Energy Storage And Conditioning System For Clean On-Site Energy Resources Supporting Grid-Interactive And Micro-Grid Operation

Leo Casey (SatCon Technology Corp., Boston, Massachusetts, USA) leo.casey@satcon.com; Janos Rajda, Colin Schauder (SatCon Power Systems)

Introduction

An increasing amount of distributed generation (DG) is being connected into the electric grid, typically comprising units of 10 MW or less, either hydrocarbon fueled or making use of renewable energy sources such as wind and solar power. This increase is driven in part by a need to strategically manage net energy costs by harnessing various different power sources, and in part by the objective of achieving a continuous power supply for critical processes, despite utility grid outages. Understandably, utilities may have viewed the advent of independent generation as an unwelcome complication. Consequently many connection standards and regulations are defensive, aimed at "protecting" the grid from independent generation by ensuring that it is rapidly disconnected during disturbances. "Anti-islanding" and "reverse power flow" regulations prohibit the use of local generation to support selected grid segments during grid outages or disturbances. As the level of installed distributed generation increases, it is important to change this mindset. Rather, distributed generation should be viewed as a valuable resource that can be used to improve the availability and quality of electric power service.

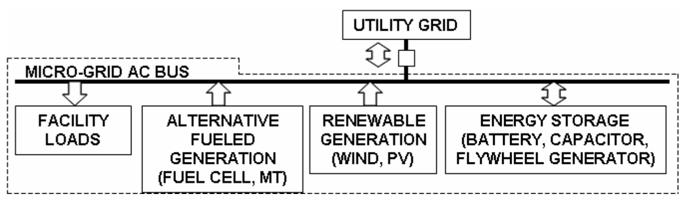

Fig.1. Grouping DG power sources with local loads enables optimum energy management when utility power is available, and independent micro-grid operation during utility outages.

When local generating capability can be grouped with corresponding local loads served by a single feeder, as illustrated in Fig. 1, the opportunity exists for an energy management scheme to be applied to the local grid segment. This situation might presently exist in a facility such as a hospital, a data center, or an industrial complex, where some level of local or emergency generation is often provided. In a future scenario, grid segments including groupings of loads with renewable or other local generation might be planned and organized by the utilities. The power drawn from the utility by such a micro-grid can be optimally regulated including time shifting of the total load to achieve such features as peak shaving, and continuity of power to local loads can be ensured, even during utility grid outages.

This paper addresses the scenario of a facility where there may be any combination of existing grid-connected Photovoltaic Array (PV), Fuel Cell (FC), or Wind Turbine (WT) based generating plants and emergency engine-generators, as well as variable on-site facility loads. Specifically, the facility owner may have installed the generators to offset utility power costs, only to discover that there is no way to keep the facility load running on local generation during outages of the main power grid. Thus the desired objective, examined here, is to convert such a facility into a self-reliant micro-grid, capable of running in either utility-grid-connected mode or, independent of the utility grid, in stand-alone (or "island") mode.

Micro-Grid Requirements

A micro-grid is a grouping of interconnected power generators and local loads that is capable of operating independently when disconnected from the main utility power grid. For this to be possible, the total instantaneously available local power generation available to the micro-grid at any time must equal the maximum peak (real and reactive) power that can be drawn by the local loads. Furthermore, it must be possible to drop the total generated power (to zero if necessary) following sudden load rejections. Unless this load-following power balance is continuously maintained, it will be impossible to maintain the micro-grid ac bus voltage and/or frequency at the specified values.

