Benefits Provided to Distributed Generation by a Parallel Utility System Connection
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Final Report, February 2003
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PRODUCT DESCRIPTION

Results & Findings
This project was conducted by looking at three primary areas of generator performance: power quality, reliability, and generator operating economics. The generator performance in these areas was evaluated and quantified with and without a parallel utility connection. The project showed that substantial improvements in voltage and frequency regulation, harmonic distortion, efficiency, and operating cost are achieved with the parallel connection. The project also showed that utility standby rates (which are charged to recover the cost of maintaining T&D standby capacity and not for the support value to the DG) are usually but not always less than the value offered by the parallel utility system connection.

Challenges & Objectives
There has been much industry focus in recent years on the power system support value offered by distributed generation (DG). However, little has been reported on the converse of this; that is, the value of support provided to the distributed generator by a parallel utility system connection. The support value that the power system offers is substantial and can make DG viable in applications where if it were standalone (not grid-connected), the performance would be marginal. This report investigates the benefits that a utility connection offers to DG, including enhanced voltage and frequency regulation during load steps, improved response to nonlinear loads, improved economic performance, and improved reliability.

Applications, Values & Use
This report is for utility planners, design engineers, and distributed generation developers to understand the interaction between the utility system and the distributed generator from the perspective of how DG performance is enhanced. Distributed generator operators can utilize this information to assess the value of a utility connection and compare various options available to them in lieu of a parallel connection such as added redundancy, multiple DG units, and power conditioning.

EPRI Perspective
There is increased interest today in distributed generation as a means to reduce power costs and enhance reliability at specific customer sites. In making the choice to deploy distributed generation, electric customers must often confront the issue of whether a grid-parallel or standalone DG approach is the most appropriate choice from an economic, reliability, and power quality perspective. Answering this question is not always easy and many factors play a role in determining which choice is best. This research provides quantification of the benefits of operating DG in parallel with the utility system, and helps electric customers and utilities make choices that are more informed in the design of DG installations.
Approach
To demonstrate the value of the parallel utility connection, various DG scenarios with and without a parallel utility connection were evaluated using the PTI PSS/E and MNT/E software as well as other analytical tools and techniques. Parametric study of the load steps, load rejections, nonlinear loads, and other conditions was performed. The results are presented within the context of the value that the utility system offers to the DG.

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Distributed generator
Transmission and distribution system support
Power quality
Standby charges
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INTRODUCTION

Background

Electric utilities and various distributed generation (DG) stakeholders have concentrated much effort in recent years on identifying the support value that DG can provide for the power system. However, little thought has been concentrated on the concept of the utility power system providing support for DG. This reverse perspective is valuable because the power system can provide considerable support to DG, allowing it to operate more efficiently, with improved power quality, and with better overall economics. This has important ramifications for the design and economics of DG and is pertinent to ongoing industry discussion surrounding “standby charges.”

Standby charges are the charges levied by electric utilities to customers that wish to maintain a parallel service connection even when DG is operated in a manner where little or no net power is consumed from the utility system. These charges are sometimes criticized as being anti-competitive barriers to DG. However, examination of the economic and technical planning principles of power systems justifies the need for such fees, and quantification of the power system support value provided to DG can help DG stakeholders better understand the role that the utility system can play in making DG viable. The objective of this report is to thoroughly examine the benefits of a parallel utility connection and show how it can influence the operation, performance, design, and economics of distributed generators.

This project compares standalone DG to equivalent grid-parallel DG in several key areas of performance, including reliability, efficiency, voltage regulation, harmonic distortion, and frequency regulation. Parametric studies were performed using the PTI PSS/E and MNT/E software to compare the response of generators to load-steps and nonlinear and fluctuating loads, with and without the parallel utility connection. The value of the enhancements yielded by a parallel utility connection is contrasted against the costs of providing similar enhancements on a standalone DG system with local equipment such as added generation capacity, solid-state high-speed power-conditioning devices, and system redundancy.

The degree to which DG performance is enhanced by the parallel utility system connection depends on many factors, including the design and layout of the DG plant and the quality and reliability of power delivered by the utility service at the point of connection. DG design factors that influence the value received include the availability of the DG, its load-following capability, and heat rate versus loading characteristic.

The results of this project cannot be universally applied to all DG. Each DG case is different and must be evaluated based on its own specific characteristics. Nonetheless, the general questions
raised here and approach utilized can be applied to specific problems. This project is focused on internal combustion engine and combustion turbine prime movers with synchronous generators, but the results can apply qualitatively to other DG technologies.

**Grid-Parallel and Standalone DG**

Two types of DG installations were considered to illustrate the value of a parallel utility connection: standalone DG and grid-parallel DG. A standalone DG is an independent island and as such must provide voltage and frequency regulation within the island (see Figure 1-1a). Standalone DG must be able to load-follow and support various loading conditions while maintaining acceptable power quality. Loading conditions may include load steps, motor starts, inrush current, load nonlinearity, reactive power needs, unbalances, and periodic load fluctuations. The standalone generator must be reliable because it is the only source of power available. The standalone application is usually more demanding and costly than the grid-parallel approach because it is designed with greater redundancy and the generator must load follow, which means that it cannot be optimally sized from a capital investment perspective and optimally operated from an efficiency perspective.

![Figure 1-1](image-url)

**Figure 1-1**

Two Types of DG: (a) Standalone and (b) Grid-Parallel

The other type of DG configuration that was evaluated is the grid-parallel system (see Figure 1-1b). DG connected in parallel with the utility system operates as an additional source of energy, feeding the local load. It is tiny with respect to the total power system and has no
significant impact on power system frequency. It may supply most or all of the energy to the local customer load, but the customer site can rely upon the utility system source should the DG fail. This means that reliability of the DG is not so crucial as it would be for a standalone system. Grid-parallel DG is normally operated in a voltage-following mode, which means the machine operates at close to unity power factor and does not attempt to directly regulate voltage with reactive power. The grid parallel system has the luxury of letting the utility system provide the reactive power for the load, handle load-step transitions and motor starts, and deal with nonlinear load currents. This may allow downsizing of the plant capacity somewhat compared to standalone approaches. Grid-parallel DG does not usually load-follow but instead is often operated at constant full load to provide the best efficiency and maximum return on capital investment. In general, a DG designed for grid-parallel operation can forego redundancy and capacity and will operate in a more economical fashion even when standby charges are factored in.

Most currently operating commercial and industrial DG is grid-parallel, when possible, to achieve better performance. This project compares the performance of standalone DG units to essentially identical grid-parallel designs. This is done only to demonstrate the impact on DG performance of the parallel utility system connection. In reality, standalone systems would always need to be designed differently to overcome the issues discussed above and so would have a different layout, more redundancy, and different control settings. In fact, those “extras” contribute to the higher cost of standalone systems.

It is clear that the design and operation of DG installations are largely influenced by whether or not they are operated in parallel with the utility system or as a standalone entity. It is possible to characterize the different requirements of each type of installation (see Table 1-1).

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type of DG Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load-following and reactive load support requirements</td>
<td>Standalone DG: DG must load-follow, be able to handle expected load steps, and provide reactive power.</td>
</tr>
<tr>
<td>Frequency regulation</td>
<td>Standalone DG: DG has total control of frequency and must maintain it within an acceptable window.</td>
</tr>
</tbody>
</table>


Introduction

Table 1-1 (cont.)
Comparison of Characteristics and Operating Philosophy of Grid Parallel and Standalone DG

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type of DG Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standalone DG</strong></td>
<td><strong>DG in Parallel With Utility System</strong></td>
</tr>
<tr>
<td>Voltage regulation</td>
<td>DG has total control of voltage and must regulate it to within acceptable limits.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Reliability is critical because DG is the only energy source available. This means that standalone systems are designed with multiple DG units and N-1 or N-2 contingency.</td>
</tr>
<tr>
<td>Utility system interconnection requirements and issues</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

Standby Charges

Understanding the concept of standby charges is important because many DG operators pay these fees and desire to understand the value received from being connected to the power system. It is desirable to know which option is more cost effective—a lower-cost grid-parallel DG design paying standby fees or a standalone entity, which avoids standby fees but incurs added DG equipment costs.

Standby charges are a necessary but controversial element of supplying electric service to customers that operate DG and want to retain a service connection. Standby charges are also referred to as backup service fees and backup tariffs. To understand standby charges, consider that the cost of electric energy delivered to a customer can be broken into two components: the energy cost and the demand cost. The energy cost is the cost per kilowatt-hour of the energy consumed. The demand cost is related to the amount of transmission and distribution system capacity devoted to serving a particular customer. Typical commercial and industrial electric customers will see these two components on their monthly electricity invoice—that is, a cost component for the energy they consume in kilowatt-hours and a cost component related to the peak demand that they impose on the system.

