Ancillary Services Provided from DER with Power Electronics Interface

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***Abstract*–Distributed energy resources (DER) are quickly making their way to industry primarily as backup generation. They are effective at starting and then producing full-load power within a few seconds. DER can alleviate the burden on the utility grid by providing ancillary services, which also helps in justifying the installation cost for the DER owner. This paper describes ten types of these ancillary services, which DG can provide to the utility grid. Of these 10 services, the feasibility, control strategy, effectiveness, and cost benefits are all analyzed for the future utility power market.**

***Index Terms* – ancillary services, distributed energy, power electronics interface.**

I. INTRODUCTION

Distributed generation (DG) applications currently are primarily designated for backup and peak power shaving conditions. Distributed generation includes microturbine generators, internal combustion engines (ICEs), and fuel cells. Frequently, these generators sustain long periods at an inoperative state until the needs of the load or the local utility require additional generation. Thus DG is costly to install, maintain, and operate for most commercial customers.

DG is cost-effective only in some niche markets where the electricity cost is extremely high, such as Hawaii and the Northeast, or where outage costs are high. Two possibilities for achieving cost-effectiveness for DG are reducing the capital and installation costs of the systems, and taking advantage of additional ancillary services that DG is capable of providing.

A market for unbundled services (ancillary services) would promote installation of DG where costs could not be justified based purely on real power generation. The provision to produce ancillary services with DG would greatly alleviate the present demands on an aging power grid. Unfortunately, the demand on the grid is increasing at a faster rate than improvements are being made. Deteriorating power quality is a result of the imbalances in the grid. Ancillary services can be the bridge between the capabilities of DG and the needs of the utility.

Power electronics offer significant potential to improve the local voltage regulation of the grid that will benefit both the utility and the customer-owned DG source. Power electronics offer the conversion of real power to match the system voltage and frequency, but this interface could do much more. Power electronics could be designed to incorporate voltage and frequency conditioning for the utility. Also, various controls could be built into the power electronics so that a DG system could respond to special events or coordinate its operation with other DG sources on the distribution system.

In this paper, we investigate the possibility of using DG to provide the following ten ancillary services:

- Voltage Control
- Frequency Regulation
- Load Following
- Spinning Reserve
- Supplemental Reserve (Non-spinning)
- Backup Supply
- Harmonic Compensation
- Network Stability
- Seamless Transfer
- Peak Shaving

To provide the ancillary services from DG, also referred to as distributed energy resources (DER), the system should contain two subsystems: one is the on-line detection subsystem, which detects the need for ancillary services and gives a signal when an ancillary service is needed; the other is a function realization subsystem, which works to provide the related ancillary services after receiving that signal.

For example, the same DG could be a voltage supporter or a harmonics compensator. The only difference is in the control part, so when the detection subsystem finds the harmonics are beyond the preset range, then it controls the operation of the DG to work as a harmonics compensator; when the detection subsystem find the voltage is beyond the preset range, then it controls the DG to operate as a voltage supporter.

A control hierarchy must be established such that the DG provides the most important ancillary service when more than one ancillary service is needed. To decide which one is the most important ancillary service, we need to consider economic issues, system reliability, and technical feasibility.

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For most of the ancillary services, we only need additional software code to provide it from DG. However, if an external energy storage capability was available, the power converter could provide high, short-duration power to start motors, which is important in providing ancillary services such as load following and frequency regulation [1].

II. TYPES OF ANCILLARY SERVICES

Each of the ten types of ancillary services is described in this section along with simulations to demonstrate how these services might be provided from DG.

A. *Voltage Control*

Voltage Control is the injection or absorption of reactive power by generation and transmission equipment to maintain transmission system voltages within required ranges or maintain the bus voltage of critical or sensitive loads [2]. Simulations will demonstrate how DG could perform the voltage control function.

