Design and Testing of an Inverter-Based Combined Heat and Power Module for Special Application in a Microgrid

Robert A. Panora, Joseph B. Gehret, and Dr. Paolo Piagi,

Abstract-- The basic design features of a new combined heat and power (CHP) module based on a reciprocating natural gas engine with generator coupled with a high efficiency inverter interface are presented along with test results obtained in the CERTS Microgrid program. The unique inverter interface enables the engine/generator to operate over a wide RPM range maximizing fuel efficiency, reducing emissions, while providing high quality electric power. This paper will focus on the application of this system as the platform for demonstrating the advanced software developed in CERTS Microgrid project with funding support from the California Energy Commission. The unique features of this control are demonstrated, including the ability to transfer between grid-tie and isolated modes of operation without supervisory controls interconnecting the modules. Application of this system in distributed generation (DG) markets for customers desiring products to serve the dual purpose of CHP and utility back-up power are also discussed.

***Index Terms*-- Variable Speed Generator (VSG), Combined Heat and Power (CHP), Distributed Generation (DG), CERTS Microgrid Control, Power Conditioning System (PCS), Internal Combustion Engine (ICE).**

I. INTRODUCTION

The Variable Speed Generator (VSG) is an ideal candidate for applications because it takes advantage of existing and well established technologies to achieve a new model for electric power generation and distribution. The CERTS Microgrid control concepts [1] allow paralleling multiple VSG's on a peer to peer and plug and play basis. Loads can be serviced at higher power quality, with higher reliability even in the event of a grid power failure. It is possible to aim at the theoretical total efficiency of 90% taking advantage of waste heat recovery.

This article describes the operation of a Variable Speed Generator (VSG) system, giving the details of the fundamental modules that are needed for a successful system and introducing the challenges that are present when dealing with system integration and optimization. Field test results are provided to validate the design features. The conclusion will present a possible landscape for the restructuring of the way that power is generated and distributed in a modern power system.

II. THE VSG MODULE

The VSG module described here has application in the area of combined heat and power (CHP), also known as cogeneration. CHP modules are typically configured as a prime mover coupled to a three-phase electrical generator, with the added feature of on-board heat recovery. CHP modules are installed in facilities requiring significant electrical and thermal energy simultaneously. The most efficient and economically beneficial operating strategy is to operate the module while the heat is usefully applied to thermal loads within the facility. Under these conditions, approximately 90% of the chemical energy in the fuel finds useful purpose, an efficiency that is 2-3 times higher than typical utility supplied electric energy.

The common prime movers for CHP are engines and turbines fueled with natural gas, although fuel cells are applied in this market, as well. Liquid fuels can be used but are less common due to various issues of cost, transportation and storage, and exhaust emissions (in the case of diesel engines). High-quality, pipeline natural gas, on the other hand, is widely available in populated areas and can be burned cleanly in most prime movers or readily cleaned of objectionable pollutants with exhaust after-treatment (3-way catalysts or ammonia injection).

The schematic configuration for the 100 kW VSG system is provided in Figures 1 and the machine layout is provided as Figure 2[1] . As shown, the natural gas engine is directly coupled to a variable speed, three-phase generator. The power

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Robert A. Panora is with Tecogen Inc., Waltham MA, 02451 (email: robert.panora@tecogen.com.
Joseph B. Gehret is with Tecogen Inc., Waltham MA, 02451 (email: joseph.gehret@tecogen.com)
Dr. Paolo Piagi is with Youtility Inc., Hudson NH, 03051 (email: paolo.piagi@youtilityinc.com)

