION FOR A 3-PHASE 30-KW MICROTURBINE OPERATING AT FULL OUTPUT WHILE GRID CONNECTED

	Initial THD*	Avg. THD**
Ph A	3.23%	3.19%
Ph B	3.23%	3.19%
Ph C	2.90%	2.85%

TABLE 1B. TOTAL HARMONIC CURRENT DISTORTION FOR A 3-PHASE 30-KW MICROTURBINE OPERATING AT FULL OUTPUT WHILE GRID CONNECTED

	Initial THD*	Avg. THD**
Ph A	3.39%	5.77%***
Ph B	3.53%	6.23%***
Ph C	3.90%	6.11%***

**Initial THD when the unit reaches full power output. **The average THD for one hour of operation. ***The maximum and average THD during the hour exceeded the 5% limit, however, it is presumably from transient load conditions.*

While interconnected to the utility, commonly-applied inverters basically attempt to generate a sine wave current that follows the voltage waveform. Thus, it would produce power at unity power factor. This control strategy could also result in current distortion that mirrors the system voltage distortion. Inverter manufacturers claim this is the case.

One new distortion problem that arises with the modern inverters is that the switching frequencies will occasionally excite resonances in the primary distribution system. This creates non-harmonic frequency signals typically at the 35th harmonic and higher riding on the voltage waveform. This has an impact on clocks and other circuitry that depends on a clean voltage zero crossing. A typical situation in which this might occur is an industrial park fed by its own substation and containing a few thousand feet of cable. A quick fix is to add more capacitance in the form of power factor correction capacitors, being careful not to cause additional harmful resonances.

B. Rotating Machine Harmonic Surprise

There can be harmonics problems with synchronous machines related to zero-sequence triplen (3^{rd}) harmonics. This may be more cause for concern than inverter harmonics, although most of the problem may be limited to the customer side of the meter.

Synchronous machines do not produce a perfect sine wave. Some designs may have about 5% third harmonic in the voltage waveform. This doesn't sound like much and isn't until it is connected to the utility system. The low impedance of the utility system basically acts like a short circuit to this frequency, which causes substantial triplen harmonic currents to flow into the grid.

Utility generation may also suffer from this flaw in synchronous machines. However, these machines are typically connected to the delta winding of the unit step-up transformer, which blocks the flow of the zero-sequence harmonics. Distribution transformers are generally not connected in this manner. They are most commonly connected wye/wye or delta/wye with the wye on the low voltage or secondary side. Thus, the synchronous generator which is connected to the distribution transformer is connected to the wye winding which enables the flow of zero sequence harmonics.

Figure 2 shows a typical situation. The facility where the generator is located is served at 480V by a common delta/wye transformer. When the generator is paralleled to the utility system through this transformer, the operator is frequently surprised to find a large amount of current circulating in the neutral. In the example shown, the current is 26% of the machine's rated current and is entirely third harmonic current. This can adversely affect the operation and efficiency of the machine and may result in the failure of some circuit elements. In this case, the problem is confined to the generator side of the transformer and does not affect the primary side of the distribution system because the triplen harmonics are trapped by the delta winding. The same thing can happen with a grounded wye/wye transformer, except that the harmonic currents would reach the primary distribution system.

This problem is well known among vendors of standby generation equipment. If known beforehand, most will recommend a synchronous machine with a 2/3 winding pitch that can be paralleled without presenting this harmonic pollution difficulty. If it is necessary to parallel a design that does produce significant triplen harmonics, a reactor can be added in the neutral to limit the current flow. A shorting switch is closed when the generator is used for backup power to maintain solid grounding.

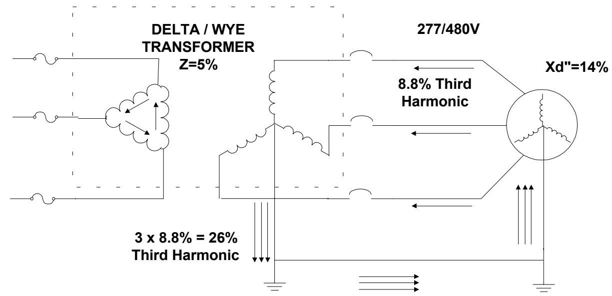

Figure 2. Generators with Significant 3rd Harmonic Voltage Distortion Can Produce Large Circulating 3rd harmonic Currents when Paralleled with the Utility System

C. Single-Phase Alternators

Some have proposed to interconnect single-phase alternators like those in use on farms for backup generation applications to provide support for the power system or to aggregate the power for bidding into the various emerging power markets. In some areas, there can be over 100 MVA of installed capacity of such generation, so it is not necessarily a trivial amount.