To understand the importance of demand in impacting the cost of energy, consider that the “power demand” is the rate at which energy is consumed. The greater the power demand, the more substantial the transmission and distribution infrastructure required for delivery of the energy. As an example, compare two cases of load on a distribution feeder: a 100-kW load lasting for 24 hours and a 28,800-kW load lasting for 5 minutes. Both of these will result in 2400 kWh of energy consumption. However, to support the 100 kW load, a relatively weak power distribution system (4.8 kV) would suffice. On the other hand, to support the 28,800-kW load...
would require a very strong distribution system operating at 34.5 kV or perhaps even higher voltage to deliver suitably regulated power to the site.

Even though both loads in the examples consumed the same amount of energy, the load with the high demand requires a higher-capacity power distribution system for delivery of the same amount of energy because the energy is delivered in a shorter time frame. This concept is important because it shows that power demand is an important factor in determining the capacity of infrastructure needed to deliver power, and capacity costs money. Even if a customer intends to use little or no net energy on an annual basis but has high demand for very short periods, the power system must still be designed to satisfy the peak demand.

Perhaps a good analogy is a cargo crane off-loading ships. If the crane removes 2-ton crates most of the time and once every five months has to lift a 50-ton crate, it must be designed to handle at least 50 tons, even though a 2-ton crane would be sufficient most of the time. Similarly, the power system must have sufficient capacity reserved for the peak load. Failure to plan for expected loading conditions can lead to power system overloads that can cause voltage regulation problems and/or thermal overloads in wires and equipment. There can also be stability issues. Short-duration power system overloads (5 minutes or less) usually lead to voltage-related problems because the thermal time constant of wires and equipment is generally longer than 5 minutes. However, as overloads become much longer than 5 minutes, thermal limits become an issue. Utility system planners design the power system to have sufficient thermal capacity and voltage regulation capabilities to handle the expected peak loads on the system. The demand charges and energy charges in the rate structure are intended to recover the cost associated with building, maintaining, and operating this required T&D infrastructure from both an energy and capacity perspective.

This brings us back to the concept of the standby charge. The standby charge is a charge for the demand that the customer will impose on the power system when (not if) the customer’s distributed generator fails to operate. Given the reliability of a single DG, which is no better than about 97% available, the utility can expect to supply the full load for the site more than 10 days each year. A redundant N-1 or N-2 design would be needed to reduce this time. Customers that utilize distributed generation to produce much or all of their energy but wish to maintain a utility system connection for periods when the generator has a scheduled or forced outage may expose the utility system to their full load during downtime periods. In this role, the utility system provides “backup” generation for the customer whenever the DG is out of service. Even though the DG may be out of service only a few days or weeks per year, this is long enough so that the power system capacity must be sufficient to handle these loading periods. Standby charges must be levied because power system capacity must be “reserved” for this customer during those periods.

Many people think standby utility service is similar to an automobile insurance policy where you do not see any benefit until the day the accident occurs. In the case of standby service, the benefit is the backup power provided by the utility, and the insurance premiums are the standby fees. However, with standby utility service, there are ongoing benefits related to power quality enhancement, efficiency improvement, and reduced cost of operating the DG. These are provided on a continuous basis, so standby service is actually much better than a typical automobile insurance policy.
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While standby charges are justified, it is difficult to quantify how high they should be, and there is no one charge that suits all cases. Each case is different based on utility company cost structure, T&D system factors, and the nature of the DG installation and customer load. It is probably not possible to develop any single standby fee formula that perfectly assigns capacity costs to each customer—some sites may be paying too little, while others may be paying too much. Nevertheless, the standby fee philosophy, with all its imperfections, is overall a fair and effective way to assign the cost of reserved system capacity.

A recent report by the U.S. Department of Energy\(^1\) presents examples of standby rates incurred in some DG projects and cited these as examples of barriers to DG interconnection. These data have been reproduced in Figure 1-2. The levels shown are mainly in the range of $25 to $200 per kilowatt per year, with the average in the range of about $75 to 100 per kilowatt per year. As will be discussed later in this report, these fees are less than the costs of installing local equipment that provide services similar to those offered by the parallel utility connection. Typical standby charges, if they are analyzed to determine how they impact the cost of energy from DG, will increase its cost by 10 to 20%. In one recently analyzed power quality park project employing a large DG at a northeastern utility revealed that the cost to produce energy with DG was on the order of 6 to 7 cents per kilowatt-hour, and the standby charges added the equivalent of about 1 cent per kilowatt-hour to that cost. The cost per kilowatt-hour due to standby charges can be calculated by taking the total annual standby rate paid by the customer and dividing it by the annual energy production of the DG plant to yield the cost per unit of production.

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\[\text{$/kW-year} = \frac{\text{Total annual standby rate paid by the customer}}{\text{Annual energy production of the DG plant}}\]

**Figure 1-2**

*Standby Charges Encountered by Various DG Projects per Reference\(^1\) (U.S. DOE Report on Barriers to Interconnection July 2002)*

What are fair standby fees? There is no one standby fee applicable to all cases because each utility operates in a different economic and physical environment. Utilities have different labor costs depending on where they are located, and the cost of building and maintaining T&D infrastructure varies considerably from location to location. Urban underground construction is

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Introduction

extremely expensive, whereas green field overhead installations tend to be the lowest cost. Generally, the cost of T&D infrastructure per unit of capacity can range from $300/kW to over $1000/kW. The annual carrying charge on such a system is on the order $60 to 200 per kilowatt, but there are O&M costs that may add another 5 to 10% to this annually. The standby fees of Figure 1-2 are in this range and so seem to be appropriate. However, each case would need to be analyzed in detail to determine this as a fact.

Standby fees are based on the assumption that the DG provides no support of the T&D system. Identification of some specific positive T&D support benefits could help offset the standby fees. In fact, some utilities are factoring that into the standby analysis. However, real T&D support is much harder to achieve with DG than is commonly realized. It is beyond the scope of this document to discuss T&D support, but numerous papers and reports have been published on that topic.

Utility System Energy Supply Characteristics Compared With DG

The utility system is a strong source, which will typically have less than 5% impedance (at the point of common coupling on the kVA base of the DG) and will be very stable from a frequency perspective. It represents a vast interconnected network of thousands of megawatts of generation capacity, and any single distribution feeder load is tiny in comparison and has no significant impact on the bulk generation dispatch needs or operating efficiency. By comparison, the DG impedance is high (20%), and the starting of large motors and other loads can create severe power quality problems. Typically, reliability of utility system power is in the range of 99% to 99.999% (national average is about 99.97%). This compares to a single DG that is on the order of 94 to 97% available. DG reliability is improved by employing multiple units so that if one is down, the others can pick up the load. An “N-1” design, where one unit can be down and there is still sufficient capacity to serve the load, can be almost as reliable as a typical utility service. Table 1-2 compares a 150-kVA transformer-fed utility service to a standalone synchronous generator DG with a similar rating.

Table 1-2
Performance Characteristics of a Standalone DG and a Utility Service Connection

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Standalone Generator (150-kVA, Three-Phase Unit)</th>
<th>Utility System Service (150-kVA, Three-Phase Transformer and Service Drop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source capacity</td>
<td>150 kVA</td>
<td>150 kVA</td>
</tr>
<tr>
<td>Site peak load</td>
<td>100 kVA</td>
<td>100 kVA</td>
</tr>
<tr>
<td>Impedance (percent of source capacity rating, 150 kVA)</td>
<td>20%</td>
<td>4% (includes service drop)</td>
</tr>
</tbody>
</table>
### Table 1-2 (cont.)
**Performance Characteristics of a Standalone DG and a Utility Service Connection**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Standalone Generator (150-kVA, Three-Phase Unit)</th>
<th>Utility System Service (150-kVA, Three-Phase Transformer and Service Drop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault level (per unit of site peak load current, 100 kVA)</td>
<td>7.5</td>
<td>37.5</td>
</tr>
<tr>
<td>Frequency dip during 100% step-load</td>
<td>Can be more than 10%.</td>
<td>No change</td>
</tr>
<tr>
<td>Voltage drop due to 20-HP motor start (locked-rotor current = 5 per unit)</td>
<td>15–20%</td>
<td>4%</td>
</tr>
<tr>
<td>Exposure to fault-related voltage sags coming from utility system</td>
<td>None</td>
<td>1 moderate to severe event per week</td>
</tr>
<tr>
<td>Impact of load variation on generation efficiency and economic dispatch</td>
<td>Strong impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Reliability (annual availability in percent)</td>
<td>97% or less (assumes a single DG with no redundancy)</td>
<td>99–99.9999% (average US value is 99.97%; range represents different T&amp;D system types and conditions)</td>
</tr>
<tr>
<td>Typical effective power generation efficiency</td>
<td>20–40% (no cogeneration)</td>
<td>35–55% (Depends on mix of utility generation resources; range includes T&amp;D losses)</td>
</tr>
<tr>
<td></td>
<td>55–85% (with cogeneration)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1-2 shows that the utility service is stiffer, more reliable, and better regulated for load-steps than a typical distributed generator operating as a standalone entity. In fact, Table 1-2 is conservative in that it compares a 150-kVA generator to a 150-kVA utility service transformer. In many cases, the service transformer is greatly oversized relative to site load, so the utility system is even stiffer than indicated in Table 1-2. The only performance areas where the utility service is worse are with incoming deep voltage sags (due to the exposure of the power system) and in the efficiency of the generator if the DG is a co-generation unit (waste heat is recovered).