Note that these power balance rules apply equally well to the utility power grid. The difference lies in the vast combined inertia of the generators connected to the utility grid, which allows it to act as a quasi-infinite power source or sink, so that local load fluctuations are easily accommodated without a frequency change. In the micro-grid, however, most power generators will only be able to absorb power transiently, if at all, and many alternative power sources (both fueled and renewable) are basically incapable of following the load. In many cases, it will not be possible to avoid situations where the actual generation exceeds the present load, or where the available generation is less than the transient requirements of the load (for example, during motor starting, or when sufficient PV output power is not available). It follows that an additional AC-Coupled Energy Storage System (ACCESS) will be needed as an essential part of the envisaged micro-grid. The basic function of the proposed ACCESS will be to emulate the utility grid when the micro-grid is operating in stand-alone mode. Thus the ACCESS will define the ac voltage and frequency of the micro-grid, while sourcing or sinking power as needed to maintain the necessary power balance. Through its electronic controls, the ACCESS will have infinite equivalent "inertia" within its rated operating range, so that the frequency can be maintained with high accuracy. In addition to exchanging real power with its energy store, the ACCESS will also (electronically) generate reactive power as needed to regulate the micro-grid voltage accurately. With the ACCESS operating as envisaged, the various other power generators connected to the micro-grid will continue running, *as if the utility grid were still connected*. This approach offers the clear advantage that it requires *no modification to the controls* of these existing units.

When the utility is connected to the micro-grid, the ACCESS is no longer needed to define the frequency of the micro-grid ac bus. It can therefore operate like the other generators, sinking or sourcing power as commanded, to charge its energy store, to reduce the total load reflected to the utility, or to provide reactive power for voltage regulation.

ACCESS Design

Energy storage devices commonly exchange energy through dc power input and output. A static power converter is needed to couple a dc storage device to the micro-grid ac bus. Figures 2a and 2b illustrate the typical elements for single-stage and two-stage conversion, respectively.

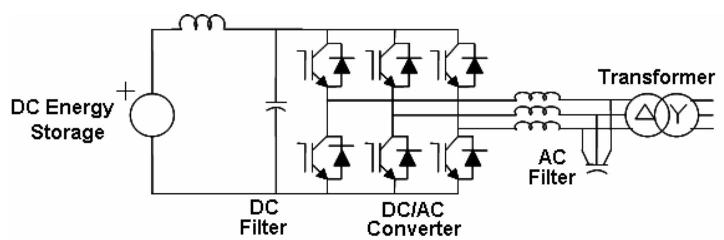

Fig. 2a. Single-stage power conversion - Energy storage device determines DC filter voltage

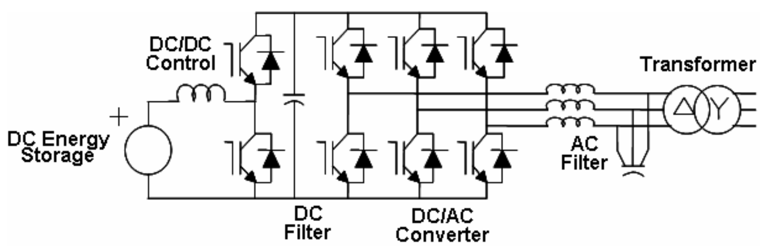

Fig. 2b. Two-stage power conversion - Converter control determines DC filter voltage

Converter power rating and energy storage capacity are the two main considerations in the design of the ACCESS. Once these factors are determined, they can be used together with the specified load/time profile, to determine the most suitable energy storage device for the application.

An accurate assessment of the expected micro-grid load profile is the essential starting point. This should include worst-case transient scenarios, such as simultaneous motor starting if this is allowed. It should also distinguish between real and reactive power requirement. At a very early stage it may be realized that it will be necessary to modify the micro-grid load profile by selective load-shedding or motor-starting restrictions while in stand-alone mode.

The next step is to assess the generation which will be available to the micro-grid. This is not a straightforward process because of the different constraints which will typically apply to various types of generation. There may be defined startup delays for emergency engine-generators that are normally out of service, restrictions on change of output power (e.g. FC), or the possibility of no power at all from certain sources (e.g. PV or WT). Ideally, the total generation available under moderately favorable steady-state conditions would be sufficient to supply the average load continuously. Clearly this involves strategic choices which will depend on the application.