The analysis scheme for voltage control is shown in Fig. 1. There are three types of conditions that may cause voltage sag/swell for the bus voltage of critical or sensitive loads:

- First condition: the load has some inductive component. The inductive component will not absorb active power; however, it absorbs reactive power, which will cause larger transmission voltage drop and a lower load voltage V_L.
- Second condition: the real power of the load changes. Changing the impedance of the load could simulate this condition.
- Third condition: a fault in the grid makes V_g change, so V_L changes accordingly.

Generally speaking, the second and third condition may cause voltage sag or swell, and the first condition only causes voltage sag.

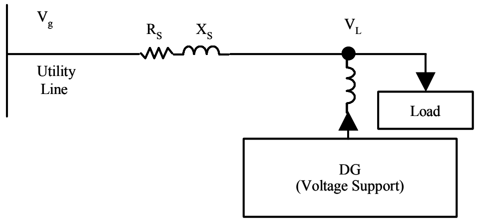

Fig. 1. System scheme for voltage support.

One of the general control methods that can realize the basic principle of voltage support is as follows: compare the actual RMS value of V_L and the reference value (for example, 480 V), and then use the difference to control the DG to provide/absorb reactive power.

Take a grid-fault condition as an example to show the simulation results. The simulation scheme is shown in Fig. 2.

Set the rated voltage to be 4160 V. Choose [3952, 4368] to be a preset acceptable voltage range; when the voltage is outside this range, the voltage supporter is started. Fig. 3 is the comparison between the compensated voltage and the original voltage, where the voltage before compensation is 3620 V (13% less than the rated voltage).

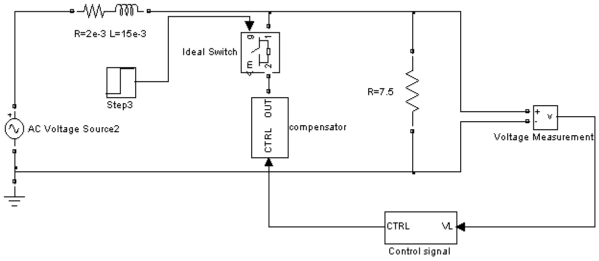

Fig. 2. Voltage control system scheme under grid fault condition.

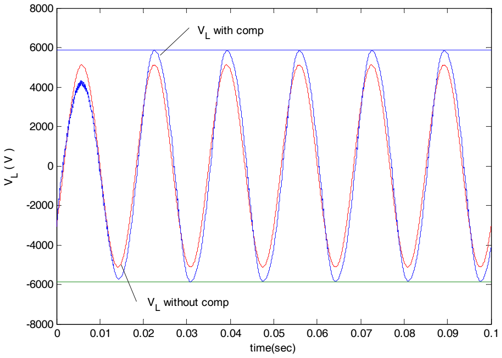

Fig. 3. Compensation effect when V_L=3620 V.

The active and reactive current provided by DG in this condition is shown in Fig. 4. Fig. 4(a) is the entire current provided by DG, Fig. 4(b) is the active component, and Fig. 4(c) is the reactive component.

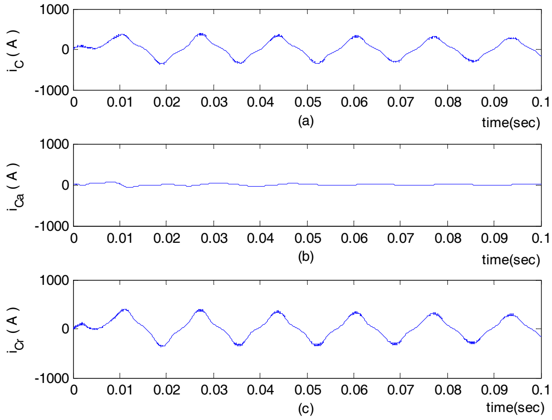

Fig. 4. Current provided by DG when V_L = 3620 V, (a) compensated current, (b) compensated active current, (c) compensated reactive current.