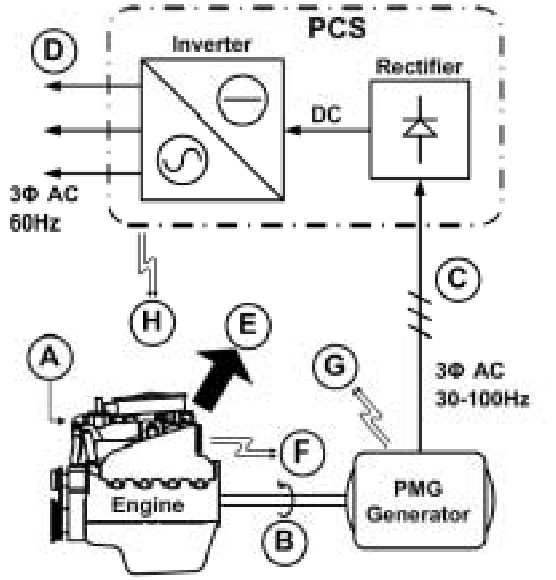
[1] The CERTS test protocol was for three 60 kW systems. As such, the units supplied were derated and simplified versions of the standard 100 kW model. The most important differences were a smaller conventional generator (75 kVA) and the exhaust heat recovery and sound enclosure eliminated, neither of which was needed in the test facility.

conditioning system (PCS) is the group of devices that performs the function of interfacing the output of the generator with the utility system. The frequency of the voltage of the generator is proportional to the speed of the engine, which is variable, depending on the operating point. The PCS takes the variable frequency voltage from the generator and converts it to a voltage at the utility frequency. This conversion requires two steps: first a rectification to DC of the generator output voltage, followed by a DC/AC conversion using an inverter. The DC intermediate state is the ideal place to locate an energy surge module that allows the system to provide a more robust response to load step changes.

Two separate controls manage the system operation. Upper level supervisory control is the function of the main controller. More specifically, it manages communication with the operator and building automation system (via MOD BUS) as well as the engine start/stop sequence, throttle motion, and emissions related devices. It also communicates to the secondary controller, whose basic function is to manage the PCS, the desired electrical output. The two controllers have various alarm functions and communicate to each other through CAN BUS protocol. The surge module is controlled by the secondary controller.

There are several important reasons for adopting the VSG approach in favor of a conventional, single-speed, engine-generator design. The first is that the VSG is an ideal platform for solving the technical challenges of controlling multiple generator sets in parallel with the grid, while also operating the same modules in parallel on an isolated circuit during a utility failure. Using conventional design methods, this problem is too complex and expensive to be practical in most sub-megawatt applications. The PCS interface and related software described herein reduces the formidable problem to a practical plug and play system; one that is ideal for small, prepackaged CHP and other inverter-based distributed generation technologies.

For an engine-generator in particular, there are other advantages to the PCS interface and variable speed drive. The inverter interface frees the engine to operate at any speed along its power band. Unlike in a fixed speed system, the controller can select the most efficient RPM for a given desired output. Speed modulation is the most efficient method of load following for a naturally-aspirated, spark-ignited, engine-generator; throttling losses can be mostly eliminated, if the engine RPM is carefully controlled to its minimal value (i.e., wide open throttle is always maintained). Also, the engine can be rated at more aggressive speeds, not being confined to fixed multiples of the electric power frequency. Operation for short duration as a peak-shaving device at elevated speeds, especially when high time-of-use tariffs are in effect, is also feasible with the VSG system.



	Energy Component	MBTU/hr	Percentage
A	Fuel Input	1,176	100.0%
B	Engine Power	(149 HP) 379	32.2%
C	Generator Power	(105 kW) 358	30.4%
D	PCS Power	(100 kW) 341	29.0%
E	Recoverable Heat	707	60.1%
F	Exhaust and Ambient Loss	90	7.7%
G	Generator Loss	21	1.8%
H	PCS Loss	17	1.4%

Fig. 1. The VSG System Concept With Estimated Heat Balance (Natural Gas Lower Heating Value Used or "LHV")