Once the load profile and the characteristics of the generation are established, the ACCESS power rating can be determined. The magnitude of the peak instantaneous power essentially determines the rating of the power electronics, regardless of the direction of power flow. In principle, to arrive at this rating, it is simply necessary to determine the maximum instantaneous kVA discrepancy that could exist between the generation and the load. This will be the required kVA rating of the ACCESS.

The energy storage capacity of the ACCESS is more difficult. Essentially the required stored energy (in stand-alone operation) will be the integral over time of the real power discrepancy between the generation and the load. The initial condition will depend on whether or not the storage was fully charged at the time of separation from the utility grid (once again, this is a strategic choice). There are clearly many possibilities in this regard, so it is difficult to generalize. However, the possibilities can be broadly separated into two groups, namely short-term and long-term storage.

Short-term storage would provide transient power corrections (e.g. lasting for seconds rather than minutes) in a micro-grid where there is adequate continuous generation but the generators are not nimble enough to follow load changes instantaneously. In this case the micro-grid could operate indefinitely, with the average real power drawn from the ACCESS equal to zero. Suitable short-term energy storage devices include ultra-capacitors and flywheel/generators.

Long-term storage would apply where there may be a net shortage of generation. In this case, the storage would be fully charged when utility grid power is available, and would then steadily discharge when the micro-grid operates in stand-alone mode. Depending on the storage technology and the installed capacity, the micro-grid may be supported for minutes or hours, providing a ride-through capability until the utility grid is restored. Batteries, including flow-batteries, are presently the most promising long-term energy storage devices.

Energy Storage Considerations for the ACCESS

Key performance metrics of the energy storage system include response time, charge/discharge limitations, total deep discharge cycles, environmental considerations, initial and operating cost and the like. While lead acid batteries continue to dominate the stationary UPS business, NiCd, NiMH and Lithium-ion batteries are seeing increasing use in Utility storage applications that are similar in nature to the ACCESS. Increasing volume for these batteries in the HEV business promises ever greater performance and life at reduced cost. Flywheels meanwhile offer very long life and very high deep discharge cycles, but will face ever increasing price pressures from the newer power battery technologies.

Utility Grid Inter-Tie

In the preceding discussion we have assumed that the micro-grid will be capable of "grid-interactive" operation in conjunction with the utility grid. This implies that the micro-grid is served by a (single) utility feeder, with an inline circuit-breaker. Considering the expected total power levels for a typical micro-grid, the utility feeder will almost certainly be at MV potential, with a step-down transformer to normal 480 or 600 VAC low voltage distribution levels within the micro-grid. This utility-grid to micro-grid inter-tie is a very important aspect of the micro-grid design. Specifically, it is important to ensure that faults and disturbances in the utility grid do not disrupt the operation of the micro-grid. Considering that a mechanical circuit breaker typically takes five cycles to open, we can rapidly conclude that such a breaker will in most cases be inadequate, and that a much faster, electronically controlled breaker or static disconnect switch is actually required.

A thyristor-based, MV, static disconnect switch (MV SDS) is a good match for this application. The opening of the MV SDS can be initiated very rapidly by inhibiting the thyristor gating after the MV SDS control logic/ protection relay function determines that the utility voltage is outside normal tolerance. Thereafter, the thyristor valves extinguish naturally on the next current zero-crossing, which may be forced to occur very rapidly in the case where the instantaneous difference between the micro-grid voltage and the utility voltage is favorably disposed. In most cases, the separation from the grid can be accomplished in a half-cycle or less. Given this capability, the effect of utility disturbances on the micro-grid voltage can be kept within the industry standard

ITIC (or former CBEMA) guidelines, and existing power generators and sensitive loads within the micro-grid should ride through the utility grid faults and continue to operate as normal, provided that the ACCESS assumes the duty of maintaining the micro-grid voltage after separation from the utility. There will be a power loss in the MV static switch due to forward voltage drop in the semiconductors, but this is much lower in the case of thyristors than it would be with other types of semiconductor switching device. Furthermore, the thyristor valves provide sufficient current surge capability to handle the large currents which might occur following faults on either the utility or the micro-grid.