From Figs. 3 and 4, the voltage can be regulated to the rated voltage, and reactive current is provided by the DG only after about one cycle of dynamic process. Since the dynamic process is very short, DG provides almost no energy during the dynamic process. In fact, the dynamic process is mostly a result of the calculation period. It needs some time (1 cycle in this simulation) to calculate the active and reactive current; and at the same time, the RMS value of the voltage V_L also needs 1 cycle to be calculated in this simulation.

From the simulation results, we could see that, by comparing the RMS value of V_L to its expected value that controls the amount of reactive current provided, DG could support the voltage well under the condition resulting from a grid fault. In addition, from the simulation results of inductive load and real power load changes, we can also get similar results. Thus, this control method works well under all these voltage control conditions.

B. Frequency Regulation

Frequency Regulation is the use of online generation units that are equipped with governors and automatic generation control and that can change in a timely fashion to regulate frequency [2].

When the mechanical power and electrical power of the synchronous generator is not in balance, then the frequency in the grid will change, and the corresponding equation is:

$$\frac{4\pi H}{\omega_e}\dot{f} = P_{mu} - P_{eu} \tag{1}$$

where P_{mu} is the mechanical power (W), and P_{eu} is the electrical power (W), H is per unit inertia constant (s), ω_e is the electrical rotational speed, and f is the frequency, $\omega_e=2\pi f$. Since f changes only slightly, we can treat $4\pi H/\omega_e$ as a constant K. In this simulation, $K = 50{,}000$.

Suppose that the load is in balance with generation supply before time t=0, and the frequency is 60 Hz. At time t=0, there is a step increase of 100 kW in the load power. DG is controlled to supply this increased amount. Comparing the frequency with and without regulation, the result is shown in Fig. 5.

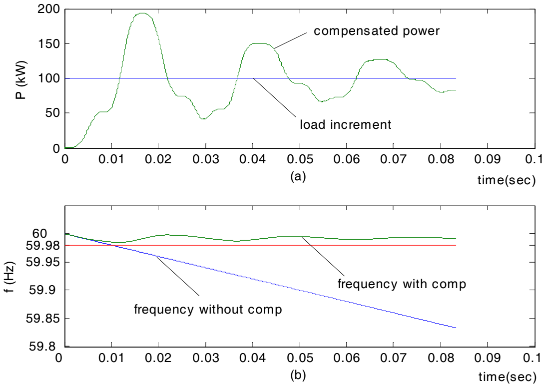

Fig. 5. Compensation effect for regulation, (a) load increment and compensated power, (b) frequency with and without compensation.

Fig. 5(a) describes the comparison between the load increment and the power that the DG provides. Fig. 5(b) shows the comparison of the frequency with DG compensation and without DG compensation. In this simulation, the frequency could be controlled to be in the preset range (59.98 – 60.02 Hz) in less than one cycle (1/60 s).

C. Load Following

Fig. 6 is the system scheme for load following. DG sells some of power to the utility, while at the same time it supplies the load and tracks changes in customer needs.

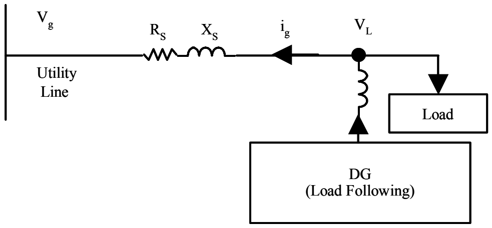

Fig. 6. System scheme for load following.

For load following, part of the function is to track the load, which is similar to frequency regulation. Load following is often mentioned together with frequency regulation; they both address the temporal variations in load.

In this system (providing ancillary services from DG), the difference between frequency regulation and load following is that: for load following, DG sells some of power to the utility and tracks the load's change at the same time, but for frequency regulation, DG only tracks the load's change. However, in some systems, the distinction between load following and frequency regulation is only the time periods over which these fluctuations occur. Frequency regulation responds to rapid load fluctuations (on the order of one minute), and load following responds to slower changes (on the order of five to thirty minutes) [3]. Therefore, their precise definitions vary from system to system.