It is expected that many of these machines would have the same voltage waveform distortion found in some three-phase machines. Since they are single-phase, there is no convenient transformer connection that will block the flow of triplen harmonics. All the harmonic currents would be injected onto the utility system. A study was performed on these interconnection issues. [10] On the rural test feeder, the harmonic distortion issue would limit the generation capacity to about 900 kVA per phase as shown in Table 2.

TABLE 2. LIMITS FOR SINGLE-PHASE GENERATORS (ROTATING MACHINES) ON A RURAL 12.47 KV DISTRIBUTION FEEDER

Criterion	Limit
5% Voltage Drop*	150 kVA per phase
10% Voltage Drop*	333 kVA per phase
Fuse Saving, 40T Fuse	300 kVA per phase
20-Ohm Fault Detected	600 kVA per phase
3% 3^{rd} -harmonic voltage	900 kVA per phase

**The voltage drop when the DG disconnects for fault clearing and fuse saving coordination.*

While this is fairly limiting, it was far more lenient than voltage regulation concerns which can limit the single-phase generator capacity to 333 and 150 kVA per phase. Also, no attempt was made to evaluate the impact of the high circulating currents on the generating equipment of the customer side of the meter.

III. Voltage Regulation

Voltage regulation is frequently the most limiting issue with respect to how much DER capacity can be accommodated without changes to the utility system.

Depending upon how the DER is configured to operate, it can have varying impacts on system voltage regulation. There are essentially two modes of operation, automatic voltage control (AVC) and power factor (PF).

When a generator is large relative to the capacity of the system, there may be some benefit to allowing the generator to operate with automatic voltage control (AVC). While the system load changes, the DER can help regulate the system voltage by holding it within a specified range. However, this must be coordinated with the other voltage control devices, such as line regulators and shunt capacitors, on the system. Figure 3 shows one example when a large DER installation with AVC interferes with the operation of the substation Load Tap Changing Transformer (or LTC).

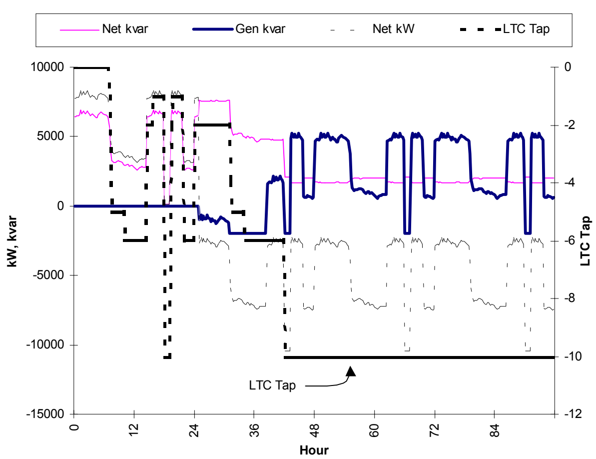

Figure 3. Interference Between Large DER Installation and Substation LTC

The generator is interconnected at the 24th hour and takes over the voltage regulation function within its var limits. As the load varies over the remaining 72 hours, the LTC tap is eventually forced into tap 10 bucking (-10 tap position). This is not necessarily harmful, but could be. The greater issue is what happens if the generator is suddenly forced off. If this were to occur, the voltage would be too low to support the load.

To avoid this condition, the LTC should be run to a benign tap position such as neutral when the DER is interconnected.

The next mode of operation for the DER is PF mode, in which the unit is usually fixed at a set power factor, typically around unity. Running in this mode allows the unit to follow the system voltage, with no attempt to regulate. The reactive power follows the real power output so that the power factor remains relatively constant as the real power is varied. This type of operation is usually preferred by most utilities. This is how the controls of the 3-Phase 30-kW microturbine at the ORNL CHP Integration Test Facility has been configured by the manufacturer. While in the grid-dependent mode (grid connected), the microturbine operates at near unity power factor. At full power output operation, the unit operates at .995 power factor lagging while at one-third power output the unit operates at .986 power factor lagging.

IV. DER Control

When DER equipment appears on the system in large numbers and total capacity size (significant % of the load), utility operating practices will have to undergo significant changes. This is basically taking a system currently designed for autonomous operation of control devices using local intelligence only and attempting to make it work as an integrated system. Whether one can modify autonomous controllers to work in this fashion is not yet known, but there is a strong push in the industry to do so.

Figure 4 illustrates a communication and control network overlaying a distribution system with DER. In this diagram, the power conversion elements represent regulators, LTCs, capacitors, DER, etc. One can see that necessary distribution system devices along with the DER is connected to a network that can be controlled from a central location (control center). This type of communication and control is necessary when the distribution system contains a high penetration of DER.