When DG is combined in parallel with the utility system, the attributes of both approaches are emphasized. A properly interfaced grid-parallel DG can offer better power quality, reliability, and efficiency to the customer site than the standalone generator or the utility service alone. The key benefits are as follows:

- **Voltage regulation:** The low impedance of the utility service (typically less than 5%) in combination with the DG means that load steps and motor starts have a far less perturbing impact on the facility voltage level than they would for a standalone generator with 20% impedance. Furthermore, the combined impedance of the DG and utility system is slightly lower than the utility system alone, enabling better voltage regulation response during load-steps than with the utility system alone.
Introduction

- **Harmonic distortion:** The lower impedance of the utility system with respect to harmonics in combination with the DG means that nonlinear loads result in far less voltage distortion than if a standalone generator had to drive them. The utility system combined with the DG may also result in less distortion than the utility system alone if the DG is not a significant source of harmonics.

- **Frequency regulation:** The parallel utility connection should hold frequency to within ±0.5 Hz of 60 Hz in all but the most unusual utility system conditions, whereas the standalone generator will be momentarily well outside ±2 Hz of 60 Hz during large load fluctuations.

- **Efficiency:** Operation of the DG in parallel with the utility system will enable heat engine devices (internal combustion engines [ICEs] and combustion turbines) to operate at a point on their loading curve that saves 10 to 20% in fuel per kilowatt-hour produced compared to the standalone application. In cogeneration applications, the DG can also be sized and operated to more appropriately match the site heat needs, which will significantly improve efficiency.

- **Reactive power:** Operation of the DG in parallel with the utility system may allow the DG to focus purely on the site real power consumption and not provide reactive support, depending on the interconnection requirements and agreement with local utility. Depending on the generator design, type, and loads at the site, this can lead to significant capacity cost savings for the DG.

- **Reliability:** A typical parallel utility connection can eliminate more than 99% of the potential power interruptions that an “N-0 designed” standalone DG installation would experience. Alternatively, it avoids the need to design for “N-1” or “N-2” and saves at least several hundred dollars per kilowatt in marginal standby capacity costs.

- **Optimal sizing cost savings:** The parallel connection with the utility system allows the DG integrator to design less capacity margin into the DG plant, thereby saving significantly on DG capacity costs.

Most or all of the above benefits apply to any type of distributed generation, including internal combustion engines and combustion turbine installations. This project focused on internal combustion engines and combustion turbine prime movers with synchronous generators because these are the most common form of DG at industrial and commercial facilities that may be paying standby charges and/or considering the pros and cons of standalone operation.

The benefits of the parallel connection can also apply to other types of DG, such as fuel cells, photovoltaic (PV) systems, and wind turbines. Some fuel cells have difficulty handling load-steps (quickly following load), and therefore a parallel utility system connection can solve that issue as well as improve reliability. Renewable wind and PV systems, due to the poor reliability of the sun and wind, cannot usually serve as standalone power sources unless augmented with battery storage and additional generation. Because battery storage capacity is more costly than conventional generation capacity, it can be argued that the parallel connection benefits for renewable resources are even more than they are for ICEs and combustion turbine installations.

Overall, the discussion of this first chapter has focused on the general reasons why a parallel utility connection makes sense and adds value to the DG installation. We have discussed that
without such a connection, the DG system must be designed for high redundancy, may need to be oversized to handle load-steps, and may generally be operated less efficiency owing to sizing and load following issues. In Sections 2 through 4 of this report, we will be looking more closely at these issues and determining quantitatively, through simulations, the performance enhancements achieved using a parallel connection.
2
POWER QUALITY SUPPORT VALUE

Introduction

This section focuses on the power quality support benefit offered by a parallel power system connection to DG. To evaluate the benefit, DG is simulated with and without a parallel utility connection, and its responses to load-steps, nonlinear loads, and periodically fluctuating loads are observed and compared. The modeling was performed using the PTI PSS/E and MNT/E software, which has the capability to simulate the dynamic responses of motors and generators and includes suitable exciter and governor models. The cases studied all involved ICE prime movers and synchronous generators, but the project findings could be applied to other types of generators, if not quantitatively then at least qualitatively.

Model and Simulations

The power quality simulations modeled a 500-kVA synchronous generator a supplying local load (see Figure 2-1). For some of the simulations, the generator and load were attached to a 13.2-kV utility power distribution system; for others, the generator ran as a standalone unit. When the generator was attached to the utility system, it was the equivalent of switch $S_1$ being closed in Figure 2-1. When the generator was isolated from the utility network, it was the equivalent of switch $S_1$ being open.

![Figure 2-1](image-url)

Circuit Configuration Employed for Simulation

The generator was connected to the utility system through a Y-delta grounded 1000-kVA padmount transformer, which has a 5% impedance on its own base that is fairly representative of a typical three-phase, mid-sized commercial service connection. The available fault level of the simulated utility source was 2000 amperes on the high-voltage side of the transformer, which is
representative of the fault level at a point several miles down a feeder from the substation. When the DG was operating in parallel with the utility system, the governor was controlled to regulate the power interchanged with the utility. A frequency-regulating governor was modeled in the standalone case. Excitation was varied to control voltage for both the grid-parallel and standalone simulations.

The generator electrical characteristics are similar to those that would be found on typical synchronous distributed generators. The subtransient reactance was 20% on the generator kVA base, and the time constants and inertia characteristics of the generator were typical of DG in this size range.

To assess the power quality response of the generator during various conditions, the following electrical loading conditions were simulated:

- Starting 50-, 100-, 200-, and 500-HP induction motors with constant torque mechanical loads
- Adding 50-, 100-, 300- and 500-kVA resistive loads
- Tripping 10-, 50-, 100-, 200- and 500-kVA resistive loads
- Operating with a 5-Hz pulsating resistive load
- Operating with loads that generate harmonic currents

Each condition was simulated both with and without the utility interconnection (S, closed and open). The time-varying response of each significant electrical and mechanical quantity is shown in this report. The plotted results from the simulations include the terminal voltage in per unit (480-volt base), the deviation in electrical frequency from 60 Hz in per unit (60-Hz base), the induction motor speed deviation in per unit (this is the negative of the slip), and the generator electrical power output as a percent of its rating (500 kVA). For brevity, the per-unit electrical frequency deviation will sometimes just be called electrical frequency, and the per-unit motor speed deviation will sometimes be called motor speed. The induction motors used in the models had locked-rotor starting currents that are about seven times the full-load running currents.

**Induction Motor Starting**

Induction motor starting is a demanding application for a standalone power system if the motors are large with respect to the generator. For this set of simulations, we investigated the ability of the standalone generator to start motor loads ranging from 5 to 500 HP. This is approximately 10 to 100% of the generator’s rated capacity, 500 kVA. Figure 2-2 through Figure 2-4 show the time-varying response of the electrical frequency, motor speeds, and terminal voltages when each size motor (50, 100, 300, and 500 HP) was started without a utility interconnection. Figure 2-5 and Figure 2-6 show the time-varying response of the motor speeds and the terminal voltages when each size motor was started with a utility interconnection. There is no significant electrical frequency deviation with the utility interconnection, so electrical frequency is not plotted in this case.
Figure 2-2
Electrical Frequency While Starting Different-Size Motors Without Utility

Figure 2-3
Motor Speed Deviations Starting Different-Size Motors Without Utility
Figure 2-4
Terminal Voltages While Starting Different-Size Motors Without Utility

Figure 2-5
Motor Speeds While Starting Connected to Utility
The results of the 50-HP and the 500-HP motor simulations are shown for cases with and without the utility connection in Figure 2-7 through Figure 2-12.
Figure 2-8
50-HP Motor Speed While Starting With and Without Utility

Figure 2-9
Electrical Frequency Starting 50-HP Motor With and Without Utility
Figure 2-10
Terminal Voltages Starting 500-HP Motor With and Without Utility

Figure 2-11
500-HP Motor Starting Speed With and Without Utility
The motor-starting simulation results show the severity of the duty imposed on the standalone generator. For example, when starting the 500-HP motor without the utility connection, the generator slows down to approximately 36 Hz (-0.4 p.u. frequency deviation) before the motor locks in. This takes approximately ten seconds, and the voltage is less than 40% of its normal value during most of this time. It takes an additional ten seconds before the system gets back to 60 Hz. During this period, the voltage peaks at approximately 1.4 times its rated value. An interesting result of the simulation is the severe overvoltage that occurred at later stages of the motor-starting sequence.