D. Network Stability

When trying to improve transmission system use, a key assumption is that the existing system stability will be maintained. Network Stability is the use of special equipment at a power plant (power system stabilizers or dynamic resistor) or on the transmission system (such as DC lines, FACTs, energy storage) to help maintain transmission system reliability [2]. For this example (providing ancillary services from DG), we use DG to help maintain transmission system reliability.

To maintain network stability, the power system needs to have adequacy, which is defined as the ability of the power system to meet energy demands within component ratings and voltage limits. Energy storage can be used to enhance operation of the transmission system power flow control equipment by supplementing the ability of this equipment to generate or absorb active power. Therefore, to maintain network stability, the energy storage needs must be fully available very quickly (on the order of one cycle).

Network stability is similar to frequency regulation, but it requires a more rapid response time. DG with power electronics could perform network stability function by monitoring frequency fluctuations and controlling the DG import/export, since it can respond very quickly. As shown in Fig. 5, by using DG, the frequency could be controlled to be in the preset range (59.98– 60.02 Hz) in less than one cycle (1/60 s), which is qualified for the network stability requirement.

E. Spinning Reserve

Normally, Spinning Reserve is the use of generating equipment that is online and synchronized to the grid such that the generating equipment can begin to increase output delivery immediately in response to changes to interconnection frequency, and be fully utilized within seconds to <10 minutes to correct for generation/load imbalances caused by generation or transmission outages [2]. Most on-line DG could perform spinning reserve and respond in less than 10 seconds.

For DG with a power electronics interface to provide spinning reserve, the control method is to control the current from DG to let it be an active current, and by changing the amplitude of the current, change the DG's output active power.

As an example, DG with a power electronics interface is simulated. Assume that at a time of 0.4 s, a frequency drop is detected, and a decision was established to use DG to supply active power. The original source provides less active power, and then the grid frequency will be normal again. Fig. 7 is the simulation result. Fig. 7(a) is the active power P_{sa} and reactive power P_{sr} the source provides; Fig. 7(b) is the active power *Pca* and reactive power P_{cr} that the DG provides; Fig. 7(c) is the active power P_{La} and reactive power P_{Lr} the load absorbs.

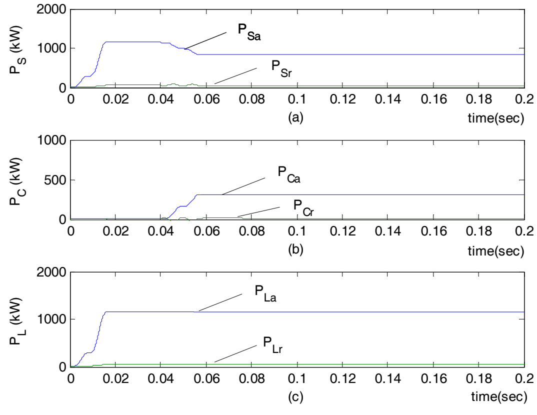

Fig. 7. Simulation results for spinning reserve, (a) source power, (b) compensated power, (c) load power.

From Fig. 7, the active power the source must provide changes from 1151 kW to 836 kW, and the DG provides this difference (315 kW). It only needs about 0.02 seconds (from t=0.04 s to t=0.06 s) for the system to finish the dynamic process. Obviously this short time is much smaller than 10 s, thus on-line DG with power electronics interface is qualified for supplying spinning reserve.

F. Supplemental Reserve (Non-spinning)

Supplemental Reserve (Non-spinning) is the use of generating equipment and interruptible load that can be fully available to correct for generation/load imbalance caused by generation or transmission outages [2]. Supplemental reserve differs from spinning reserve because supplemental does not need to respond to an outage immediately. Traditional non-spinning reserve needs to be available within 10 minutes.