A. Advantages of DER Control

There are a number of advantages to providing direct DER control on the electric distribution system and they include:

Scheduled Dispatching- One advantage of new DER technology is their capability to dispatch power quite rapidly in response to varying utility and local load conditions. The power dispatch characteristic of a 3-phase 30-kW microturbine is shown in Figure 5. The unit requires ~20 s to vary its power output from one power setting to another. In this particular case, the microturbine's power output was adjusted from one-third to full output power. The startup and shutdown of the unit, which aren't shown, are much longer. The startup required 200 (3 min and 20 s) while the shutdown required more than twice as long or 520 s (8 min and 40s).

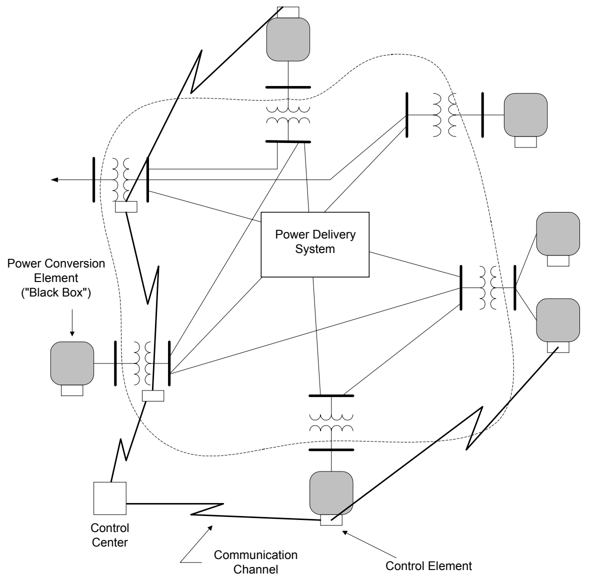

Figure 4. Communication and Control Overlaying Distribution System

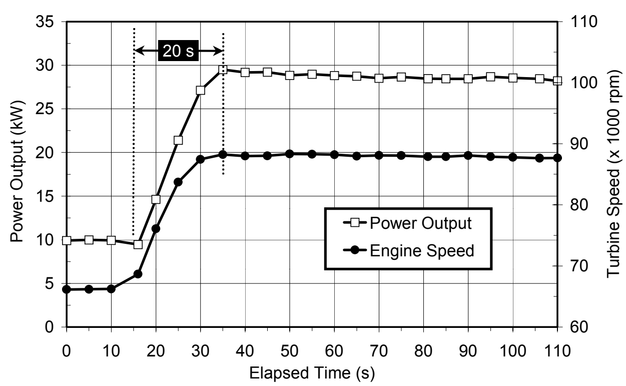

Figure 5. Power Dispatching Response (power output and speed dynamics) of the 30-kW Microturbine.

Cold-load Pickup – DER may be controlled to reduce the amount of load that has to be picked up by central generation after a significant outage event. The DER and its load can be transitioned from grid-dependent to grid-independent operation. By adjusting the power output of the DER, the amount of load can be reduced significantly, especially if the size of the DER is close to the amount of local load being supplied.

Load Management – DER can be used to reduce load during peak demand periods. By increasing the power output from these units during high load periods, the stress on central generation as well as local transmission and distribution lines can be relieved. Furthermore this mode of operation for the DER prevents actual load shedding but serves the same purpose.

Voltage Regulation- By coordinating existing distribution elements with DER, improved voltage regulation is possible. It may be necessary for certain distribution equipment to operate under different settings, or modes, when the DER is operable and others while it is not. If the equipment operates autonomously, undesirable conditions may arise, or possibly even cause damage to equipment over time. For example, in the LTC case study presented previously, if the LTC had some way of knowing that the unit was on, certain control capability could be added that would allow it to operate in a "DER" mode, where the LTC assumes neutral fixed position to prevent it from setting its tap position to its lowest setting and thus avoiding a low voltage condition if the DER is suddenly removed or ramped down.

B. Control Issues of DER

In order for DER to be of benefit to the electric system as a whole it must be able at the very least to respond to control signals from a central control system. One such signal that may be relayed to the DER is the price of electricity. A high price value could reflect the increased load demand and growing unavailability of central generation. Obviously, the DER owner/customer will not perceive any benefit from selling power into the grid unless the system cost per kWh is less than the cost of generating electricity from the DER.

No standard procedures have been developed for incorporating DER control into the utility control of the power system. Most DER applications are being installed solely for the use of the owner/customer with many being sized to prevent net generating into the grid. Some are by the owner/user's choice and many are due to the technical and cost barriers being put up by utilities. [11]

C. Communication Standards Development for DER

No communication or control standards currently exist for DER. Although some DER technology, such as microturbine systems, are being packaged with ModScan communication bus. However, no standard communication or control protocols are being followed such as EPRI's UCA. DERs that have communication and control software use proprietary protocols developed by the manufacturer. Many DER not currently grid-connected, such as backup generation used on poultry farms, do not even have any means for tying into a central communication network and depend on a third-party to develop/design such hardware and software.

