CERTS MICROGRID

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Abstract--*Application of individual distributed generators can cause as many problems as it may solve. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "microgrid". The sources can operate in parallel to the grid or can operate in island, providing UPS services. The system will disconnect from the utility during large events (i.e. faults, voltage collapses), but may also intentionally disconnect when the quality of power from the grid falls below certain standards. Utilization of waste heat from the sources will increase total efficiency, making the project more financially attractive. Field verification of the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid control concepts are included.*

Keywords: CHP, UPS, distributed generation, intentional islanding, inverters, microgrid, power vs. frequency droop, voltage droop.

I. MICROGRID CONCEPT

CERTS Microgrid has two critical components, the static switch and the microsource, [1]. The static switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid insuring a transient free operation without having to match frequency and phase angles at the connection point. Each microsource can seamlessly balance the power on the islanded microgrid using a power vs. frequency droop controller. This frequency droop also insures that the microgrid frequency is different from the grid frequency to facilitate reconnection to the utility.

To enhance reliability, a peer-to-peer and plug-and-play model is used for each component of the microgrid. The peer-to-peer concept insures that there are no components, such as a master controller or central storage unit that is critical for operation of the microgrid. This implies that the microgrid 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 electrical system without re-engineering the controls thereby reducing the chance for engineering errors. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes.

Peer-to-peer and plug-and-play concepts also impact the protection design. The peer-to-peer concept insures that there are no protection components, such as a master coordinator or communication system critical to the protection of the microgrid. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the protection thereby reducing the chance for engineering errors. This implies that microgrid protection is part of each source.

II. AEP/CERTS MICROGRID

The basic American Electric Power (AEP) test site is shown in Figure 1., [2]. The SS (static switch) separates the utility from the microsources in the microgrid. The islandable part contains two loads and two inverters based sources on one feeder and a single load and source on the parallel feeder. The two sources are in series use a four-wire cable with a common ground point. The cable between the two sources is 100yds, providing impedance to verify the plug and play feature and local stability. In Figure 1. this is identified by three protection zones, Z-2, Z-3 and Z-4. The second feeder with a single load and source is a three-wire system with an isolation transformer, (zone Z-5). The microgrid assumes that the sources have adequate ratings to meet the load demands while in island mode. Zone Z-6 remains connected to the utility in all modes. In an actual system zone Z-6 includes several feeders that will not be part of the islandable part, but are part of the microgrid and can received power for the microsources without injecting power into the utility.

This is a simple solution to the problem of load dropping in the islanding portion of the system. The island portion will always have enough generation to meet it's maximum load. The loads that exceed the generation will be on feeders (Z-6) on the utility side of the static switch. This also provides the opportunity for the islandable portion to provide UPS level power quality to its loads.

The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open first for all faults. With the static switch open, faults within the microgrid need to be cleared with techniques that do not rely on high fault currents.

