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Extended Microgrid Using (DER) Distributed Energy Resources

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I. INTRODUCTION

The electric power industry is in the midst of a critical period in its evolution. The re-regulation of the industry has resulted in the creation of self-locating merchant generation and wholesale electric power markets that are using the transmission system in ways for which it was not designed. This had resulted in a system operation closer to its edge. The retail customers have increasingly sophisticated energy service requirements that require much higher power quality than in the past. On way to approach these issues is to focus on robustness at the networked transmission and generation system while providing reliability locally. The distribution system should focus on providing the customer with the required level of power quality. Distributed energy resource (DER) is a way to enhance the distribution system's level of power quality.

At the same time, public policies involving global climate change initiatives, reductions in CO2 and other polluting emissions, and incentives for renewable energy will continue to put pressure on the energy industry. Focus on a renewable energy future implies rethinking our use of distributed energy resources, DER, and the end use of energy. Generation include the full range of technology include technologies based on solar energy, wind, hydroelectric power, bio-fuels and the utilization of waste products as fuels. Each of these sources, collectively are referred to as renewable. Some of these renewable sources can be effective at small scale, (kW). Small scale systems also promote application at customer premises allowing for the opportunity to locally utilize the waste heat.

The realities facing future power systems that require rethinking the distribution system and the use of distributed energy resources, DER, fall into four major areas These realities require that the T&D system;

- Provide for load grow and enhanced robustness with minimal addition growth of the transmission system.
- Make greater use of renewable such as wind and photovoltaic systems.
- Increase energy efficiency and reduce pollution and greenhouse gas emissions.
- Increase the level of local reliability to insure the necessary power quality demanded by customers' loads.

Currently there are DER applications that can help alleviate some of these issues, but a comprehensive solution require integrating DER with distribution in such a way as to radically changing the way distribution and transmission are used to deliver power to the customer. The basic concept is to use DER to provide for a more robust transmission system and enhance local reliability. This can be achieved by moving load following requirements to the distribution system and design for intentional islanding within the distribution system.

II. ISSUES/REALITIES

Provide for load grow and enhanced robustness of the transmission systems with minimal addition of new lines.

It is well known that our transmission system is under greater stress every year resulting in a greater possibility for stability problems. The most basic solution to our overstress system is to build more transmission. It is also known that it is very difficult to construct new transmission lines. One way to handle load growth and enhance stability with transmission is to use the existing system in a more effective way. For example if a transmission line was loaded uniformly over a 24 hour period the total energy transmitted could more than double with increase in stability margins and robustness. This could be pushed further by assuming that all generation and transmission could operate at a fix loading 24 hours, seven days a week. Of course this neglects the fact that loads and demands for electrical energy are always changing. DER on the distribution system can be designed to meet all load following needs. The objective is to place storage and generation throughout the distribution system of such ratings and at such locations that the transmission system could be more uniformly loaded. With correct sizing and placement of DER it should be possible to have a system with less losses, more transmission capabilities, more stable markets, higher level of security and robustness with more total energy transfer without new generation or transmission.

Make greater use of renewable systems.

Currently the relatively low penetration levels of renewable systems cause few problems. As penetration becomes greater the available of wind and sun become a greater problem requiring central generation to provide the power backup. Such systems are usually intermittent sources and can cause similar stability problems found with intermittent loads such as roiling mills and arc furnaces. Central generation or distributed generation and/or storage can provide this back-up energy. In any case there is a need for reserves when there is no sun or wind. The obvious solution for high penetration levels of renewable sources is also DER on the distribution system. Without storage and/or local generation there is a technical limit to the amount of wind generation that can be added to the greater electric supply system, perhaps as much as 20% of the peak demand is possible. Because wind generation is intermittent, and because it may not occur when electricity is needed (i.e., during periods when demand for electricity is high), wind generation must be supplemented with “dispatchable” resources such as storage and local generation that fill-in when both demand for electricity is high and wind generation is low. One can now envision a system where DER and renewable sources at the same substation. The DER has a duel role; smoothing both the transmission system loading and provide a power fill-in when intermittent generation is low.