The severe power quality problems encountered when starting the 500-HP motor would not be acceptable, so starting a motor this large with the standalone generator is, as a practical matter, not possible. In reality, the starting sequence would not likely be completed in real life because under-frequency and undervoltage protection would likely trip the generator.

The voltage and frequency dips and peaks are less severe when starting smaller motors without a utility connection, but they are still very significant. Starting even the relatively small 50-HP motor (about 10% of the generator’s kVA rating) in a standalone configuration resulted in a several-Hz dip in generator frequency and approximately a 10% dip in voltage.

In simulations where the utility system is connected, there is a dramatic improvement in voltage and frequency during motor starting. With the utility connection, there is essentially no dip in
electrical frequency when starting the motors. The 500-HP motor gets up to speed in less than half a second, and during this period, the voltage is approximately 90% of rated voltage. The voltage stays close to the rated value after it locks in. Therefore, starting large motors is possible, and the disruption in frequency and voltage caused by starting smaller motors is much less than without the utility connection. One interesting finding is that the interaction between the generator exciter and motor during starting can lead to overvoltages that are potentially large enough to damage loads in the standalone case. The parallel utility connection limited this overvoltage to a safe level, which is another benefit of the parallel connection.

**Step Increases in Resistive Load**

Stand-alone systems must also be designed to handle resistive step-loads. Figure 2-13 and Figure 2-14 show the time-varying response of the electrical frequency and terminal voltages for 50-, 100-, 300- and 500-kVA step increases in resistive load without a utility interconnection. Figure 2-15 shows the time-varying response of the terminal voltages with a utility interconnection. There is no significant electrical frequency deviation with the utility interconnection, so electrical frequency is not plotted in this case.
Figure 2-14
Terminal Voltages for Step Increases in Resistive Load Without Utility

Figure 2-15
Terminal Voltages for Step Increases in Resistive Load With Utility
For the 50-kVA and the 500-kVA step-load, the results with and without the utility connection are plotted together. Figure 2-16 and Figure 2-17 are for the 50-kVA step, and Figure 2-18 and Figure 2-19 are for the 500-kVA load step.

Figure 2-16
Frequency for a 50-kVA Resistive Load Increase With and Without Utility
Figure 2-17
Voltage for a 50-kVA Resistive Load-Step Increase With and Without Utility

Figure 2-18
Frequency for a 500-kVA Resistive Load Increase With and Without Utility
With a utility connection, the voltage and frequency excursions for step-changes in resistive load are minimal. The only deviation that is even worth noting is a momentary (for a few cycles) voltage drop to approximately 85% of nominal for the 500-kVA step in resistive load.

Without the utility connection, the frequency drops to less than 25 Hz following a 500-kVA load step, it drops to 30 Hz following a 200-kVA step, and to 58 Hz following a 50-kVA step. The voltage drops to 65% of nominal for the 500-kVA step and remains low for several seconds. However, it only drops to 95% for a 200-kVA step. As would be expected, the voltage excursions for a step increase in resistive load are less severe than for starting a motor with the same steady-state power requirements. However, the frequency excursions are actually worse because of the immediate need for real power in the step resistive load case.

Overall, in the case of the step resistive load, the parallel utility system connection provides a dramatic improvement in both the frequency and voltage conditions compared to the standalone generator.

**Load Rejection**

Load rejection is the sudden loss of load on a power generation system. Load rejection may occur due to the tripping of a circuit breaker feeding loads or switching off a large device. A sudden large load rejection on a generator results in an increase in speed (frequency) and voltage at the terminals until the machine’s governor and exciter can respond and bring the unit back into
the appropriate range. For a standalone DG, the load rejection response is very important because unacceptable power quality conditions could arise. Figure 2-20 and Figure 2-21 show the time-varying response of the electrical frequency and terminal voltages after tripping 50, 100, 200 and 500 kVA of load without a utility interconnection. Figure 2-22 shows the time-varying response of the terminal voltages with a utility interconnection. There is no significant electrical frequency deviation with the utility interconnection, so electrical frequency is not plotted in this case.

Figure 2-20
Electrical Frequency Response Following Load Rejections Without Utility (0.5 per Unit is Equivalent to a 30-Hz Deviation)
Figure 2-21
Terminal Voltage Following Load Rejections Without Utility

Figure 2-22
Voltage Following Load Rejections While Connected to Utility
For the 50-kVA and the 500-kVA load rejection cases, the results with and without the utility connection are shown plotted together. Figure 2-23 and Figure 2-24 are for the 50-kVA load rejection case, and Figure 2-25 and Figure 2-26 are for the 500-kVA load rejection. The improvement in voltage regulation between the case with the utility connected versus the case without it is clearly evident.

**Figure 2-23**
Voltage Following 50-kVA Load Rejection With and Without Utility
Figure 2-24
Frequency After Tripping 50-kVA Load With and Without Utility

Figure 2-25
Voltage Following 500-kVA Load Rejection With and Without Utility
The simulation results show that without a utility connection, if large amounts of load are rejected, the generator speed will increase to an unacceptable level before the governor speed control can respond. To avoid unacceptable over-speed, the generator protection will therefore most likely be designed to trip the unit for such an event. If a 200-kW load is rejected, the frequency excursions will still be quite severe, but the generator may not have to be tripped.

Except for the 500-kVA load rejection case, the voltage excursions are modest for the cases represented. Much larger voltage excursions can occur following load rejection if the generator is isolated with a large shunt capacitor that causes self-excitation. The overvoltage excursions for large load rejections were not as severe as for motor starting but were still unacceptable from a power quality perspective.

Overall, the load rejection studies show that the parallel utility connection provides an excellent sink for excess energy when a local load rejection occurs. This keeps the generator frequency from accelerating and limits the voltage rise that would occur in the standalone case.

**Pulsating Load**

Pulsating loads are a cause of annoying light flicker on power systems. Due to the weak nature of standalone DG, pulsating loads may cause unacceptable flicker conditions more easily in the standalone case than in the grid-parallel system. To see the effect of a utility interconnection with the DG on electric lighting flicker, 5-Hz pulsating loads of varying magnitudes were simulated.
with and without a utility connection. Load variation at 5-Hz was chosen because the human eye is particularly sensitive to variations in lighting around this frequency (per the IEEE 519-1992 Flicker Curve). Figure 2-27 and Figure 2-28 show the time-varying response of the generated power and the terminal voltages with 5, 10, 20 and 100 kW of pulsating load without a utility interconnection. Figure 2-29 and Figure 2-30 show the time-varying response of the generated power and the terminal voltages with a utility interconnection. There is no significant electrical frequency deviation in either case so electrical frequency is not plotted.

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**Figure 2-27**

Generator Power for 5-Hz Load Variations Without Utility
Power Quality Support Value

Note: The deep spike-shaped voltage dip is an artifact of the simulation technique. Use only the actual RMS variation for flicker evaluation.

Figure 2-28
Voltage for 5-Hz Load Variations Without Utility

Figure 2-29
Generator Power for 5-Hz Load Variations With Utility
The fluctuating load simulations are a bit deceptive at first glance because there is a deep voltage dip that occurs as an artifact of the simulation (see Figure 2-28 and Figure 2-30). This artifact is too fast to be noticed as flicker. This artifact is apparently due to the switching of the load, which creates a short-duration transient dip in the simulation each time it switches on. This transient should be ignored. As labeled on the two plots, the parameter “Actual RMS Voltage Variation” is the appropriate result to consider in our voltage flicker analysis.

Using the Actual RMS Voltage Variation as a guide, the simulations show that the level of flicker for a standalone generator with a 100-kW fluctuating resistive load is about 1.5 to 2%. This would be above the borderline of irritation on the GE flicker curve at a 5-Hz repetition rate and quite visible. A 20-kW fluctuating load has about 0.4% flicker, just below the borderline of irritation but still visible. A 5-kW fluctuating load results in less than 0.1% voltage fluctuation, which is not visible.

With the utility system connected, the flicker is dramatically improved by a factor of about 5 and not even the 100 kW fluctuating resistive load results in irritating flicker, although it still would be noticeable according to the GE flicker curve. The results of the analysis are shown plotted on the GE flicker curve (see Figure 2-31). The dotted lines show the voltage change that would be
created by a 100-kW resistive load stepped on/off. The generator is a 500-kVA unit with 20% subtransient reactance. It should be noted that because the load that was simulated in the flicker analysis was resistive, the voltage drop due to resistive current through the generator reactive impedance was nearly in quadrature with the generator voltage and did not create as much voltage drop as “reactive load current.” Use of an inductive fluctuating load would result in larger voltage fluctuations on the generator, so the benefits of reduced voltage flicker afforded by the parallel utility connection for that type of load would become even more important for those types of loads.