If a DG system is not on-line, it needs some time to start.

- A microturbine requires approximately 2 minutes to start up.
- For an internal combustion engine, the time necessary to start is from 2 – 5 seconds.
- For a fuel cell, most have a start-up time of approximately 5 minutes.

For most DER, 10 minutes is an adequate time to start, and it is conceivable that an off-line DG system is appropriate to perform supplemental reserve.

G. Peak Shaving

Peak Shaving is the use of generation equipment during certain peak load periods. Customers must purchase power at a higher cost during peak load periods, and the demand charge is a function of the peak demand at any time during a year; therefore, utilization of generation for peak shaving can reduce a customer's operational costs. DG could perform the peak shaving function.

Peak shaving provides active power to the user during peak load. Because this is similar to spinning reserve in the supply of active power, the accomplishment of the two ancillary services is similar. However, spinning reserve is a service provided to the utility, and peak shaving is a service for the DG owner.

H. Backup Supply

Backup Supply is a service that customers would purchase to protect against forced outages by the generating units that provide their energy or against loss of transmission between their normal supply and their load [2]. Unlike spinning reserve and supplemental reserve, which are system services required for reliability, backup supply is a commercial service that supports individual transactions. DG could perform backup supply.

The basic principle is that during forced outages of the utility, DG is used to supply the load. The method is to control the output voltage of the DG to give the load uninterruptible supply.

For example, a DG with power electronics is used in a simulation. The results are shown in Figs. 8 through 11 for four different cases. Ideally the algorithm is able to detect an outage very quickly.

For an outage that occurs at t=0.0375 s, when the voltage is at its peak amplitude, the outage is detected and then the DG begins to supply the load (Fig. 8). In fact, this is the worst condition, since the source voltage is lost when the load voltage is at its maximum amplitude. Under this condition, DG needs approximately 1/12 cycle to supply the load normally.

For an outage at t=0.05 s, when the voltage is crossing through 0, it is detected and then the DG starts to supply the load (Fig. 9). Under this condition, there is almost no transition process, and the DG could supply the load normally immediately.

For an outage at t=0.04 s, when the voltage is not 0 and not at the maximum amplitude, it is detected and the DG starts to supply the load (Fig. 10). Under this condition, there exists a transition; however, it is less than 1/12 cycle.

By decreasing the value of the inductance, which connects DG and the load, the transition process may be short and almost disappear; however, the voltage waveform will not be as smooth as before. Take an outage that happens at t=0.0375 s as an example, since this is the worst condition, and the result is shown in Fig. 11.

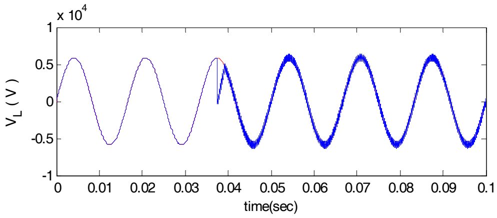

Fig. 8. Outage occurs at t_s=0.0375 s.

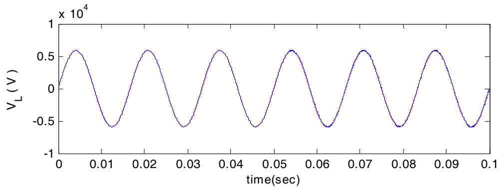

Fig. 9. Outage occurs at t_s=0.05 s.

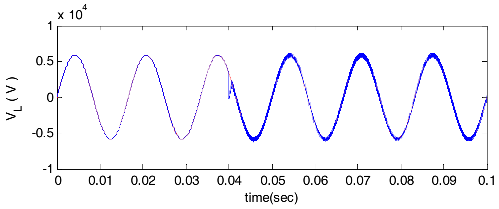

Fig. 10. Outage occurs at t_s=0.04 s.