Increase energy efficiency and reduce emissions

Use of waste heat through co-generation or combined heat and power (CHP) implies an integrated energy system, which delvers both electricity and useful heat from an energy source such as natural gas. Combined heat and power or CHP, which produces both electricity and useable heat using distributed generation, can converts as much as 90 percent of it’s fuel into usable energy. This intrinsic efficiency and resulting environment improvements has enormous potential benefits to the power system. Unlike electricity, heat, usually in the form of steam or hot water, cannot be easily or economically transported long distances, so CHP systems typically provide heat for local use. Electricity is more readily transported than heat, generation of heat close to the location of the heat load will usually make more sense than generation of heat close to the distribution substation. Under present conditions, the ideal positioning of cooling-heating-and-power cogeneration is often hindered by the distribution system and its operation, whether legitimate or obstructionist. In a new distribution system such obstacle would not exist. CHP plants can be sited optimally for heat utilization. A distribution system that is integrated with DER is very *pro-* CHP. A principle example of effective use of CHP is the microgrid that is designed to allow CHP systems to be placed anywhere the waste heat can be effetely used.

Increase the level of local reliability.

Many industrial, commercial and residential customers now require a high level of quality of power do to the increase of digital systems and sophisticated controls. These customers are especially sensitive to momentary voltages sags caused by remote faults. Power quality, availably and reliability are important issues to all customers. There have been proposals to create a self-healing power system with nine-nines of reliability to meet customers’ demands. This approach is complex and costly and is not necessary if distribution and DER are well integrated. DER has the potential to increase system reliability and power quality due to the decentralization of supply. Increase in reliability levels can be obtained if DER is allowed to operate autonomously in transient conditions, namely when the distribution system operation is disturbed upstream in the grid. In addition black start functions can minimize down times and aid the bulk distribution system. Distribution systems that are designed to island loads with generation can provide the necessary high levels of power quality, availably and reliability required by the customer. One example is the microgrid concept that clusters loads with generation and can intentionally island the DER with loads.

III. BASIC CONCEPT

To realize the potential of integrating the distribution system with DER one must take a system approach which views generation, storage, protection and loads as an integral part of the distribution system. Such integration must not depend on fast, complex command and control systems. Each active component of the new distribution system must react to local information such a voltage, current and frequency to correctly change it’s operating point. This is no different than what we currently do on our T&D system. Currently generation and transmission does not use fast centralized communication for load following, response to transients or faults.

Distribution systems can effectually handle disturbances using extended microgrid concepts. These concepts require that some of the generation, storage and corresponding loads need to separate from the distribution system to isolate sensitive loads from the disturbance (and thereby maintaining service) without harming the integrity of the remaining T&D system. This difficult task is to achieve this functionality without communications and extensive custom engineering and still have high system reliability and DER placement flexibility. To achieve this we promote a peer-to-peer and plug-and-play model for each DER component including intermittent sources.

Local control without fast-centralized communication requires that each active component controls its reactive injection based on local voltage and has a power vs. frequency droop function to insure power balance when the parts of the feeders intentionally island during a disturbance.

The peer-to-peer concept also insures that there are no components, such as a master controller, generation or central storage unit that is critical for operation of a distribution feeder. For example this implies that the system can continue operating with loss of any component or generator. With one additional source (N+1) we can insure complete functionality with the loss of any source. Plug-and-play implies that a unit can be placed at any point on the distribution system without re-engineering. Plug-and-play functionality is much akin to the flexibility one has when using a home appliance. That is an appliance can be attached to the electrical system at the location where it is needed. In the new distribution system this