Although rapid separation from the utility is a primary concern, it is important to also mention the procedure for reconnection when the utility grid is restored. In general the phase of the micro-grid voltage will be different from that of the utility voltage at this time. This means that the MV static switch must be equipped to block double nominal voltage. Once the MV SDS control logic determines that the grid voltage is within tolerance again, the ACCESS will slowly bring the micro-grid into synchronism with the utility, at which point the MV SDS gating can be resumed, and the ACCESS can revert to isochronous operation.

Control Concepts

The micro-grid concept which has been described here is somewhat different from the prevailing concept which has been developed through the efforts of CERTS [1, 2]. In order to fully explain the differences as well as the reasons for proposing this different approach, it is necessary to provide some background on the control of generators.

Conventional engine-generator sets are traditionally equipped with governors that offer either "frequency droop" or "isochronous" operating modes. Connected to a utility grid, each generator operates in an isochronous mode, with constant frequency (set by the grid), and responding to a scheduled power output command. Separated from the grid, however, a group of engine-generators would use frequency (and voltage) droop to ensure equitable sharing of the real (and reactive) load power. In this case, the frequency changes slightly as the generators follow the variable load. A group of interconnected generators is also generally subject to "transient stability" concerns. Transient stability problems occur because the generators have finite rotational inertia and limited damping so that the phase angles of their induced voltages tend to swing following load transients. This leads to power oscillations between the generators which can ultimately cause loss of synchronism.

In contrast, existing PV, FC, or WT generators commonly operate only in grid-connected (isochronous) mode. They act as current sources, and must usually be shut down during grid outages when the local voltage is no longer supported. Furthermore, the output power from PV and WT generators fluctuates unpredictably and cannot be scheduled, while FC generation <u>can</u> be scheduled but must be maintained at substantially constant power levels for long periods. Typically this type of inverter-based generator is not subject to any transient stability concerns, since the output is fixed in phase relative to the ac bus voltage.

According to the CERTS approach, it would be desirable for all generators in the micro-grid to be autonomous, thereby limiting the need for inter-communication and central controls, and minimizing the effect of single unit failure. To achieve this, all generators would be required to operate under a droop control which emulates the engine-generator behavior described above. In essence, each generator would be controlled as a voltage source, subject to a frequency versus power characteristic with dynamics determined electronically rather than electro-mechanically.

While the CERTS approach may be feasible or even desirable in certain new applications, it appears to have certain shortcomings, especially with regard to retrofitting existing installations, which is the focus of this paper. First and most importantly, existing inverter-based alternative power generation does not typically have the built-in capability to operate as a voltage source in a droop mode. Secondly, the droop approach means that all connected generators will carry their fair share of the total load. This implies that all connected generators should be capable of load following, but as we have discussed, this is not generally possible with many forms of alternative generation (e.g. PV, FC, WT). Finally, a group of inverter-based generators operating under the prescribed droop algorithms will still be subject to transient stability concerns, since the droop algorithm must still include a transfer function between power and frequency that is analogous to the effect of inertia in a rotating machine.

The approach proposed here obviates all of the problems described above. It presents the idea that an energy storage function is an essential part of the envisaged type of micro-grid, and offers the addition of an ACCESS as the most practical solution. With the ACCESS acting as a surrogate utility grid, all other connected generation is free to operate in the mode that was originally intended. While the ACCESS is admittedly a significant additional cost, it does provide considerable benefit, and in many cases it will be the only viable technical solution.