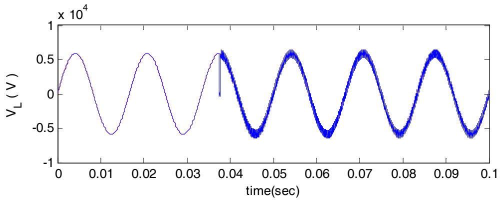

Fig. 11. Outage occurs at t_s=0.0375 s with less output inductance.

I. Harmonic Compensation

Harmonic Compensation is the use of online generation equipment to compensate for harmonics caused by non-continuous loads. Harmonics can cause poor power quality, voltage imbalances, and excessive zero-sequence currents.

1) Harmonic Detection:

Before harmonic current compensation, harmonic current must be detected. There are many methods to detect harmonic current. We use instantaneous active current calculation theory to separate the harmonic component and fundamental reactive component from the fundamental active component.

Instantaneous active power [4] is defined as the time rate of energy generation, transfer, or utilization, where *M* is the phase number of the system:

$$p(t)=\sum_{i=1}^{M} p_i(t)=\sum_{i=1}^{M} v_i(t)i_i(t) \qquad (2)$$

The nonactive current/power definitions are based on this definition and an extension of Fryze's idea of nonactive current/power [5]. The definitions of instantaneous active current $i_p(t)$ and nonactive current $i_q(t)$ are:

$$\begin{aligned} i_p(t) &= \tfrac{P_L(t)}{V_p^2(t)} v_p(t) \\ i_q(t) &= i(t)-i_p(t) \end{aligned} \qquad (3)$$

where $P_L(t)$ is the average power of $p(t)$ over the interval $[t-T_C, t]$:

$$P_L(t)=\tfrac{1}{Tc}\int_{t-Tc}^{t} p(\tau)d\tau \qquad (4)$$

and $v_p(t)$ and $V_p(t)$ are the instantaneous and rms values of the reference voltage:

$$V_P(t)=\sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} v_P^2(\tau)d\tau} \qquad (5)$$

Using this method and selecting the reference voltage to be the fundamental of the source voltage, the calculated active current will be a current that is in phase with the fundamental component of the source voltage.

2) Harmonic Compensation:

The principle for harmonic compensation is: first, calculate the fundamental current i_f from the load current i_L, then subtract i_f from the load current i_L to get the harmonic current, which is the current i_c that the compensator should provide. The system scheme is shown in Fig. 12.

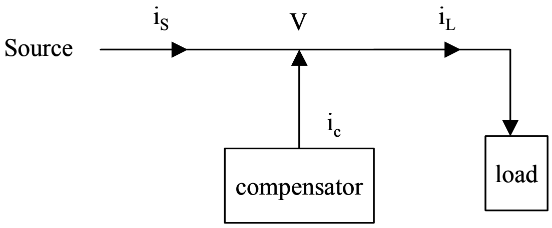

Fig. 12. Harmonic compensation schematic diagram.

Fig. 13 is the compensation result. Fig. 13(a) shows the source current i_{S1} (before compensation) and the fundamental current i_f. Obviously i_{S1} has harmonic components and does not match i_f. Fig. 13(b) shows the source current i_{S2} (after compensation) and the fundamental current i_f. Fig. 13(c) shows the calculated harmonic current i_h and the compensated harmonic current i_c. We can see that the compensated harmonic current i_c is almost exactly equal to the calculated harmonic current i_h and after compensation, the source current i_{S2} matches the fundamental current i_f very well.