Harmonic Response

Harmonic distortion is an important parameter in the quality of power. High levels of harmonic distortion can cause overheating of cables, transformers, and motors. Harmonics can also excite resonances, especially if power-factor-correction capacitors are nearby and happen to be “tuned” in conjunction with nearby inductive reactances to one of the harmonic frequencies. DG has high impedance compared to the utility system, which can make it vulnerable to distortion caused by nonlinear loads when it is operated in a standalone mode. To illustrate this, the impedance at various harmonic frequencies of a standalone system with DG is compared to the impedance with the utility connected.
Figure 2-32 is a plot of the harmonic impedance seen by the load for each integer harmonic up to the 20th (1200 Hz). The top trace represents standalone DG, which is not connected to the utility, and the bottom dashed trace represents distributed generation with a utility connection. The impedance is in per-unit on a 100-kVA base. Zero-sequence current is normally produced at the 3rd-order harmonics, so the zero-sequence impedance is shown for these frequencies. The positive-sequence impedance is shown for the other harmonics. This is, of course, also almost exactly equal to the negative-sequence impedance. Because the circuit does not include a significant amount of capacitance, there are no resonances, and the impedance increases linearly with frequency.

The harmonic voltage is equal to the harmonic current injected by the load or some other harmonic source multiplied by the harmonic impedance. Figure 2-32 indicates that for this test system, there will be more than five times as much positive- and negative-sequence harmonic distortion without a utility interconnection and twice as much zero-sequence distortion.

**Summary of Power Quality Findings**

Overall, the simulations in this section show a clear and dramatic improvement in voltage regulation, voltage flicker, frequency regulation, and harmonic response of the grid-parallel DG.
Power Quality Support Value

compared with the standalone DG. The basic conclusion is that the parallel utility connection provides a substantial positive impact on the power quality of the DG.

Of course, not all power quality impacts of the parallel connection are positive. The utility system connection will expose the generator to occasional momentary interruptions and fault-related voltage sags that the site would not experience if it were standalone. A typical feeder site might see one or two sustained service interruptions each year on the utility system, as well as five to 15 momentary interruptions per year and about two to four deep voltage sags per month due to faults on the feeder, the adjacent feeders, and transmission system. However, exposure to these conditions, while a significant concern, is minor compared to the power quality problems identified in this section that would occur if the standalone DG had to start large motors or supply pulsating loads. For example, according to the simulations presented here, a standalone DG with a motor rated at 60% of the generator capacity that cycles on/off on an hourly basis would expose the site to 24 voltage sags each day to about 60% of nominal voltage. In such a scenario, in one day, the site would encounter almost as many deep voltage sags due to motor starting as it would from the utility system over one year. In addition, exposure to the utility power quality conditions can be mostly dealt with by using an appropriate control scheme that rapidly transitions the DG site to a local customer island during such utility power quality events. So, the utility system contribution to power quality problems can be partially eliminated with proper design.

A parallel utility connection is not the only approach to solve the power quality problems we have discussed here. The performance of a standalone distributed generator can be modified so that it behaves as a much stiffer energy source, even though it is still not connected with the utility system. This would involve lowering its effective impedance by installing shunt-connected power-conditioning devices and using energy-storage devices that provide active power support for load steps and rejections. Voltage-regulating devices, such as high-speed tap-changing transformers and voltage conditioners, can also play a role in improving the generator power quality performance. Perhaps the simplest corrective solution is the approach of specifying generator over-capacity in the DG design. That is, making the generator and its prime mover rating larger than needed for the steady-state load. This can alleviate many of the problems outlined in this section. However, the cost of these solutions and ongoing maintenance must be weighed against the cost and benefits of the parallel utility connection. A parallel utility connection may cost $50 to $100 per kilowatt per year in standby fees, whereas some of the equipment needed to emulate the parallel system performance can cost more than $500/kW. In addition, some of these solutions have a negative impact on system efficiency and reliability and can lead to substantial underutilization of generation capacity, which results in added costs. For example, partially loaded machines that are oversized by a factor of two may solve some of the load-driving issues but will operate much less efficiently and will cost much more per kilowatt of “utilized” generation capacity. The issues regarding optimal sizing and efficiency are discussed in the next chapter of the report but play a role in the overall assessment of the value of parallel utility connection.
Introduction

The focus of this section is to identify how a parallel utility connection impacts the operating efficiency of a distributed generation plant. As was discussed in preceding sections, a standalone generator is operated with a significantly different philosophy than a generator that is grid-parallel. Standalone generator plants must be sized to handle at least the peak load of the customer site and will always be load-following designs. However, grid-parallel DG is more likely to be operated in manner where it is heavily loaded most of the time and performs little if any load-following. As will be shown in the following discussion, grid-parallel operation can improve the efficiency and utilization of DG, which ultimately helps reduce the cost of energy produced by the power plant.

Impact of Demand Cycles on Generator Loading

For standalone DG, if the load has a poor load factor (meaning large variation throughout the day and year), then there are times when the prime mover is loaded to only a fraction of its rating. As an example, Figure 3-1 shows the demand cycles of a hypothetical load over the course of a year. Serving this load with a single standalone DG would require underutilization of plant capacity. If a generator plant composed of a single unit DG were sized to operate as a standalone system to serve this load, it would need to be rated at least for 100% of the peak demand. However, this would mean that during most of the year, the DG would be operating at substantially less than 50% of its rated power. If the load were operating in parallel with the utility system, then the DG could be sized for about 30% of the peak annual load, and the utility system could make up the difference on days when demand exceeded the capacity of the DG. This would allow the generator to operate “heavily loaded” most of the time.
To make sure that the generator units are heavily loaded, it is possible to design the DG plant to be composed of not one large unit but instead multiple smaller units that add up to the needed peak capacity. Several smaller units are better than one large unit because small units can be cycled on and off as the load varies. Using this approach can allow any running generators to be loaded to above 75% of their rating most of the time, even if the total load at the site is varying considerably throughout the day. Multiple units also offer redundancy, which is not obtained when using a single large unit. Redundancy is very important for reliability, which is discussed in Section 4.

For standalone installations, the design practice is always to use multiple generator units because small units can be loaded more effectively. Even grid-parallel DG systems often employ multiple generator units for this reason, but the grid-parallel approach can maintain higher levels of loading on generators by allowing the utility to do the load following as much as possible.

**Impact of Loading on Electrical Efficiency**

The loading level of the DG is an important parameter because combustion turbine-driven and many internal combustion engine-driven distributed generators are designed to run most efficiently when they are generating near their rated power. Figure 3-2 indicates how the efficiency of a gas turbine generator varies with loading. A unit operating at half load will use 18% more fuel per kilowatt-hour of energy produced than a unit operating at full load. The same effect occurs for ICEs, although their efficiency holds up slightly better at light loads (see Figure 3-3). An analogy for this is automobile fuel economy—if a car is waiting at a traffic light, it is achieving “0” miles per gallon fuel economy. If it is cruising at optimal highway speed, the mileage achieved is very close to its full EPA highway rating. These two conditions are analogous to the 0% and 100% loading points for a generator.
Note: For illustration purposes only—consult turbine manufacturers for data relevant to specific products.

**Figure 3-2**
Gas Turbine Efficiency Versus Loading

Note: For illustration purposes only—consult turbine manufacturers for data relevant to specific products.

**Figure 3-3**
Internal Combustion Engine Efficiency Versus Loading

Fuel consumption per unit of electrical energy produced (heat rate) increases significantly as the loading level on the generator is reduced. Fuel use will increase by 10 to 20% for most ICE or turbine generators at half load and will almost double at loading levels of only 10 to 20% of the generator rating. Because fuel costs tend to be about half to 2/3 of the cost of generating power, a 20% increase in fuel use results in up to about a 13% increase in the cost of energy produced by the DG. A doubling of fuel use will result a 67% increase in the cost of energy.

The actual value of the efficiency improvement that can be achieved by employing a grid-parallel design will vary greatly from case to case and depends on type of loads served (load factor, power factor, and nature of load steps) and the type of DG plant design employed. Certainly, efficiency-related cost savings (on the DG side) could range anywhere from a few percent up to 20% in many applications simply because the parallel utility connection allows the
generation to be more efficiency dispatched. The types of DG installations that benefit the most from a parallel utility connection will be those that are serving poor load-factor loads (have a large daily variation in load demand), have plant designs employing relatively few or just a single DG unit, and are located in areas where the cost of fuel is high. As noted earlier, combustion turbines (includes microturbines) are more sensitive to heat-rate performance degradation at partial loading than internal combustion engines, so they would benefit a bit more than typical ICE units.