Case Studies

Figure 3 illustrates a micro-grid of the type discussed here. There is sufficient existing fuel cell capability to supply the 2.2 MW critical facility loads continuously, although it may not always run at full capacity. This is supplemented by output from a PV array whenever available. For the case study we assume the installation of a new ACCESS on the 480 V bus, and a MV SDS in the utility feeder.

Simulated waveforms have been generated to illustrate the behavior of this system. In Fig. 4, a three-phase fault on the utility 21 kV feeder is shown. In this case the PV is out of service, and the fuel cell is generating 1.5 MW. Initially the utility is connected to the micro-grid and there is a constant facility-load of 2.2MVA 0.8 p.f. on the 21 kV bus. The ACCESS is initially charging, while using generated reactive power to regulate the 480V bus voltage. In this case, when the fault starts, the separation from the utility is extremely fast, because SDS thyristor gating is rapidly disabled and residual feeder current is forced to zero by the favorable voltage polarity. In other cases the separation may take longer (typically half a cycle), during which time the micro-grid voltage will deviate from normal. The fuel cell continues to generate 1.5 MW throughout the event. While separated from the utility, the ACCESS discharges in order to maintain the real power balance, and it supplies reactive power to regulate the 480V bus. After reconnection to the utility, the ACCESS returns to the charging mode.

In Fig. 5, load steps on the micro-grid 21 kV bus are shown. In this case, the micro-grid is in stand-alone mode, the PV is again out of service, and the initial load on the 21 kV bus is 1.1 MVA 0.8 p.f. A mechanical circuit breaker is closed to add another 1.1 MVA 0.8 p.f. load, then shortly afterwards the breaker is opened again. The ACCESS is initially absorbing the excess power from the fuel cell, while supplying reactive power to the load. When the load increases, the ACCESS supplies the shortfall in real power from the fuel cell, as well as the reactive power needed.

Conclusion

The addition of separate, AC-coupled energy storage, together with a fast-acting MV SDS has been proposed to convert facilities with existing DG resources into fully-fledged, grid-interactive micro-grids with stand-alone operating capability. The presented simulation cases have shown the viability of using the proposed ACCESS to serve the micro-grid as a surrogate utility grid. Given the need for energy storage in the micro-grid, the use of a separate ACCESS is thought to be preferable to alternative approaches, where additional energy storage might be retro-fitted on the DC side of existing power converters.

References

[1] Lasseter, R.H., et al., "The CERTS Microgrid Concept," White paper for Transmission Reliability Program, Office of Power Technologies, U.S. Department of Energy, April 2002.

[2] Piagi, P., and Lasseter, R.H., "Autonomous Control of Microgrids," IEEE PES meeting, Montreal, June 2006.