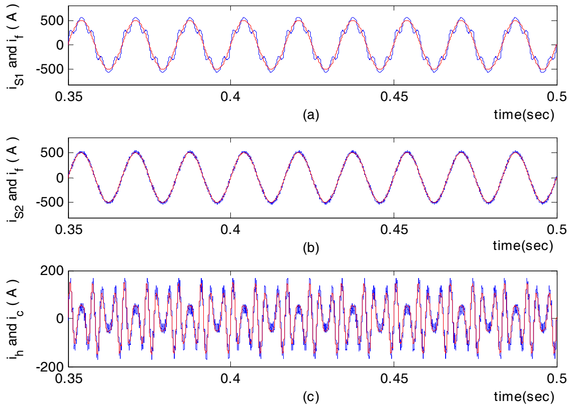

Fig. 13. Simulation results for harmonic compensation, (a) source current i_{S1} (before compensation) and the fundamental current i_f, (b) source current i_{S2} (after compensation) and the fundamental current i_f, (c) calculated harmonic current i_h and the compensated harmonic current i_c.

J. Seamless transfer

When DG transfers from stand-alone mode to grid-connection mode, or transfers from grid-connection mode to stand-alone mode, it is expected to transfer almost instantaneously, which is called seamless transfer. A good reference that contains algorithms for seamless transfer can be found in [6]. In a wider definition, seamless transfer is the ability for online generation to transition among various ancillary services without power delivery disruption.

III. BENEFITS TO GRID AND CUSTOMER

By the goal of the ancillary services, these ten types of ancillary services could be divided into those that mostly benefit the grid, those that mostly benefit the DER owner, and those that benefit both more or less equally.

A. Providing the most impact to the grid

Spinning reserve, supplemental reserve (non-spinning), and network stability provide the most impact to the grid. All three of these ancillary services aim to keep the load and supply in balance, which keeps the frequency of the utility at its normal value (60 Hz), so they are system services required for reliability and provide the most impact to the grid.

B. Providing the most impact to the DER owner

Backup supply, peak shaving, load following, and seamless transfer provide the most impact to the DER owner.

Backup supply is a service that customers would purchase to protect against forced outages at the generating units that provide their energy, or against loss of transmission between their normal supply and their load. Thus backup supply is a commercial service that supports individual transactions and provides the most impact to the DER owner.

Peak shaving is the use of generation equipment during certain peak load periods. Customers must purchase power at a higher cost during peak load periods; therefore, use of generation for peak shaving can reduce customers' operational costs. Thus, peak shaving provides the most impact to the DER owner.

Load following is the use of online generation equipment to track the changes in customer needs. This minimizes the power purchased from the utility. Thus load following provides the most impact to the DER owner.

When DER transfers from stand-alone mode to grid-connection mode, or from grid-connection to stand-alone mode, it is expected to transfer seamlessly. By providing uninterrupted service to a company's loads, seamless transfer provides the most impact to the DER owner

C. Provide the most impact to both the grid and the DER owner

Voltage control, frequency regulation, and harmonic compensation impact the grid and the DER owner more or less equally.

Voltage control regulates a bus voltage, which improves the power quality of the DER owner, but it also minimizes reactive power drawn from the grid, improving system efficiency and stability.

For frequency regulation, the goal is to maintain the rated frequency of the grid by tracking the load's demand. The DER owner is also a part of the load, so frequency regulation provides impact to both the grid and the DER owner.

Through harmonic compensation, the source avoids the need to provide harmonic current to a load with harmonic components, because it has been provided by the DER. Thus there will be no harmonic current flowing through the rest of the grid. This improves system efficiency and stability by reducing losses in the rest of the system. It may also enable the owner of a harmonic-producing load to avoid paying penalties to the utility for harmonic-producing loads that do not comply with IEEE 519, "Harmonics Control in Power Systems."

IV. ADDITIONAL CONSIDERATIONS WHEN USING DG FOR ANCILLARY SERVICES

Reliability and quality are the two most important facets of any power delivery system. In recent times, the issues involved with power quality issues and custom power solutions have generated a tremendous amount of interest among power system engineers. Since these power quality problems bring so much loss to utility users, ancillary services must be provided to solve them.