Reactive Support, Incremental Capacity, and Reserve Margin

In addition to sizing and loading the generator for the peak real power requirements described in the preceding material, there is also the need to supply steady-state reactive power, to supply transient-reactive power during motor starts, to have capacity margin for facility load growth, and to have spinning reserve for reliability purposes. The power ramp-rate capability of the generation also needs to be sufficient for load following. All of these issues can result in a further decrease in the ability to optimally size and dispatch standalone DG units to ensure good operating efficiency and economics. Each is discussed below.

Steady-State and Transient Reactive Power Needs

Motors and other magnetic devices have reactive power consumption in addition to the real power operating needs. Depending on the load characteristics, a standalone DG may need to provide significant reactive power support to certain loads. Because generators are usually rated at 0.8 power factor, they can provide significant reactive power support without a significant impact on their ability to be loaded with active power. However, additional steady-state reactive power needs above what are allowed at 0.8 power factor come at an active power generator loading penalty, which, depending on the design of the generators, may lead to lower prime-mover efficiency. Some distributed generators have ratings at unity power factor and suffer a decline in real power capability if they supply any reactive power at all. Some devices cannot even supply reactive power owing to their design but are actually reactive power sinks (induction generators and certain types of inverters). If there is a major reactive load that must be supported by the DG, it may mean that one or more DG units are operated at lighter real-power load and therefore less efficiently.

In addition to the steady-state reactive loads, there are very large transient reactive power needs associated with starting motor loads that can go beyond the ordinary capacity of a DG plant that is sized just to meet the steady-state power demand. Extra generating units may have to be online in standalone installations to start large motors. An induction motor will draw approximately four to eight times its normal operating current while it is starting. This current is mostly reactive current, so little additional power has to be generated. However, additional generating capacity may be required to supply enough reactive power to support the voltage while the motor is starting. To have sufficient reactive support available to start large motors (>50% of the DG capacity), it may be necessary to keep almost twice as much generating capacity spinning as would be required just to supply power. Of course, keeping this capacity spinning results in reduced real power loading on the DG and results in reduced efficiency, higher fuel consumption, and greater cost of power. A parallel utility connection can provide both steady-
state and transient motor starting reactive power and can avoid the need to keep additional capacity spinning for transient motor starting support. This will improve DG efficiency significantly.

**Capacity Margin for Load Growth**

A standalone DG may be sized to allow for “load-growth breathing room” if it is expected that the load will grow at the facility. The amount of margin needed depends on the load growth rate, the size of each unit in the DG plant, and other factors. Furthermore, this capacity margin needed is interrelated to the spinning reserve and reactive support requirements discussed in this section. Capacity margin installed for planned load growth is just another reason why a DG plant designed for standalone service may have generators that are not as optimally loaded as might be desired. A parallel utility connection allows the design to focus mainly on optimal generator sizing for efficiency and lets the utility company deal with any load growth. Figure 3-4 compares a hypothetical load growth and generation plant build-out scenario for both a grid-parallel and standalone system. The grid-parallel design can actually have some undercapacity, whereas the standalone will normally need overcapacity. The standalone must always have at least one unit of capacity more to allow an N-1 design (see reliability issues) and for other reasons discussed in this report. The capacity additions shown in Figure 3-4 would be made if the load growth is predictable. When it is not possible to predict the load growth, having a utility connection may be even more advantageous. With standalone DG, Unit 4 would probably be added too late, and Units 8 and 9 would probably be added too early because of a failure to anticipate the changing rate of load growth. With a utility connection, the unit additions can be delayed until the load growth is actually experienced, so there is less chance of overbuilding. With a utility connection, the penalty for underbuilding is also much less.

![Figure 3-4](image-url)  
**Figure 3-4**  
Hypothetical Example of DG Units Added to Support Facility Load Growth
Reserve Capacity for Reliability Purposes

The next section will discuss in detail the issue of standalone versus grid-parallel DG reliability. However, it is addressed briefly in this section because the requirement of “reliability” for a standalone DG plant will potentially reduce the operating efficiency of the plant.

A standalone DG plant must be reliable, which typically means an N-1 or N-2 design. That is, it can continue to serve the load with a loss of one or two generator units. If the objective is to avoid any interruption (even short ones to the load), then sufficient reserve capacity may need to be kept spinning at all times such that after the loss of any single unit, there is still sufficient generation capacity to serve the load. Depending upon the type of DG, it may be necessary to keep a unit spinning. It could take many seconds or minutes to start another unit from a stationary standby mode, which could be too slow to avoid collapse of the system following a generator outage. Many DG can handle temporary overloads for several minutes, so depending on the type of equipment employed, temporary overload capability may substitute for spinning reserve. Each standalone design must be looked at carefully from the perspective of the ability of the remaining units to pick up the load when one unit fails and the speed with which a standby unit can be brought on line. In cases where “spinning reserve” is required, this is yet another reason why a DG plant would not be able to optimally load all of its generating units from an efficiency perspective. A parallel connection to the utility system serves as the backup source if a DG unit should fail and helps avoid the need for spinning reserve.

Load Following and Frequency Regulation

A final reason why additional capacity may be needed for standalone DG units is due to the speed at which the load may change. The problem with this is the throttle response (power ramp rate) of the generation system. Generators, such as ICE, combustion turbines, and fuel cells, can have a lag between the power demanded by the load and response of the prime mover—they can only increase their output at a finite rate. ICE units are some of the fastest performing DG from a load-following and ramp-rate perspective. Combustion turbines are significantly slower. Fuel cells can be extremely slow depending on the design of the fuel cell stack but may employ battery or ultracapacitor storage to solve the problem. If the load variations at the site are too fast for the generator to keep up with, then serious frequency fluctuations can occur. If the changes in system load are too large, it may be necessary to keep extra generators connected and synchronized so that enough generating capacity is available to cover each load addition. Even if the connected generator capacity is sufficient, the steady-state load may ramp up or down faster than the generators can respond. To avoid large frequency swings, it may therefore be necessary to have extra generators on-line so that the rate of change in each generator’s output is a fraction of the speed at which the load is changing (see Figure 3-5). With more units on-line, each unit will be generating at lighter load and therefore be operating less efficiently.
Cogeneration is an important feature of distributed generation. Most DG are between 25 and 45% efficient at converting fuel energy into electrical power and so are actually a bit less efficient electrically than typical central station power plants (35 to 60% for central station). This means about 55 to 75% of the DG fuel energy is converted to waste heat. In the cogeneration process, the waste heat can be recovered and used for space heating, water heating, process heat, or refrigeration (absorption chiller). When heat is recovered and effectively put to use, it means that DG is actually much more efficient than a utility central station plant. A carefully designed cogeneration application can have a total efficiency in the range of 70 to 85% (or even higher). Such high efficiencies are obtained when the generator heat output is carefully matched to the heat load. When distributed generation plants are operating in parallel with the electrical power system, it is easier to match the heat output with the thermal load because the generator only needs to produce electrical power at times that the heat load is needed.

A common problem for cogenerators that are operating as standalone systems is that it is more difficult to match the electrical and thermal needs of the facility. That is, the electrical load is such that either the plant is producing too much heat or too little heat at the time that the heat is needed. If the plant is producing too much heat, then the extra heat must be dissipated in cooling towers or by some other means, which lowers the efficiency of the process. As a standalone source, the plant must be operating to supply electricity at all times, and if there is no heat load at certain times, then the heat must be wasted (rejected into the atmosphere). In some cases, thermal storage can be added to shift the heat load to the appropriate time window, but this costs money and is often not practical.

Overall, having the utility system available as a parallel connection allows the generation plant to be better dispatched to improve the cogeneration efficiency. More than a 20% improvement in
cogeneration efficiency could be obtained in many cases due to the availability of a parallel utility system connection. The actual improvement possible in projects would depend on a variety of factors and so could range from no improvement to more than 20%.

**Efficiency Conclusions**

The preceding discussion showed that power quality, reliability, and load-following issues drive the need to have significant excess capacity in standalone DG installations. Generator overcapacity results in generator under-loading (causes low efficiency) and under-utilized capital investment, which essentially raises the cost of energy produced by the DG. Because there are so many issues that require surplus generation capacity, the probability that at least one issue will come into play at any particular DG site is high. This is why so many standalone sites have significant overcapacity installed and why generally they perform at lower electrical efficiency than grid-parallel systems.