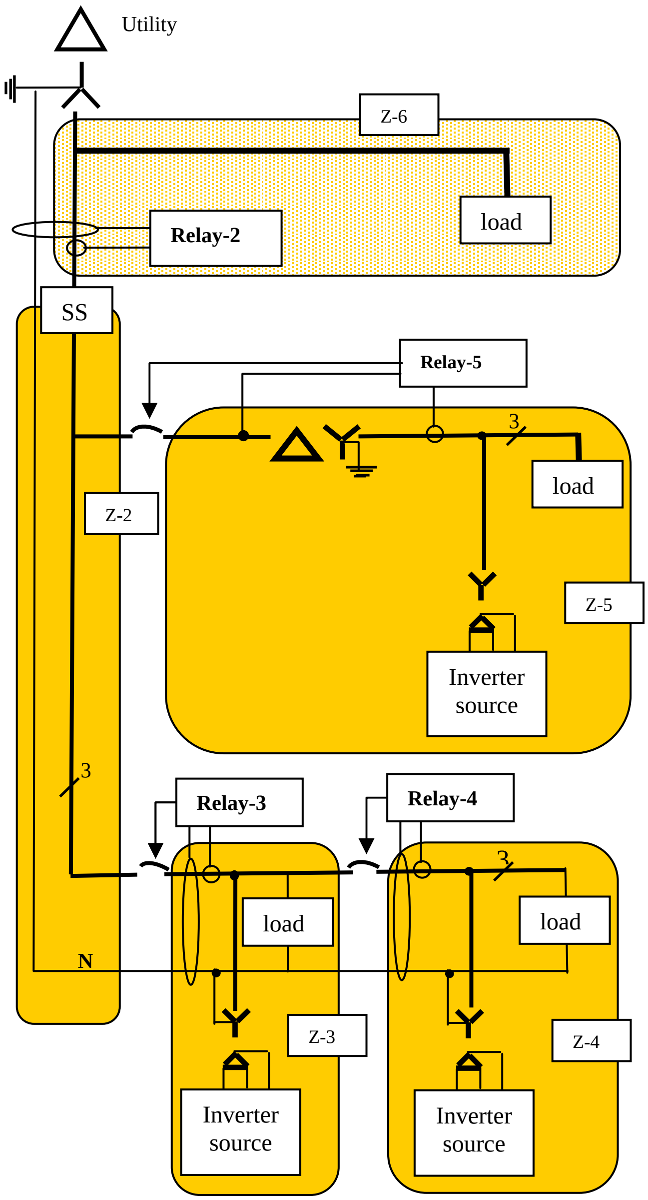

Figure 1. AEP/CERTS Microgrid.

The AEP/CERTS microgrid assume four protection zones, within the islandable portion, with shunt trip circuit breakers between Zone 2 and Zone 3, Zone 3 and Zone 4 and between Zone 2 and Zone 5. The system could be designed without these circuit breakers but the protection zones remain the same. In either case, sources feeding the fault must shut down without communications. For example, for a fault in Zone 2 we would expect the SS in Zone 2 to open in ½ to 2 cycles, the circuit breakers between Zones 2-3, 3-4 and 2-5 to open with the inverter-based sources in all zones shutting down. If the fault was in Zone 4, ideally the SS would open and the circuit breaker between Zones 3 and 4 would open but the breaker between Zones 2 and 3 would not. The source in Zone 4 would also shut down. This would result in Zone 2, Zone 3 and Zone 5 operating as an island.

Microsource

Each microsource can seamlessly balance the loads when the microgrid islands using a power vs. frequency droop controller. Stability is insured by regulating the ac voltage at it's connecting point through var control, [3]. The basic source consist of a prime mover and a power conditioning system which together provide the necessary power and voltage control required for operation of the CERTS microgrid

At the AEP site the prime mover is a 7.4 liter, naturally aspirated V-8, specially modified for natural gas, [4]. The block and exhaust manifolds are liquid cooled. Typical coolant temperatures supplied to the host facility are in the range of 185/235 F when exhaust heat recovery is used for CHP applications. Heat is recovered from an external oil cooler as well. The fuel supply, natural gas at low pressure (18 inches of water column) is combined with air in a venturi mixer upstream of the throttle and intake manifold. To maintain the precise air/fuel ratio control required for the catalyst emissions system, a closed loop feedback control system is utilized incorporating twin oxygen sensors in the exhaust system.

The generator is liquid-cooled permanent magnet type designed specifically to match the speed and power curve of the engine. Voltage and power are proportional to RPM. The cooling fluid can be combined with the main heat recovery system in some cases where temperatures are relatively low.

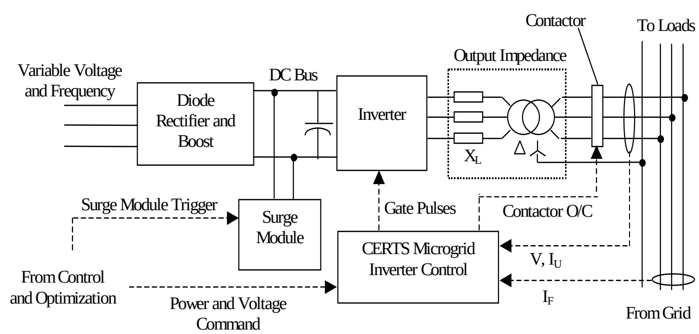

Figure 2. Tecogen's Power Condition System

The power conditioning system is shown in Figure 2. There are three fundamental stages: an AC/DC diode rectifier bridge with voltage boost, dc storage and a DC/AC inverter. Diode rectifier and boost has two tasks: the first is to convert the AC waveform into a DC voltage and the second is to increase the DC voltage to a higher level so that the inverter has extra room to be able to synthesize a voltage larger than nominal. When