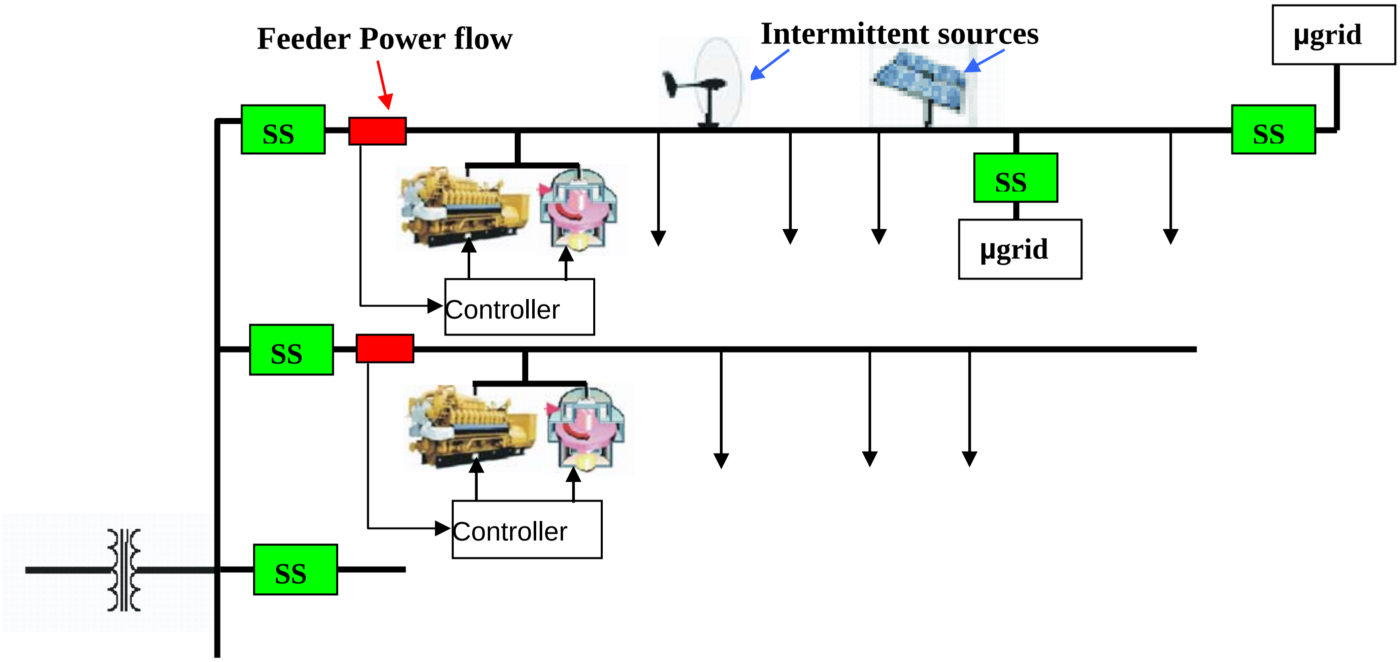

Figure1. Extended Microgrid Architecture.

implies that DER devices can be located where they are needed.

IV. EXTENDED MICROGRID ARCHITECTURE

The basic architecture is shown in Figure 1. This consists of a group of radial feeders. Each feeder at the substation has the same structure, which includes storage and distributed generation. Storage helps keep the power demand from the grid constant as the loads and renewable sources change their operating points over a day, week or season. The generator is used to assist the storage during high load times. The microgrid is included in this architecture to provide for increase energy efficient through the use of combined heat and power, (CHP) and high power quality for sensitive loads through intentional islanding. Ideally we want as much generation as possible operating in a CHP mode.

There are two critical components, the static switch, SS, and the distributed energy resource. The static switch has the ability to autonomously island the feeder(s) from disturbances such as faults, IEEE 1547 events or power quality events. After islanding, the reconnection of feeder(s) is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded feeder and the utility grid insuring a transient free operation without having to match frequency and phase angles at the connection point. Each distributed energy resource can seamlessly balance the power on the islanded portion using a power vs. frequency droop controller. This frequency droop also insures that the islanded feeder frequency is different from the grid to facilitate reconnection to the utility.

There are interesting DER sizing issues related to how we want the system to operate. For example if the storage is very large allowing for total load swings over a 24 hour period there is no need for ICE generation. Today this is not practical and generation is required to reduce the required storage capacity.

The “feeder power flow” control techniques worked out for the CERTS Microgrid are important in this application. For example the “feeder power flow”, FPF, allows for load changes down stream. For example assume the FPF is set at ½ MW. When the flow increases above ½ MW the ICE generator will increase its output to hold the flow at the set point and reduces output if the flow drops below ½ MW. If the total load becomes less that ½ MW the generator output becomes zero and cannot absorbed the extra energy. In this case the storage component will absorb the energy. This is expect during low load time like the middle of the night.

The “feeder power flow” controller is equally effective with renewable/intermittent sources. When an intermittent source changes it output the DER flow controller will change its output to hold the flow from the substation constant. This greatly reduces the utility’s concerns related to intermittent or non-disputable sources.