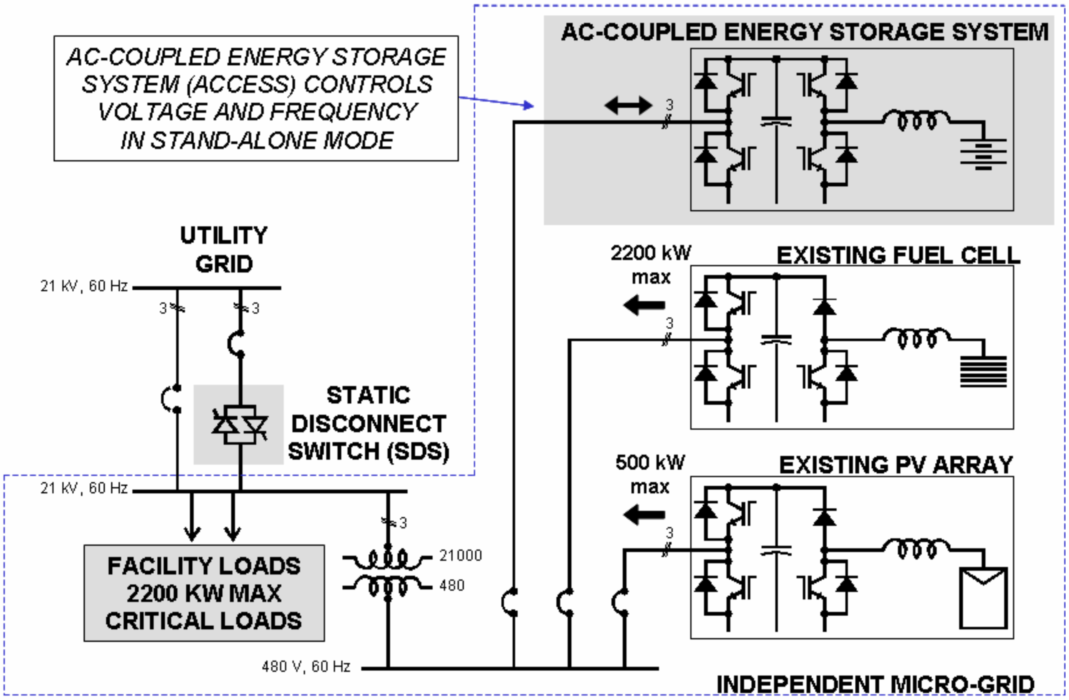

Figure 3: Adding a fast static disconnect switch (SDS) and an ACCESS allows existing DG units to support local micro-grid loads in stand-alone mode.