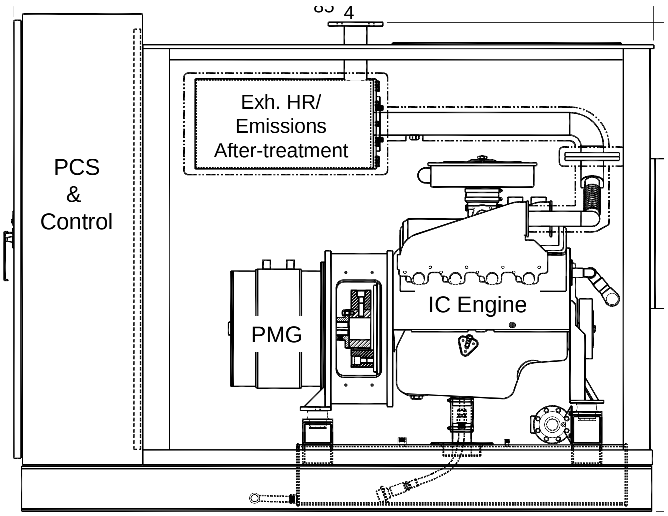


Fig. 2. The VSG System – Major Component Layout

Lastly, the inverter-based interface is generally preferred by most utilities with their relative interconnection requirements. Factory certification standards that make fast-track interconnection possible, such as UL 1547 and California's Rule 21, are only possible for inverter based machines because of the anti-islanding requirement. Utility interconnection engineers consider the lower short circuit fault-feeding capability of inverters as a significant, positive attribute in some situations, such as in congested portions of their system and in networks.

III. ENGINE/GENERATOR SYSTEM

The VSG prime mover is a 7.4 liter, naturally aspirated V-8, specially modified for natural gas. 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 added. 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 (less than 160 F).

The performance of the engine-generator is provided as Figure 3. These tests were conducted in the manufacturers test cell utilizing a resistive load bank, using a special coupling equipped with a calibrated torque meter. The PCS was not present so that its losses are not included. As shown, the RPM range for the module can be from 1000 to 3000 RPM with power output more or less proportional to speed. Full load for continuous operation (105 kW because the PCS is not included) is achieved at about 2400 RPM. Notably, both engine and generator maintain efficiencies that are nearly constant and close to their peak values. High engine part-load efficiency is maintained because throttling losses are minimized in the control strategy of maintaining the minimum RPM to achieve any given output.

Figure 3 also shows the VSG's ability to operate in an "overspeed" condition for short duration as a peak shaver. At 3000 RPM the module is able to produce about 25% in excess of its continuous rating. This rating would be applied for approximately 200 hours per year.

IV. POWER CONDITIONING SYSTEM

The components of the PCS are represented in Figure 4. There are two fundamental stages: an AC/DC diode rectifier bridge with boost and a DC/AC inverter.

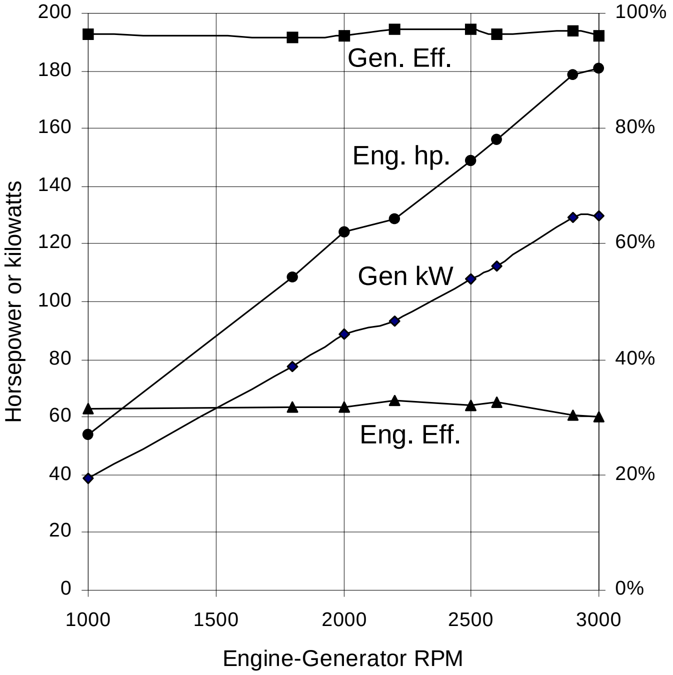


Fig. 3. Performance Curves for IC Engine and Permanent Magnet Generator as a Function of Drive Speed (Note: For Engine Efficiency Calculation the Lower Heating Value of the Natural Gas Used "LHV")

The surge module is a device that when called upon, it can provide short bursts of energy to supplement the power that is provided by the engine. During large load insertions the response of the engine may not be fast enough to support the voltage at the DC bus: the surge module would intervene and inject an amount of energy that allows the engine not to stall.