the inverter injects reactive power to regulate voltage at the feeder, the magnitude of the voltage at the inverter can exceed 1 PU. To make sure that the inverter does not operate in the over modulation region, a larger DC bus voltage is used.
The dc storage can provide short bursts of power, drawing from an internal supply of stored energy. This is to insure that the inverter can provide the power required by the microgrid independent of the rate of the prime mover. Subsequent to a burst and settling to steady state, a charger ensures that the energy is slowly replenished into the batteries. For this prime mover the storage needs are small. For other prime movers, such as a micro-turbine or fuel cell the requirements could be much larger.

The inverter is a power electronic block composed of a matrix of solid state devices with high switching frequency that can convert a DC voltage into an AC voltage. The power electronic based source is inertialess: unlike a classic generator, it does not have usable energy stored in rotating masses. Another important difference from the classic generation is that inverters can at most inject 2 PU of their rated current under a bolted fault while rotating machines can provide up to 9 PU of current during faults.

Each inverter controller must autonomously respond effectively to system changes without requiring data from the loads, the static switch or other sources. The same applies to the static switch. Controls have two important droops one which controls inverter terminal voltage the other the phase of the voltage. Operating the inverter as a voltage behind an impedance results in $P \approx \delta$ and $Q \approx |V|$
Integration of large numbers of microsources into a Microgrid is not possible with basic unity power factor controls. Voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must also insure that there are no large circulating reactive currents between sources. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power, Q, generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased, [5].

When the microgrid is connected to the grid, loads receive power both from the grid and from local microsources, depending on the customer's situation. If the grid power is lost because of IEEE 1547 events, voltage droops, faults, blackouts, etc., the Microgrid can autonomously transfer to island operation.

When regulating the output power, each source has a constant negative slope droop on the P, ω plane. Figure 3 shows that the slope is chosen by allowing the frequency to drop by a given

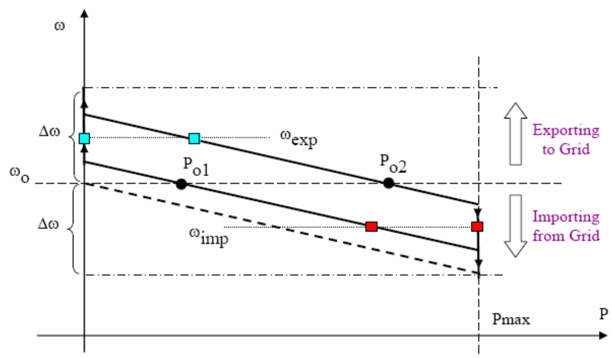

Figure 3. Steady State Power vs. Frequency Droop

amount, Δω, as the power spans from zero to Pmax, dashed line. Figure 3 also shows the power set-points Po1 and Po2 for two units. This is the amount of power injected by each source when connected to the grid, at system frequency.