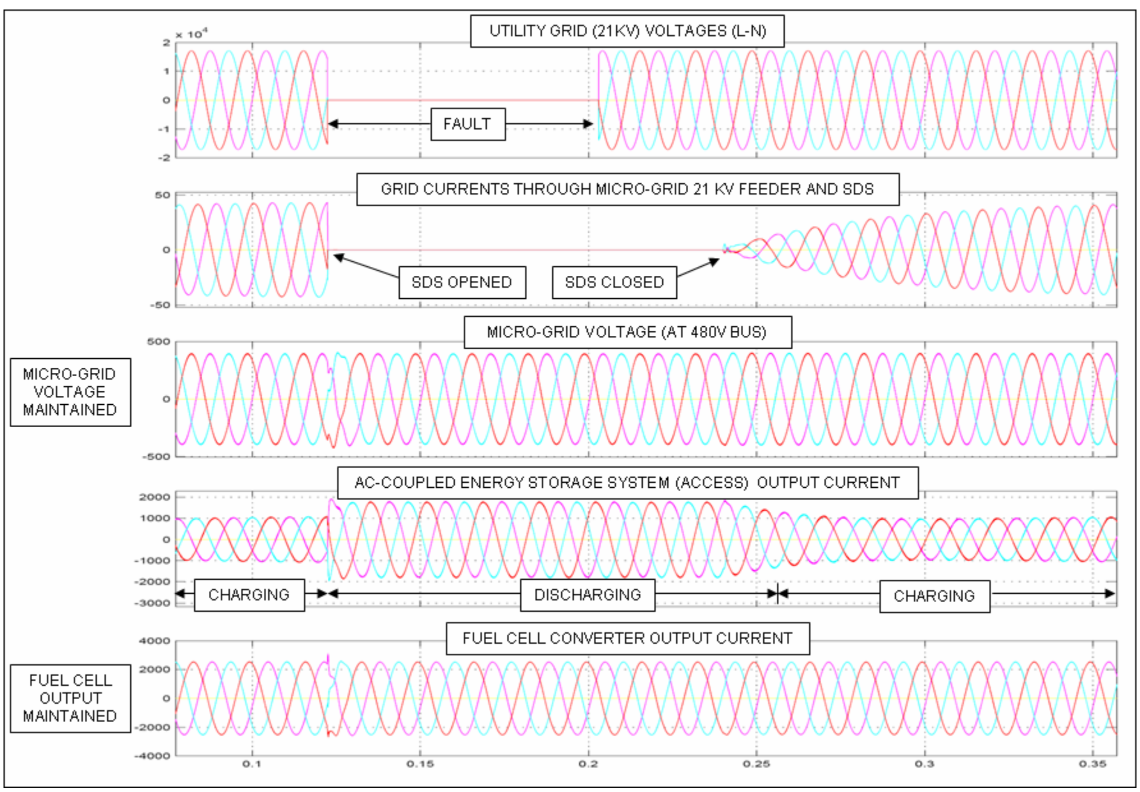

Figure 4: Simulated 3-phase fault on utility grid in system of Fig. 3. Constant facility load (2.2 MVA, 0.8 p.f.) on micro-grid 21kV bus. Fuel Cell and ACCESS are operational on the 480 V bus (no PV output).

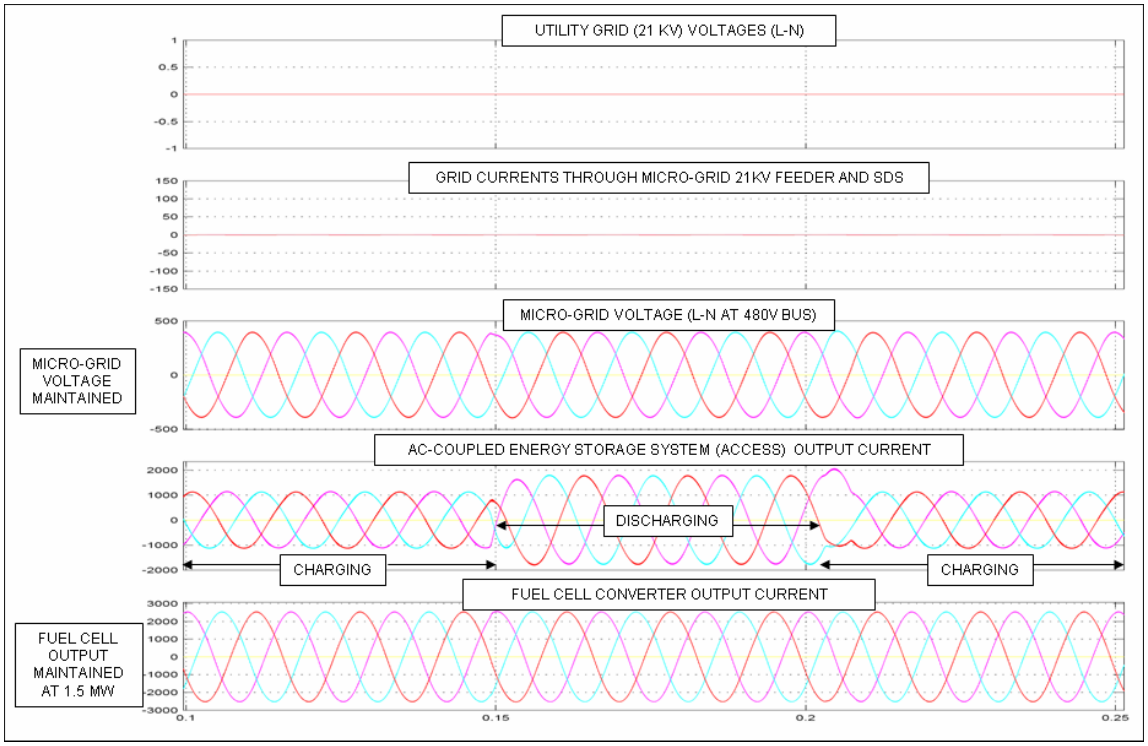

Figure 5: Simulated load steps on micro-grid in stand-alone mode. System of Fig. 3, with facility load on micro-grid 21kV bus stepped from 1.1 MVA, 0.8 p.f. to 2.2 MVA 0.8 p.f. and back again. Fuel Cell (1.5 MW constant output) and ACCESS are operational on the 480 V bus (no PV output).