A. *Diode Rectifier and Boost*

This stage performs 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 1pu. To make sure that the inverter does not operate in the over modulation region, a larger DC bus voltage is used.

B. *Surge Module*

The surge module can provide short bursts of power, drawing from an internal supply of stored energy. In this application, the storage function is performed by batteries. Subsequent to a burst and settling to steady state, a charger ensures that the energy is slowly replenished into the batteries. The amount of energy stored in the system is very small, due

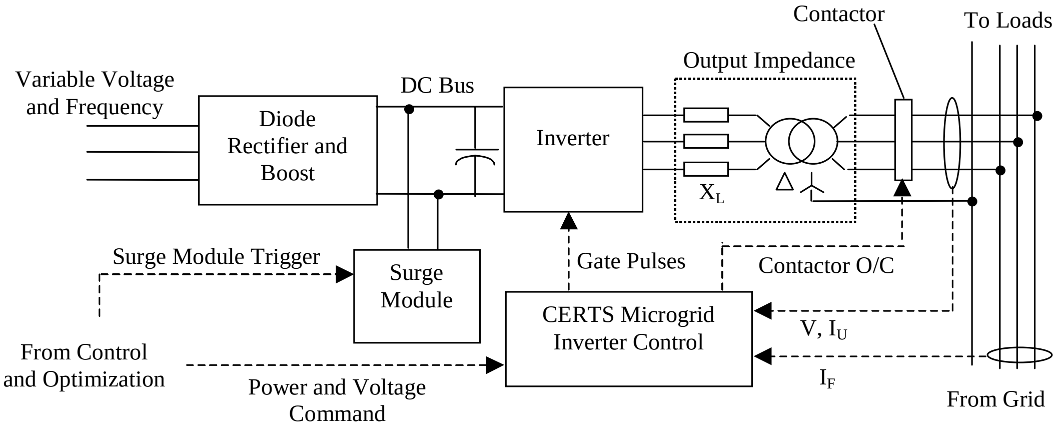


Fig. 4. Power Conditioning System Details .

to the fact that the burst of power is needed only for a short time. The surge module is required because the load demand is instantaneous, while the engine response comes with a certain delay. Due to the relatively fast time response of the ICE to load step changes, the energy required to avoid stalling is very low.

C. Inverter

The inverter is a power electronic block composed by 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 any sort of energy stored in rotating masses. The inverter control needs to be able to overcome this fact so that the VSG system can operate as a power source. Another important difference from the classic generation is that inverters can at most inject 2pu of their rated current under a bolted fault while rotating machines can provide up to 9pu of current during faults. This implies that there is a need to rethink the traditional protection system that expects high fault currents in order to maintain the capability of detecting and protecting from fault currents with such lower amplitude.

D. CERTS Microgrid Control Concepts

Under the CERTS definition, microgrid is a cluster of loads, sources and storage located on the same side of the Point Common Coupling (PCC) that is presented to the utility as a single dispatchable load [2]. In their basic operation, sources regulate the feeder bus voltage and the power injected into the system. The net power demanded from the load that is not provided by the sources is taken from the grid. When the connection with the grid fails, the sources autonomously and independently readjust their operating point to continue supplying the loads with their demands. The basic assumption is that the total generation capacity is enough to satisfy all of the critical loads in the system. A key role in the microgrid architecture is played by the static switch that connects the cluster of sources and loads with the grid [3]. The static switch is the location where the all the interconnecting standards [4] are enforced, relieving each single source behind it from the burden of having its own complex and costly interconnecting gear, therefore promoting their addition to the pool.

Units are connected to the feeder by means of a simple contactor. The voltages on either side of the contactor are compared with each other and when their phase is aligned, then a “close” signal is given and the source is added to the Microgrid.