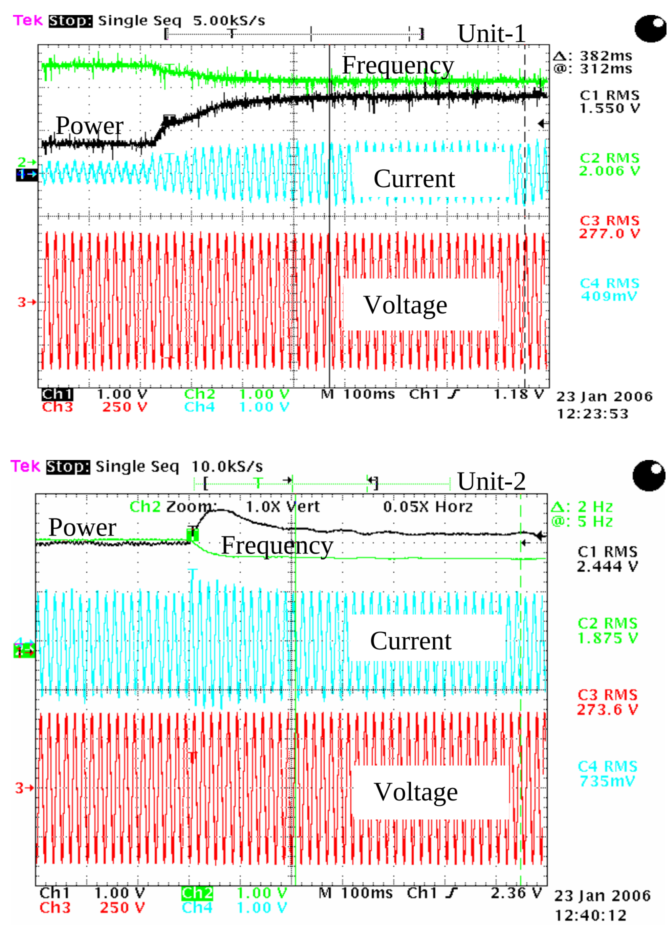

Figure 4. Islanding traces for Unit-1 and Unit-2

If the system transfers to island when importing from the grid, t the generation needs to increase power to balance power in the island. The new operating point will be at a frequency that is lower than the nominal value. In this case both sources have increased their power output with unit 2 reaching its maximum power point. If the system transfers to island when exporting power to the grid, then the new frequency will be higher, corresponding to a lower power output from the sources with unit 1 at its zero power point.

The characteristics shown on Figure 3 are steady state characteristics. They have a fixed slope in the region where the unit is operating within its power range. The slope becomes vertical as soon as any limit is reached. The droop is the locus where the steady state points are constrained to come to rest, but during dynamics the trajectory will deviate from the characteristic.

Dynamic traces are shown on Figure 4. The system transfers to island when both units are regulating output power. When connected to the grid (steady state “Po1 and Po2” in Figure 3) the system is importing power. In the new steady state after islanding both units feed the total load, (The squares in Figure 3 show the new steady state power points). Unit 2 is sitting on Pmax output, while unit 1 provides the needed load power. Figure 4 shows the actual traces of this test from both units. The active power of unit 2 overshoots maximum but then the control backs off the generation while unit 1 increases its output to meet the loads. Voltage magnitude is unchanged and the frequency drops in both machines following the event. He current traces are from the inverter.

Static Switch

The static switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events or power quality events, [6]. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid insuring a transient free operation without having to use communications to match frequency and phase angles at the connection point.

Figure 5. S & C Static Switch (from their Purewave product).

The microgrid includes loads and non-compliant microsources, making it necessary for an intelligent SS to be installed at the PCC to maintain IEEE Standard 1547 compliance at that point. This SS is an SCR-based sub-cycle switch, which is installed in the customer’s low voltage (480V) bus upstream of the desired loads to be protected. This arrangement proves to be very flexible, allowing the customer to isolate only sensitive loads and their supporting resources behind the SS with other loads residing in the low voltage bus portion are protected by traditional practices. The design of the SS is important to ensuring it is capable of operating reliably and predictably. It is capable of measuring voltage and frequency on both sides of the switch as well as current in the switch. From these measurements the SS is capable of detecting IEEE Standard 1547 non-compliances, power quality problems, faults both external and internal to the customer site, as well as reconnecting the microgrid when synchronization criteria are acceptable. The SS also incorporates various levels of intelligent control, which continuously monitors the PCC for the above conditions and operates the SS accordingly, separating the customer from the utility system if necessary.