The microgrids, Figure 1, would be used to utilize as much of the waste heat as possible while providing local improvement in power quality. The full feeder could also provide higher power quality using the same SS functionality and DER power vs. frequency characteristics used by the microgrid. This would take advantage of the storage and ICE generation to make up for the power loss from the grid when islanding. If there was a disturbance on the substation, Fig 1, the SS would open and the islanded feeder's sources would lower frequency while increasing their power output to make up for the lost power from the substation. This frequency reduction would trigger the opening of the static switch for each microgrid resulting in multi-islands. When the substation returns to "normal" the main SS would automatically re-connect to the utility and the frequency would return to "normal". This "normal" frequency would then allow each microgrid to re-connect.

Control Configurations

There are two basic control configurations that could be applied to the cluster architecture: they are characterized by which component performs the base loading and the peak shaving. Figure 2 shows a assumed load demand over 24 hours. The feeder power flow, FPF, is set at 1.5 MW. During the night, when the flow from the grid is larger than the loading level, the storage will be charging (slanted lines area). During the daytime, either storage or generator could provide the base power (dark region area), while the other component would provide the load following (light region area).

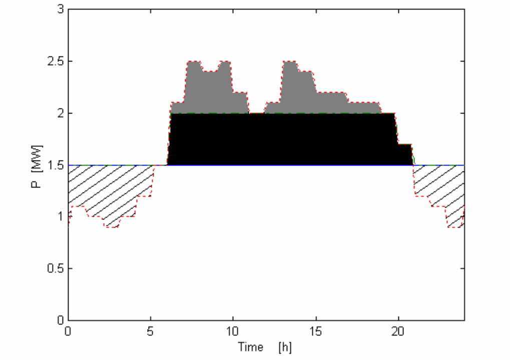

Figure 2. Load Demand Curve.

Each component (storage and generator) has a flow versus frequency droop function to allow for load following at any time during of the day. Each component also independently controls the voltage magnitude using a reactive power versus voltage droop. These concepts are derived from the concepts implemented in the CERTS Microgrid. Different operational concepts can be implemented by properly resetting the active power limits of the storage/generator, allowing either storage or generation to track load.

V. CASE STUDIES

For this case studies the load demand in Fig 2 was used. The load has a typical periodical profile with peak demand at 2.5 MW during daytime and minimum value of 1.0 MW during the night. The dispatched flow from the grid is 1.5 MW. This value is below the midpoint of the day and night excursion of the load power demand. The distributed generation has a rating of 0.5 MW, while the storage has a charging rate of 1.0 MW and a peak rating of 2.0 MW. This value could only be reached during operation in island from the main utility, since the value of power flowing from the grid normally would allow the storage to never exceed 0.5 MW.

The energy storage has also its own limits: to allow peak power output in island for an hour, the value of the energy reserve has been chosen to be 2.0 MWh. A maximum useful energy is set of 6.0 MWh. The maximum capacity is 6.5 MWh.