The success of the CERTS control algorithm derives from its simplicity in achieving a multiunit cluster that operates without relying on a fast signal network between the units. To allow the units to re-dispatch power during island each of the units adopts an active power versus frequency droop, interpreting a sag in the frequency as a signal to increase output power and vice versa [5]. The control has a built-in strategy to enforce unit maximum and minimum (zero) output power. To allow the units to be installed in close electrical proximity without exchanging high reactive currents the control uses a voltage versus reactive power droop to interpret an injection of capacitive power as a signal to decrease the voltage command, and vice versa.

The CERTS control algorithm also allows operation with an alternative control mode [6], where units regulate the power coming from the feeder on the grid side to a desired value. Figure 4 shows the current sensors that measure the current IF to calculate the regulated feeder power flow.

E. Output Impedance

A crucial element of operating the unit as a voltage source inverter is the coupling inductance between the voltage source inverter and the feeder where the unit is installed. Power is regulated by synthesizing a correct phase angle for the voltage at the inverter side. The analytical formula that expresses power as function of the angle is:

$$P = \frac{VE}{X}\sin(\delta_P)$$

Here V and E are respectively the inverter and the feeder voltage magnitudes, and δ_p is the relative angle between the two voltages. Increasing the angle increases the power output. The scaling factor of this relationship is given by the inverse of the impedance. Because the angle is synthesized with a certain finite resolution (given by the switching frequency of the inverter), then it follows that the value of X must be large enough to allow a stable tracking of P despite the uncertainties in δ. A value of delta near 7^o corresponding to maximum power is chosen to identify the value for X. In Figure 4 the output impedance is given by the series of the inductor impedance, X_L, and the transformer leaking inductance.

V. SYSTEM OPTIMIZATION/INTEGRATION

The system optimization is achieved by an intelligent control that takes into account of multiple factors such as efficiency, emissions and desired customer setpoints. The control mode with the unit regulating its output power supports CHP applications: if there is demand from the heat loads then the unit will be producing electric power in an amount that the recovered heat matches the request, maximizing efficiency. In this case the grid provides the remaining quota of electric power needed for the loads. If the there is no demand from the heat loads then the system will be idle because electric power production would be uneconomical and the grid would provide all of the electric power.

The system optimization block is also responsible for sending the signal to the surge module to ensure that when a load step is larger than a certain value, a value of energy is injected into the DC bus to supplement the engine as it ramps up its output power.

The fuel valve is regulated as to maintain a desired engine speed and in turn, this speed is selected depending on the desired output power.

VI. TEST RESULTS

This section displays some of the results obtained from an industry field testing facility that is carrying out a CERTS microgrid proof of concept [7]. The site has three main feeders, two of them supply sensitive loads, the third supplies non sensitive loads. When the connection with the grid fails, power supply is only maintained on the sensitive load feeders. Because of the inherent testing nature of the site, there are plenty of metering sensors that can be triggered and data can be collected for further analysis. The facility has a total of three VSG units: this paper will present results with only one and two units. The value of the most significant parameters of the units is also given: all sources are identical.

A. System data

The unit ratings are:

Rated Voltage: 480V
Rated Electric Power: 60kW
Maximum frequency excursion during island: 0.5Hz
X ~ 10%
Engine size: 7.4 liters
Inverter Switching frequency: 5kHz
DC Bus: 880V

B. Test bed description

The results shown below are relative to a single unit testing and two units testing. Figure 5 shows the single line diagram of the circuit used to obtain the following results. This circuit is only a subset of the larger CERTS microgrid test bed present at the facility.

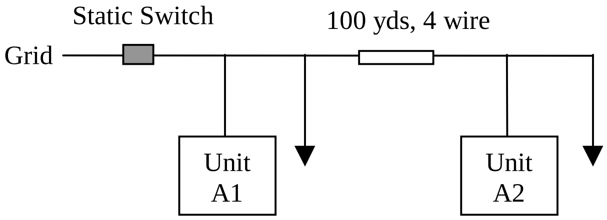


Fig. 5. Subset of Test Bed Used for these Results.