Initially, communications and control for DER was a prominent section of the P1547 draft standard on DER interconnection, but after much debate it was decided that this topic should be addressed in a separate standard. A working group was then formed and is presently in the initial stages of developing a draft document. The goal of this working group is to develop a recommended practice for the remote monitoring and control of DER. The intent is to help facilitate the interoperability of DER to the electric power system (EPS) by recommending functional approaches, methods, and parameters. The protocols and practices recommending will hopefully assist in the exchange of information between the DER and other entities (i.e., EPS).

V. Conclusions

Distributed Energy Resources (DER), especially new technology, offer new options for the operation of the electric system. They bring power generation closer to the load and can be used in combination with thermal recovery systems to provide HVAC and increase the DER plant efficiency and decrease operational costs.

Present-day inverters which employ pulse-width modulation (PWM) are much more harmonic friendly than their predecessors the line-commutated inverters. The PWM inverters are much better at replicating a clean current waveform and produce significantly lower harmonics. For typical distribution transformer connections, synchronous machines operated in parallel should have a 2/3 winding pitch to avoid third harmonic problems.

DER in significant numbers and size can be used to provide peak load relief, voltage regulation control, and relieve generation, transmission, and distribution capacity stresses. While harmonics limit the amount of DER that can be connected, voltage regulation issues are usually more limiting. Present systems with autonomous, local voltage regulation devices place significant limits on DER penetration.

In order to fully utilize DER technology, better control and communications is needed. Currently, the technology lacks standardized communications and control protocols. Most manufacturers are developing their own communications and controls and have not designed their hardware for easily interfacing to external communications systems, such as for web-based control and communications. Most DER systems that are being operated today have to utilize custom-developed communications hardware/software developed by a third party in order to provide remote communication of the DER and remote control its settings.

Current electric power systems lack the needed communications backbone for significant DER penetration. The advancement in distribution automation both in functionality and lower cost has increased it use and may support DER control in the near future on distribution systems. A shorter-term option that is currently being pursued is the control of DER via the Internet although this is slower it may provide some technical benefits. Additional options, especially with the growth of cell towers, may be use of wireless communications to control and communication with remote DER.

VI. Acknowledgements

The authors would like to thank the U.S Department of Energy (DOE) for supporting this work. This work was conducted by Oak Ridge National Laboratory (ORNL) under DOE contract DE-AC05-00OR22725 with UT-Battelle, LLC.

VII. References

[1] G. L. Campen, *Results of the Harmonics Measurement Program at the John F. Long Photovoltaic House,* ORNL-5834, Oak Ridge National Laboratory, US DOE, Mar 1982

[2] R. C. Dugan, *Computer Simulation Harmonics Study,*, ORNL/Sub/81-95011/1, Oak Ridge National Laboratory, US DOE, Aug 1983.

[3] R. C. Dugan, M. F. McGranaghan, D. T. Rizy, J. P. Stovall, *Electric Power System Harmonics Design Guide*, ORNL/Sub/81-95011/3, Oak Ridge National Laboratory, US DOE, Sept 1986.

[4] R. C. Dugan, D. T. Rizy, *Harmonic Considerations for Electrical Distribution Feeder*, ORNL/Sub/81-95011/4, Oak Ridge National Laboratory, US DOE, Mar 1988.

[5] R. E. Owen, M. F. McGranaghan, et. al., *Study of Distribution System Surge and Harmonic Characteristics,* EPRI EL-1627, Final Report to RP 1024-1, Nov 1980.

[6] R. C. Dugan, D. T. Rizy, et. al., *Protection of Electric Distribution Systems with Dispersed Storage and Generation (DSG) Devices*, ORNL/CON-123, Oak Ridge National Laboratory, US DOE, Sept 1983.

[7] IEEE Std 519-1992, *Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems.*

[8] IEEE Std 929-2000, *Recommended Practice for Utility Interface of Photovoltaic Systems*.

[9] Rizy, D.T, Zaltash, A., Labinov, S., Petrov, A., Fairchild, P., "DER Performance Testing Of A Microturbine-Based Combined Cooling, Heating, And Power (CHP) System", Power System 2002 Conference, Clemson, SC, March 13-15, 2002.

[10] Dugan, R.C.; McDermott, T.E.; Rizy, D.T.; Steffel, S.J. "Interconnecting single-phase backup generation to the utility distribution system ", *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES* , Volume: 1, 2001 Page(s): 486 –491

[11] "Making Connections - Case Studies of Interconnection Barriers and their Impact on Distributed Power Projects", NREL/SR-200-28053, National Renewable Energy Laboratory (NREL), Golden, Colorado, May 2000, Revised July 2000. (http://www.eren.doe.gov/der/documents_resources.html)