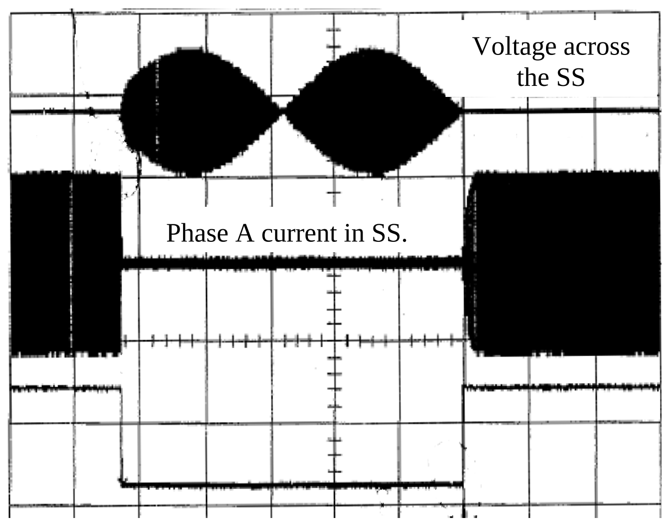

Figure 6. Static Switch Synchronization.

Figure 6 shows the re-closer of the static switch during testing at AEP. The synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid. Since the voltage phases of the utility and microgrid are changing at different rates the phases difference will see zero points insuring a transient free closing. The top trace in Figure 6, is the voltage across the static switch, which has a beat frequency proportional to the frequency difference. In this trace the point of zero phase difference are shown by the minimum points in the voltage trace. The switch is closed at the second zero phase difference point resulting in a transient free re-closer of the switch. This is shown in the phase A current through the static switch. The lower plot is the command signal, which first blocks and then unblocks the firing signals to the tryristors.

III. DETAILS OF THE CERTS TEST BED

Figure 7 is an aerial shot of the CERTS Microgrid test bed. This test bed is located at American Electric Power's Walnut site near Columbus Ohio. The trailer on the left provides weather protection for the three 60kW microsources from Tecogen. The above ground conduit provides the required distance between the microsources. The site is connected to the AEP distribution system through a step down transformer.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 7. CERTS Microgrid test bed (AEP's Walnut Site).

The four load banks shown in Figure 1. can be remotely controlled from 0-90 kW and 0-45 kVar. Each load bank also has remote fault loads which range from bolted faults to high impedance faults (60 kW and 83 kW). Other loads include an induction motor 0-20 HP, a harmonic injection using a three phase diode bridge, 0-15 kW, and a digital dc loads. The other equipment includes; protection relays, shunt trip breakers and a complete digital acquisition system.

System Tests

There are four major system tests planed: demonstration of control of load flow, microgrid operation with difficult loads and fault testing. The objective of control of load flow is to demonstrate the flexibility of the microgrid both grid connected and islanded for different loads, power flows and impact on the utility. For example there can be power flows from the islandable portion to the third feeder, Z-6, followed by an islanding event. The control algorithms can either be operated in the "unit" or "feeder" power control modes. In the unit control mode, DG output is monitored and controlled. In the feeder control mode, the power on the main circuit is monitored, and the DG output is controlled in response to circuit power flow. This control mode would be used to control the amount of power imported to that circuit from other sources, as would be the case for peak shaving. Unit and feeder flow control are described in more detail in reference, [5].

Operation with difficult loads focuses on the limits of operation of the microgrid (power quality, protection and inverter limits) with low pf loads, motor loads, harmonic loads and unbalance loads both in grid connected and islanded operation.

The protection test are to demonstrate the effectiveness of the microgrid protection concepts and the impact of faults on the utility, the sources and the loads. Understanding the sensitivities of setting and coordination is also a key part of this set of tests. This information is critical to moving protection logic from the SEL-351 relays to the inverter's DSP chips.

IV. CONCLUSION

The CERTS Microgrid test bed, hosted by American Electric Power, provides a full scale Microgrid to demonstrate the key components of the Microgrid concept. It provides a facility to demonstrate that the control algorithms developed for the Microgrid performs robustly during a variety of transient events. These events include separation from the utility power system as well as step load changes while the microgrid is islanded. The peer-to-peer and plug-and-play model is key for each component of the microgrid. The effectiveness of this model can be studied at the test site. It can demonstrate that the microgrid can continue operating with loss of any component or generator without use of a central controller or storage system.

V. ACKNOWLEDGEMENTS

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