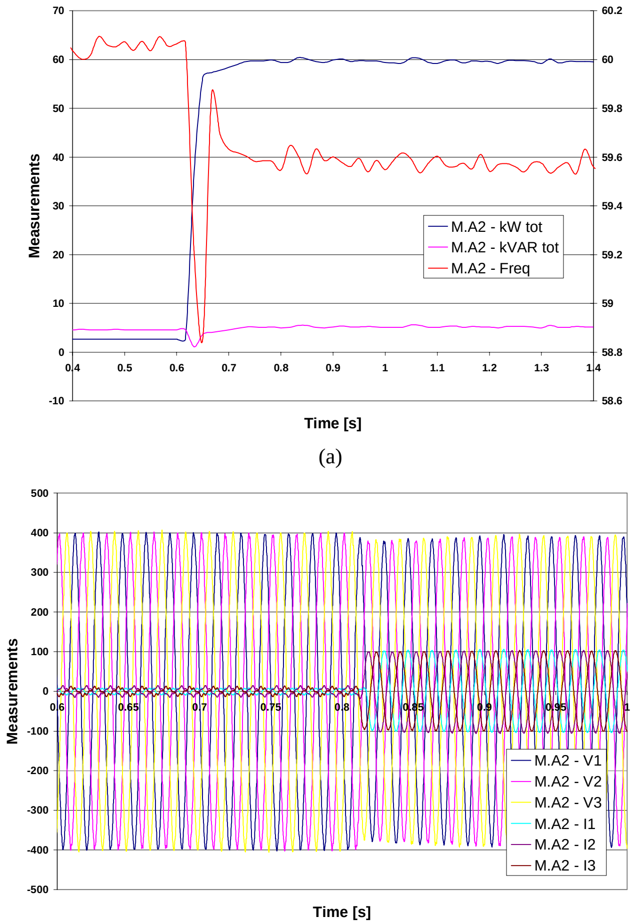
C. Traces

The traces shown in this section are relevant to a set of two tests. The first is with a single unit in island subject to a step load change, the second is with two units in grid-tie transferring to island mode.

i) Single VSG in island

In this test the unit is subjected to the worse case scenario load step change. The unit starts operating idle in stand alone, providing voltage, but with no loads connected. Then a load corresponding to the full ratings of the unit, 60kW, is suddenly connected.

Figure 6a shows the traces for active and reactive power (P and Q) and frequency, Figure 6b shows the waveforms of three phase voltages at the feeder and currents injected by the source. The units for P and Q are respectively kW and kVAR, scale on left side of the plot; the unit for the frequency is Hertz, scale on the right side of the plot. The units for voltage and current waveforms are Volts and Amperes.



(a)

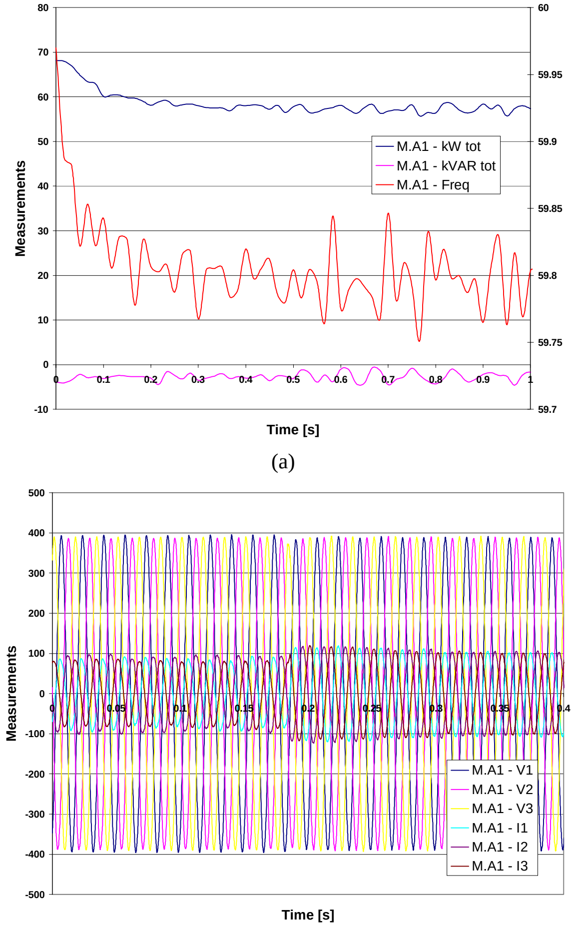
(b)

Fig. 6. Traces from Single VSG with 60kW Step Load.