At this juncture, it is important to point out that a good DG system designer is usually able to reduce the amount of excess capacity by studying the served load carefully and applying the proper number of DG units, unit sizes, and controls to a given situation. A good designer also will realize that with improvements made on the load side (such as power-factor-correction capacitors, soft-start motor controls, and load shedding), the amount of capacity margin needed can be reduced significantly. However, no matter how good the DG design, the need for significant surplus capacity cannot be eliminated. A parallel utility system connection with the DG plant is very attractive because it gives the DG designer the freedom to focus on active power optimal loading of generators instead of reactive power requirements, motor starting, reliability, and load following. The utility connection also helps with cogeneration applications by making it easier to dispatch the generation in a manner that is suitable for the heat load.
Introduction

One of the greatest benefits that a parallel utility system connection offers DG is cost-effective reliability enhancement. Stand-alone DG can be designed to be as reliable or even more reliable than the typical utility connection, but to achieve such performance requires a redundant design and many of the cost and efficiency penalties we have discussed in earlier sections.

To put things into perspective, the availability of a *standalone* facility powered by distributed generation can be compared with the availability of electricity from the *utility grid*. The availability of electricity from U.S. utilities varies significantly from region to region. It is also different in urban, suburban, and rural areas. The number of outages depends upon the length of the distribution circuit, whether it is underground or overhead, its voltage class, and so on. In an area served by an underground low-voltage distribution network, electric customers may experience less than one interruption every 10 years. However, in some rural areas served by long overhead distribution circuits of radial design, the cumulative outage time may be counted in days per year. However, the vast majority of utility customers have come to expect an electrical outage rate that is well below 10 hours per year—the availability normally exceeds 99.9% and often approaches 99.99%.

By comparison, ICE generators and gas turbine driven generators in continuous operation are *available approximately 95 to 97% of the time*. While this may sound good from an individual machine perspective, it means that they will be out of service 263 hours a year, which is about 11 days. Most DG equipment manufactures will not even guarantee this level of availability. Some of this downtime is for planned outages to perform maintenance; these outages may not impact power quality if they can be scheduled at non-critical times. However, ICE generators and gas turbine generators (taken on an individual basis) are also out of service because of unplanned events about 1 to 2% of the time, or 88 hours per year, a little over three and a half days. Even this level of reliability is worse than that of typical utility-supplied power. In fact, it is worse than the worst performing U.S. rural utility service connections. Of course, the reliability figures discussed are for a single DG unit and not for DG designed with multiple units and redundant capacity.

**Using Multiple Generators to Enhance Reliability**

When DG planners develop designs for distributed generation power plants, these designs typically employ multiple small generators with a combined capacity that is sufficient to satisfy the load and reserve requirements. This is a necessity for a standalone system if suitable reliability is to be achieved. In the case of a standalone system, the DG planner would identify...
the desired performance level of system reliability (3 nines, 4 nines, and so on) and develop suitable plans based on the forced outage rates and scheduled outage rates of the generators selected for the project. Depending on the desired reliability level and characteristics of the generator, an N-1, N-2, or N-3 design may be necessary. Rarely would greater than N-2 be needed. An N-1 design can still serve the load if any single generator fails. An N-2 design can serve the load if any two generators fail, an N-3 if three units fail, and so on.

Generally, a design with fewer large generators will cost less per kilowatt of capacity and require less redundant switchgear costs than using a large number of small generators. However, smaller generators, though they cost more per kilowatt, ultimately require less “surplus” capacity to achieve a specific level of reliability performance.

Figure 4-1 is an example showing how the surplus generation capacity required for an N-1 design decreases as the number of generation units increases. Table 4-1 and Table 4-2 show this effect for N-1 and N-2 designs.

**Figure 4-1**
The More Generator Units are in Parallel, the Smaller the Amount of Surplus Capacity Needed for a Fixed Level of Contingency Design (in This Example, N-1)
### Table 4-1
**Surplus Generating Capacity Needed for an N-1 Design Decreases as the Number of Generators Increases**

<table>
<thead>
<tr>
<th>Number of Generators (N)</th>
<th>Contingency Design</th>
<th>Surplus Capacity Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>N-1</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>N-1</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>N-1</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>N-1</td>
<td>25%</td>
</tr>
<tr>
<td>6</td>
<td>N-1</td>
<td>20%</td>
</tr>
</tbody>
</table>

### Table 4-2
**Surplus Generation Capacity Needed With Parallel Generators Sized So That Any Two Can Fail and the Load Can Still Be Served (Data for N-2 Design)**

<table>
<thead>
<tr>
<th>Number of Generators (N)</th>
<th>Contingency Design</th>
<th>Surplus Capacity Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>N-2</td>
<td>200%</td>
</tr>
<tr>
<td>4</td>
<td>N-2</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>N-2</td>
<td>66%</td>
</tr>
<tr>
<td>6</td>
<td>N-2</td>
<td>50%</td>
</tr>
<tr>
<td>7</td>
<td>N-2</td>
<td>40%</td>
</tr>
<tr>
<td>8</td>
<td>N-2</td>
<td>33%</td>
</tr>
<tr>
<td>9</td>
<td>N-2</td>
<td>29%</td>
</tr>
<tr>
<td>10</td>
<td>N-2</td>
<td>25%</td>
</tr>
</tbody>
</table>

As an example of an N-1 design, if there are two generators and each can cover the load by itself, then 100% surplus capacity is available and overall reliability is improved dramatically. The probability that both units will be out of service at the same time is small but not infinitesimal. Each can be forced out of service 1% of the time while the other is being maintained (2% of the time). Forced outages during maintenance will therefore occur 0.04% of the time. The two units can also both be forced out of service at the same time. This will happen 1% of 1% of the time, or 0.01% of the time. Therefore, both units will be unavailable 0.05% of the time, which is 4.38 hours per year. Overall, it will be possible to supply the load 99.95% of the time.
As an example of another N-1 design approach, with three generators sized so any two can cover the load (each generator rated at 50% of the load), it will be possible to supply the load 99.85% of the time. Two of the three units will be unavailable 13 hours per year.

The analysis above assumes that there are no periods of light load. With a varying load, it is often possible to schedule maintenance when fewer generators are needed. The risk of not being able to satisfy the load because a generator is out for maintenance will then be minimal. If maintenance is scheduled when only one of three generators is needed, then the load will only be lost when two of the three units are forced out of service at the same time, about 2.6 hours/year. Sufficient generation will be available 99.97% of the time. The availability could be higher if the load is light for long periods of time, so that two units are needed only occasionally. This is comparable to the unavailability experienced by a typical utility.

For N-2 designs, the reliability improves even more. Any two units can fail and the load can still be served. For a three-unit system, with each unit sized at 100% of load, there is 200% surplus capacity available. One of three units will be available 99.999993% of the time. All three will be out an average of 0.06 hours/year. This level of reliability is far better than the average radial power distribution system and equivalent to the best network systems.

Of course, the design details of the generation plant are driven by more than just reliability needs. As has been discussed in preceding sections, the efficiency of power production, thermal energy uses (for cogeneration plants), and power quality issues all demand attention in the design of the power plant. For example, reliability based criteria may dictate a six-unit N-1 DG plant design that has only 20% surplus capacity, but if the facility has large motors that must be started, the designer may be forced to employ a design with more surplus capacity to maintain adequate power quality during the motor-starting condition.

Parallel Utility Connection in Lieu of Redundant Generators

By operating DG in parallel with the utility system, high levels of reliability are readily achieved without the need for surplus DG capacity. In addition, the utility connection alleviates much of the need to have surplus capacity for the power quality and reactive power reasons discussed in preceding sections. As an example, if the generation in the facility is out of service 3% of the time, there are no spare generators in the facility, and the utility is 99.95% available (0.05% unavailable), then electrical power will be unavailable only 0.13 hours of the year. Even better availability can be achieved if the plant capacity is made of several small units and maintenance of units can be scheduled during periods of light load. This is one reason why even grid-parallel DG designs may employ multiple generator units. Excess generation capacity can marginally cost as little as $200 per kilowatt but is more likely to be in the range of $500 per kilowatt owing to the use of smaller generators (which have higher cost per kW) and additional switchgear/controls. The parallel utility connection can help avoid this expense.

A word of caution regarding the ability of a parallel utility connection to avoid the need for surplus generation capacity; power quality considerations may still create a need for some redundancy. When the utility system is off-line, the grid-parallel DG plant temporarily becomes a standalone entity. It must have adequate capacity during this mode of operation to power the loads and maintain adequate power quality. If there are large motors, then DG overcapacity is
still likely needed for power quality. Of course, due to the short duration of most power outages on the utility system (a few hours per year or less), the DG will not be operating in standalone mode very long, so somewhat reduced power quality might be acceptable. Nonetheless, the power quality conditions that occur during short transitions to standalone mode still need to be carefully considered to determine if surplus generation capacity can be avoided. The power quality sensitivity of loads, the types of loads (large motors or large step-loads), and generator characteristics will determine whether a parallel utility system connection can avoid the need for surplus generation capacity. In most cases, at least some significant surplus capacity can be avoided.