Providing ancillary services from DER will be a good solution to power quality problems, which could be seen from the following points:

- Local regulation is much more efficient with local sources, and the DER can supply precisely the level of regulation needed [7]. Here the regulation not only means the regulation of voltage, but also the regulation of frequency (network stability, load following, and frequency regulation). Therefore, DER is quite suitable to provide network stability, load following, and frequency regulation.
- For harmonic compensation and network stability, both of them require fast response ability; the DER with power electronics is quite appropriate to provide these two ancillary services.
- For backup supply and peak shaving, DER is perfect to provide them because of its proximity to the user. In fact, distributed generation applications today are primarily designated for backup and peak power shaving conditions.
- DER could be reserve to the utility, and perform other ancillary services when the utility has enough real power. Thus, there will be no waste for the resource.

There are several recommendations in support of providing ancillary services from DER:

A. Ability to interface with energy storage devices

The ability of accepting power from a storage device such as a battery or ultra capacitor will help DG to provide a large amount of active power. For some of the ancillary services, such as Voltage Sag Support and Harmonic Compensation, only reactive power is supplied, so they do not need an external energy storage device. However, if external energy storage was available, the DG could provide very high, short-duration power to start motors, which is very important in providing ancillary services such as load following and frequency regulation.

Battery energy storage (BES) and superconducting magnetic energy storage (SMES) are the most universally applicable forms of energy storage for transmission applications. Both have relatively high efficiency, few requirements for sitting, and are capable of storing energy in amounts appropriate for transmission applications. There are many other forms of energy storage, including capacitive energy storage (CES), flywheel energy storage (FES), compressed air energy storage (CAES), pumped hydro, etc., but these either have stringent site requirements (CAES and pumped hydro), are still under development for sizes suitable for transmission applications (FES), or appear to be prohibitively expensive for the energy requirements of transmission systems (CES) [8].

B. Interconnecting DGs together

This is another way instead of using external energy storage devices to produce more power to supply. DG with power electronics is not difficult to connect with each other, since most have a DC link. So by using the common DC link, DGs will act just like one DG with a higher power rating [9].

C. Use of advanced semiconductors

Some cost reductions may also be realized from advances in semiconductors. IGBTs are currently leading the market for semiconductors used in medium-level (up to 750 kVA) Power Conversion Systems. IGBT technology has wide industry support and is most likely to provide the greatest cost reduction potential for the near future [8].

Recently, silicon carbide- (SiC-) based power devices have been drawing increased attention because of their superior characteristics compared with silicon- (Si-) based power devices. A SiC-based power converter would have the benefits of reduced losses, higher efficiency, up to 2/3 reduction in the heatsink size, smaller passive components, and less susceptibility to extreme ambient heat. DG power converters would certainly benefit from utilizing SiC-power devices.

V. CONCLUSIONS

DER is gaining ground in the area of power quality improvement. Increasingly, digital loads that demand high power quality are showing up on the electrical network. A momentary outage of a few cycles that used to be of no concern can now be disastrous to digital loads such as semiconductor plants. The outage costs alone can range from thousands to millions of dollars; thus outage avoidance can make it cost-effective to install onsite generation at the load.

Unfortunately, most DER systems are not designed for uninterruptible power supply operation. The integration of power electronics, DER, and energy storage could ultimately be the answer for power quality. However, this integration will not occur until the cost of DER is lowered, along with the cost of its power electronics.

A market for unbundled services (ancillary services) would promote installation of DG where costs could not be justified based purely on real power generation.

Power electronics offer the conversion of real power to match the system voltage and frequency, but this interface could do much more. This paper describes ten types of the ancillary services, which DG with power electronics interface can provide. Of these 10 services, the feasibility, control strategy, effectiveness, and cost benefits are all analyzed for the future utility power market.

For most of the ancillary services, we only need additional software code to provide it from DG. However, external energy storage devices may enhance the DG capability to provide these ancillary services.

VI. ACKNOWLEDGMENT

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