The currents step up to the full value as soon as the load is inserted, the voltage regulation takes place in few cycles and the drop is hardly noticeable. The steady state voltage magnitude is lower because of the action of the reactive power versus voltage droop: as Q increased (Q>0 means the unit is supporting voltage, behaving as a capacitor) the voltage setpoint is decreased. The value of the inserted load forces the unit to output maximum rated power. The power vs frequency droop lowers the operating frequency as the power is increased. The slope of this droop is chosen so that the frequency sags at most of ½ Hz between zero and full load, that is why the sag in frequency seen in Figure 6a corresponds to that amount.

ii) Two VSGs transferring to island

This test simulates a grid failure, when the microgrid transfers to island mode. The loads are supplied with power seamlessly during the event. The units increase their output power to match the amount that was previously provided by the utility. Figure 7a and 7b show the traces of the quantities in the same order of Figure 6 relative to unit A1; Figure 8a and 8b are relative to unit A2.



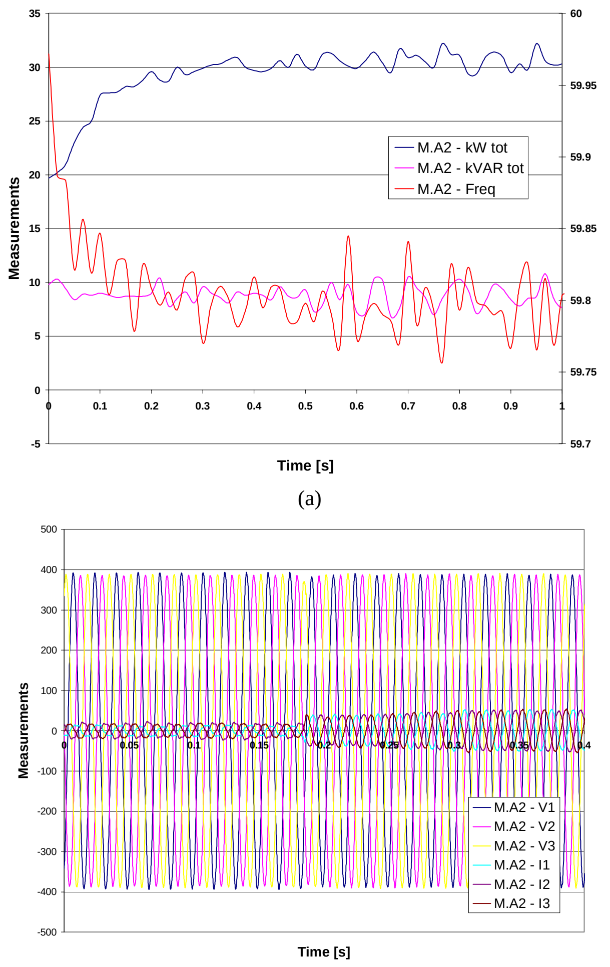
(a)

(b)

Fig. 7. Traces from Unit A1, Two VSG's, Transfer to Island.

The capture of traces in Figures 7a and 8a is triggered by the islanding event (no data available prior disconnection), while Figures 7b and 8b are in a continuous capturing mode. The unit setpoints are P1=54kW and P2=6kW: these are the amounts of power injected by the two sources during grid tie. As the system transfers to island, the power vs frequency droop will ensure that power is automatically and autonomously increased in both units to maintain the unchanged load demand of 95kW. The bus voltages are unperturbed by the loss of the grid supply: from the load standpoint it is business as usual.

Figure 9 shows the P-frequency plane: each unit has its own characteristic, with identical slope. The intersection point with the value of 60Hz determines the amount of power injected during grid tie (points A). After islanding the frequency sags and the units ramp up their power: unit A1 transiently overshoots the maximum power of 60kW (Figure 7a), forcing its frequency to lower even more: then unit A2 increases the power correspondingly until unit A1 is injecting no more that its rated output power (points B).



(a)

(b)

Fig. 8. Traces from Unit A2, Two VSG's, Transfer to Island.