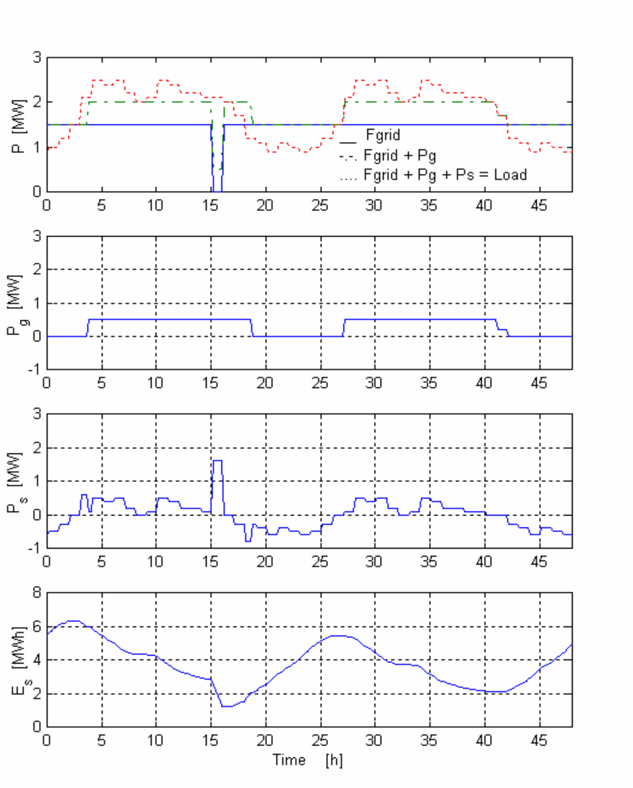

Figure 3. Generator Base Power, Island Details

Generator Base Loaded with Storage Peak Shaving

In this configuration particular choices in the controls need to be made to ensure that grid flow is hold constant, that the storage is operating within the reserve level (i.e. minimum) and maximum values of stored energy and that both components operate within their rated output power.

Figure 3 shows a two-day interval, steady state power profiles for the load, grid flow, and contributions for each component. Figure 3 also shows the output power for the generator, the storage and the amount of energy in the storage.

The flow from the grid is successfully held constant at all times. The distributed generation provides the power to the load in excess of the grid flow. As soon as the generator has reached its rated output, then the storage will provide the difference, following the profile of the load. With this choice of grid flow value and load profile, it turns out that the storage tends to charge more in the night than it discharges during the day. The consequence is that the energy in the storage would indefinitely increase. Any time that maximum limit of 6.0 MW is reached, a corrective action is taken to bring that value down, to ensure that the storage never overfills (6.5 MW). This corrective action overrides the normal behavior of the configuration, where the generator provides the base power. When the energy in the storage exceeds maximum, the generator reduce its output to allow control of the storage charge. In this Fig 3 the excursion of the energy in the storage are always above the minimum value, 2.0 MW.

Here it is possible to notice that near time t=3.5 h the load demands more power that comes from the grid. Normally the generator would provide this base power , but because the energy in the storage is above limit, the storage provides it instead, up until near time t=4.0 h when the value of the energy falls below maximum and generator start up.

At t=15.0 h the distribution system transfers to island from the main utility. The generator provides the base power, while the storage provides all power demanded by the load. At this time the loading level is 2.1 MW and the storage provides 1.6 MW, well within its peak output power capabilities. The value of the stored energy falls into the reserve level. When the system reconnects to grid (t=16.0 h) the low energy level of need to be corrective. This action requires the generator and the utility to supply some of the needed energy to charge the storage up to minimum level.

The generator is operating at peak power, supplying the load and the storage between t=16.0 and 17.0 h. Then, when the load level falls below the grid flow, the generator continues operating at peak power so that the storage is charged both by the difference from the grid and the load as well as from the generator. As soon as the energy level in the storage is increased above the reserve value (2.0 MW near t=19.0h), then only the extra power from the grid will charge the storage and the generator will shut off.

VI. CONCLUSION

The results show that it is possible to control a distributed generator coupled with storage to maintain grid flow constant at all times. Furthermore, it is possible to achieve a steady state operation with a periodic loading profile while enforcing active power limits and energy storage limits. An energy reserve for the storage is necessary to guarantee power to the loads during an islanding event. The control of the clustered pair, generator plus storage, is identical to microgrid source control, with some added constraints on the active powers. These constraints depend on the configuration that one chooses to adopt, either generator or storage performing the base loading function while the other performs the peak shaving function.

Robert H. Lasseter (F92) received the Ph.D. in Physics from the University of Pennsylvania, Philadelphia in 1971. He was a Consulting Engineer at General Electric Co. until he joined the University of Wisconsin-Madison in 1980. His research interests focus on the application of power electronics to utility systems and technical issues which arise from the restructuring of the power utility system. This work includes interfacing micro-turbines and fuel cells to the distribution grid, control of power systems through FACTS controllers, use of power electronics in distribution systems and harmonic interactions in power electronic circuits. Professor Lasseter is a Fellow of IEEE, an expert advisor to CIGRE SC14.

Paolo Piagi obtained his B.S. and M.S. in Electrical Engineering at the Polytechnic of Turin, in Italy. He received his Ph.D. in EE at the University of Wisconsin-Madison under the supervision of Professor R.H. Lasseter. Paolo developed a control for distributed resources. He then implemented his design on DSP and has been involved in testing it in a lab scale microgrid. He is currently is at Semikron Inc., Hudson, NH.