**Transition From Grid-Parallel to Standalone Mode**

If a grid-connected DG system is to achieve improved reliability, the utility interconnection interface and control system should be able to detect failure of either the local generation or the utility system supply and perform the appropriate switching to isolate the affected device. In the case of a utility system supply failure, the voltage will either sag deeply or disappear entirely. A grid-connected generation plant has the responsibility to quickly sense this condition (with appropriate protective relay functions) and create a standalone island composed of the DG and local site load. Once the island is formed, it will be maintained until the utility service voltage is restored, at which time the DG can resynchronize and reconnect to the utility system. In the case of a DG failure, the DG is quickly tripped off-line, and the load is served by the utility system. Figure 4-2 shows the basic layout for such an interface.

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**Figure 4-2**

*Grid-Parallel Connection Scheme to Allow “Local Island” During Utility Interruptions and Isolation of DG Plant During DG Failures*
DG in a grid-parallel system will need to have all of the usual required utility system interface equipment and protection and will need to be applied with suitable grounding, acceptable power quality, and safety considerations for the utility system.

In the transition from a grid-parallel state to a standalone state, the DG must change its operating mode from a voltage-following and utility-synchronized state to a voltage- and frequency-regulating state that can load-follow. The transition from one state to another need not be seamless. A short power quality disturbance or interruption might be acceptable at many sites. However, a long interruption during the transition would be considered a reliability failure. Whether or not a seamless transition is required depends on the power quality design objectives of the facility. Using mechanical switchgear and traditional control-sensing methods, a very fast seamless transition is not possible. Nevertheless, it is possible to transition using conventional switchgear methods if a few cycles of disturbance are allowed to reach the load. For a seamless transition (within ½ cycle) with no disturbance reaching the load, a static switch is the only real option.

The control scheme to transition the DG to/from the islanded state needs to have the proper sensitivity to avoid false triggers during minor voltage anomalies that repeatedly send the DG site and customer load into an islanded state. On the other hand, it needs to be sensitive and fast enough to successfully transition the site to the islanded state whenever a real interruption or deep voltage sag on the utility system occurs. Improper execution in either direction could degrade the reliability performance.

The control scheme must handle load/generation unbalances at the instant the system transitions to an islanded state. It is easiest to handle the situation when the load exactly balances the output of the generator before separation. If the generator is producing too much power (exporting to the utility system), the imbalance can cause the generator to accelerate (over-frequency) and can cause overvoltages. If the generator is producing too little power, then the frequency declines and an undervoltage may occur. Imbalances between local load and generation at the moment of separation must not be so large that the DG and load at the site cannot ride through the transition. High-speed load shedding and dynamic breaking load resistances can be used to deal with large imbalances.

**Reliability Summary**

To obtain the level of reliability enjoyed by the average utility customer using standalone generation, the standalone facility must have at least enough surplus capacity at peak load to replace the largest generator. Two redundant generators may be needed to match the availability of the best utility systems.

In a standalone facility, it is normally more economical to have a small redundant unit with several small units instead of a large redundant unit to back up a single large unit. This approach, however, cannot be taken to extremes because small units cost more per kilowatt of capacity and require additional switchgear. An installation with five generators, four plus a spare, is typical. If the facility is connected to the utility, then better reliability can be obtained without the spare generator. The installation cost without a utility connection (five generators) will therefore be approximately 25% more than the installation cost with a utility connection (four generators).
It is possible to have the best of both worlds by connecting a facility with its own generation to the utility system. The utility system will then act as a highly reliable redundant generator. During normal operation, local distributed generators can supply the facility’s load. If one of these units is out of service for any reason, however, the utility will make up for any power deficit. If the utility experiences an outage, the distributed generation and load can temporarily separate and continue normal operation. This of course assumes that the interface between the facility and utility is designed to permit suitable disconnection and reconnection for utility disturbances.
Summary of Parallel Connection Benefits

The preceding material shows that a parallel utility connection provides value for distributed generators in the areas of power quality, reliability, and efficiency. Specific improvements that were identified included:

- Improved voltage regulation during load steps and motor starts
- Reduced levels of harmonic voltage distortion when driving nonlinear loads
- Improved frequency regulation (especially when starting motors and during load steps)
- Improved electrical generation efficiency
- Improved cogeneration efficiency (by better match of heat load to electrical production)
- Reactive power support
- Enhanced reliability
- Optimal sizing (surplus capacity cost savings)

The value of these benefits usually exceeds the cost of being connected to the utility system. The cost of connection includes standby service fees, which in most cases range between $25 and 200 per year per kilowatt of expected peak demand, and interconnection controls, equipment, and routine studies, which can have an incremental cost of $25 to 50 per kilowatt of generation capacity (for larger DG). Because the annual carrying charge on interconnection equipment would ordinarily be 15 to 20% of equipment capital cost, its annual cost is between $3.75 and $12.50 per kilowatt per year. Overall, the total cost of interconnection at most sites, including the standby fees and equipment, is somewhere between $28.75 and $212.50 per kilowatt per year. There are sometimes additional costs of interconnection that include special (not just routine) studies and utility system upgrades that are not factored into these numbers. In some cases, these would make the choice of a parallel connection impractical.

We can calculate the impact that the cost of interconnection has on the cost of the DG to produce electricity. Assuming an 80% capacity factor for the generation plant, the annual costs of interconnection will add between 0.4 and 3 cents per kilowatt-hour of energy produced. We can also estimate the dollar value of benefits of the parallel interconnection. The improved efficiency of the generator may effectively lower the cost by up to 1 cent per kilowatt-hour in many cases, and the cost savings due to reduced capital cost of the DG plant will lower the cost by several more cents per kilowatt-hour (see the next section, “Comparison to Alternative Approaches,” for details).
Comparison to Alternative Approaches

Alternative approaches to a parallel connection were identified that can make standalone DG installations as reliable as parallel connection and improve power quality to a level equal or exceeding the utility system performance. To solve the reliability issues, redundant DG plant designs that have a large number of smaller generation units (five or more) and sufficient excess capacity to allow units (N-1, N-2, or greater) to fail and still be able to service the load can be employed. Excess capacity can also function like a synchronous condenser to provide reactive support during motor starts and load steps, helping to improve power quality. For enhancement of power quality beyond what can be provided by employing surplus generator capacity, inverter based high speed power conditioning devices with energy storage can be employed. These devices can absorb surplus energy or dump out energy as needed to stabilize frequency during load steps and motor starts. Reactive power from such devices can also help stabilize the voltage during load steps and motor starts. Use of large numbers of smaller generators (sites with five more units) as opposed to one or two units not only improves reliability but also allows much improved generator dispatch so that the units can be optimally loaded for improved efficiency.

While all of the above improvements can make standalone DG function with the same or better performance than the utility system, generally they cost much more than a parallel utility system connection. Capital costs can run anywhere from $500 to over $1500 per kilowatt for the improvements needed to make a standalone system function like a grid-parallel design—the specific costs would vary for each site and depend on the type of generation equipment, the size of the system, load characteristics, and performance requirements. The annual carrying charge of 15 to 20% on equipment investments at the costs shown is equivalent to between $75 and $375 per kilowatt of capacity per year. This can be converted into cents per kilowatt of additional cost of producing power, but because standalone systems have a lower capacity factor than a grid-parallel design, a 50% capacity factor as opposed to 80% is used for the conversion. Using this data, the total cost to make a standalone DG behave as well as the grid-parallel approach is expected to be between about 1.7 and 8.5 cents per kilowatt-hour. This would be the gross benefit of connecting to the utility system because this cost should be avoidable in that case. To calculate the net benefit of the utility connection, we need to also add to this the energy production efficiency benefit and then subtract utility interconnection cost (including standby fees). Doing this, the benefit of the utility connection will range from a low value of negative 1.3 cents per kilowatt-hour to nearly 10 cents per kilowatt-hour. Note that in some cases, the benefit is negative, meaning that it would be better to employ a standalone DG system with the needed upgrades. However, in the vast majority of cases, the benefit would be positive, so the parallel utility connection approach makes better sense. The situations where the utility interconnection costs and standby fees are highest would be the sites least likely to benefit from the parallel connection approach.

Recommendations

Overall, the findings of this study show that in most cases, the parallel utility system connection offers more benefits to the DG than it will cost in standby charges and interconnection costs.

Of course, standby charges are not intended to be a fee paid for all of the benefits outlined in this report. Standby charges are intended to just recover costs associated with maintaining and
reserving the T&D system capacity needed for standby service. Nonetheless, as a byproduct of standby service, the various benefits outlined in this report can be obtained if the DG is properly coordinated with the power system. Therefore, it is fair to compare the cost of such service to the benefits provided.

This report is not intended to be the last word on this topic but is simply intended to identify the key issues and start further thinking on the topic. The data used in this report are for the purposes of illustrating the concepts discussed here. While the data here represent typical values, each DG case at a specific utility must be examined individually based on local economic factors, utility system characteristics, and the DG site characteristics.
Target:
Power Quality for Customer Systems

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