Figure 9 shows that the island mode steady state value for the frequency is 59.8Hz: the same value that is seen on the experimental traces in Figures 7a and 8a.

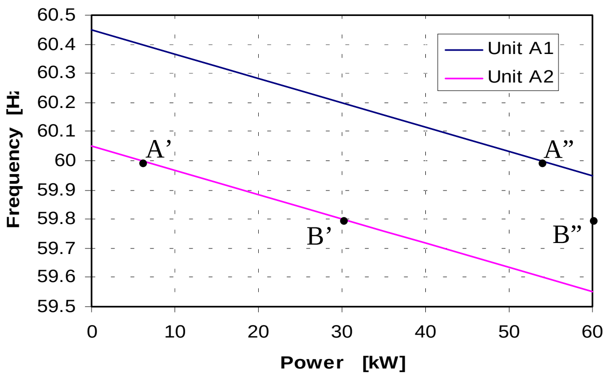


Fig. 9. Power vs Frequency Plane. Two Units Transferring to Island.

VII. Simplified Applications

The microgrid shown in Figure 4 is the most general case of the concept and would apply to any inverter system and also to those customers requiring seamless transfer and extremely demanding power quality. Simpler versions are possible, however, and are worth mentioning. Specifically, the VSG has extremely fast load response and would not generally require the surge module. Also, the transformer is not a requirement if the PCS has a 4-wire output, which is the case here. We anticipate some operators would be satisfied with a brief restart period for load shedding. This would make possible a simpler facility isolation device and allow the unit to operate in a certified mode while grid tied.

VIII. Conclusions

The power electronics generally associated with alternative, advanced distributed energy technologies (solar PV, wind power, microturbines, and fuel cells) provide unique and compelling advantages when applied to the more familiar, conventional IC natural gas powered engine-generator. In particular, the PCS interface lifts the constraint of a single, fixed operating speed as well as providing a platform for the innovative CERTS control technology. Variable speed operation, as the method of adjusting the system output, allows the maximum fuel efficiency to be maintained at all power levels and permits higher speed (and power) operation in special circumstances such as outages and for peak-shaving. The CERTS control method solves the heretofore intractable problem of providing clusters of small-scale prepackaged CHP modules that can operate in both grid-tie and during power during outages without complex and expensive controls, and without energy storage. The single VSG power module, equipped with this control architecture, can be applied in a building block fashion to many types and sizes of facilities, provide power outage security in addition to their CHP benefit.

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X. Biographies

Robert A. Panora, President and COO of Tecogen, Inc. is a 26-year Tecogen employee. The departments that report to Mr. Panora are sales/marketing, engineering, service, and manufacturing. His previous positions at Tecogen relative to gas-engine products are: Manager of Product

Development (1984-1990); Engineering Manager (1984-1990); Operations Manager (1991-1996); General Manager (1996-2000).

Mr. Panora has both BS and MS degrees in Chemical Engineering from Tufts University (1976, 1978).

Joseph B. Gehret, Jr. is Principal Engineer at Tecogen, Inc. Mr. Gehret has been employed by Tecogen for 20 years, first in the Engine Technology R&D group, and for the last eight years, with the Product Group. His primary responsibility is for advanced engineering development and design for the company. Mr. Gehret has a S.B. in Mechanical Engineering and S.M. in Nuclear Engineering, both awarded in 1984 from the Massachusetts Institute of Technology. He was inducted into both the Tau Beta Pi mechanical engineering fraternity and Alpha Nu Sigma nuclear engineering fraternity based on his academic achievement.

Paolo Piagi holds a BSEE from the Polytechnic of Turin, in Italy and received a Ph.D. in EE from the University of Wisconsin-Madison in 2005. During his doctorate he developed a control for inverter-based distributed resources and then implemented his design on DSP on a lab scale microgrid. As a post-doc researcher at the UW-Madison he was involved on the CERTS microgrid project development aspect, helping industry implement the control on a real world prototype. He joined Youtility, Inc. in 2006 as a design engineer where he is currently working on projects developing power electronic based sources to interface engine and generator systems with the utility.