Compatibility Study of Fuel Cell Protective Relaying and the Local Distribution System

R. H. Staunton, J. B. Berry, and C. A. Dunn

Abstract–The goal of this study was to characterize the compatibility between the protective relaying system of a fully-commercialized, 200-kW fuel cell and the local electric power system. This study was motivated by the fact that, for several reasons, distribution utility engineers are uncomfortable with the "synthesized" protective relaying and hardware that is generally provided in distributed generation (DG) systems. This study collected power grid disturbance electrical data and event-related, building-load electrical data over a period of 6 months. The study dealt with a larger-than-expected number of interruptions to grid-connect power generation. Problems relating primarily to load tracking and also to low power factor, complex load balance dynamics, and possible harmonic-distortion-induced instrumentation error produced some valuable conclusions and several recommendations that would be useful for companies interested in installing a grid-connected DG system.

I. INTRODUCTION

This study considered the safety and protective relaying system of a fully commercialized fuel cell power plant, which uses "synthesized" protective relays (digital control circuitry rather than conventional relays). The project's goal was to characterize the compatibility between the fuel cell's interconnection protection system and the local electric power system (EPS) or power grid. The Oak Ridge National Laboratory (ORNL), with assistance from the EPRI-PEAC Corporation in Knoxville, Tennessee, monitored and characterized the system compatibility over a period of 6 months and issued a technical report [1] with recommendations.

The Model PC25C, 200-kW, phosphoric acid fuel cell was produced by International Fuel Cells (IFC), a United Technologies Company. Hundreds of these fuel cells have been delivered to locations around the world (see http://www.dodfuelcell.com). The near-zero-emissions unit uses natural gas to produce hydrogen (H_2) in an internal reformer; and the H_2 and oxygen (O_2) chemically react in a catalyst to produce clean, high-quality electric power at an electrical efficiency of 37%. The system is advertised to have a combined electric/thermal efficiency of ~60%. This fuel cell was installed at the National Transportation Research Center (NTRC), an ORNL facility (see Figure 1), where it provides electrical power to a number of offices and experimental laboratories where engine research is conducted.

There are circumstances when EPS engineers may lack confidence in the protective relaying and hardware used in DG systems. This may be the case when the protective relaying circuitry (1) comes from sources other than those that normally supply their instrumentation, (2) relies on digital circuitry rather than conventional relays, (3) is difficult to test and validate, and (4) can be changed by the vendor at any time. Thus, at a minimum, EPS engineers will install a reverse power relay (RPR) at DG sites to ensure that the integrity of the power grid safety and protective relaying systems is preserved.

Fig. 1. Fuel Cell Installation at ORNL

The study includes an evaluation of the effectiveness of the fuel cell's synthesized relay protection scheme relative to the IEEE 1547-2003 interconnection standard [2]. Although the full implications of the new standard will only be understood over time, the relay protection scheme for this system cannot help but fully satisfy its intents since it is designed to very rapidly place the fuel cell in the idle mode when EPS anomalies are detected. The conservative design approach makes the fuel cell transparent to the EPS during EPS anomalies.

The findings of the study should serve to reduce the number of unknowns pertaining to unconventional protective circuits, to the benefit of DG manufacturers, vendors, prospective and current users of DG, and electricity suppliers/distributors.

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II. SYSTEM DESIGN AND CONFIGURATION

The project collected power grid disturbance [3] electrical data and event-related, building-load electrical data from July 2003 until the end of December 2003. The primary sources of data were a data logger for the building load and a Schweitzer Engineering Laboratories (SEL) Model SEL-351A [4] relay at the building line transformer that was part of the RPR system installed by the EPS provider. Between these two locations, the fuel cell injected real power and, in the second half of the study, modest levels of reactive load compensation in addition to real power. The event history log contained in the fuel cell also provided valuable information.

Throughout the study, load tracking was not operable; hence, the power output level from the fuel cell was essentially fixed. There were numerous times when the chiller for the NTRC shut down and/or other building loads were low enough that the total load fell below the fixed fuel cell output power level setting, resulting in episodes of reverse power flow into the EPS beyond allowed limits[2]. This caused trips of the RPR.

The 480-Vac, 200-kW fuel cell provides constant-level power as selected (e.g., 180 kW) in parallel with, and synchronized to, the power grid. The system is capable of providing up to 125 kVAR of reactive power correction; however, this decreases proportionally with the power generation level. The fuel cell is designed to track the building load at a maximum rate of 20 kW/sec using a power dispatch signal (4–20 mA) from either a building power monitor that has analog output channels for general control functions or a watt transducer.

This analog control signal for load tracking proved to be very elusive during the study for many and varied reasons. There were administrative reasons related to the fact that the building power monitor was the property of the building owners (the building was leased). Other reasons included, cryptic messages on the fuel cell control software that hid the fact that the load tracking system was not activated, underestimation of need for load tracking, electrical storm damage to the building power monitor, use of volatile memory in the power monitor, a second latent and gradual degradation/failure of the power monitor, lack of program resources, and limited alternatives for replacing the power monitor. A number of lessons learned resulted from these experiences and are included in the recommendations of the study.

The protective relaying functions included in the PC25C fuel cell include power demand not met, loss of synchronization, kVA limiting, undervoltage, overvoltage, grid voltage imbalance, abnormal frequency, excessive interrupts, overcurrent, timed overcurrent, and thermal/magnetic overcurrent trip [5]. The functions are all equivalent to ANSI C37.2. The number and types of safety and protective relays are far more extensive than those in the EPS provider’s substation for outgoing feeders. When any one of the protective devices that signal for a disconnect send a permissive signal to the control system, it begins a rapid, two-stage process. The first stage shuts down the inverter for 0.5 sec. If the permissive goes away, a return to normal grid-connect state results; however, if the permissive remains, the fuel cell disconnects from the EPS.

A battery-powered uninterruptible power supply (UPS) is provided in the fuel cell to supply power to control circuitry during certain switching operations and grid outages when control power is briefly interrupted. The UPS has a rating of one hour.

As long as the EPS is energized, fuel cell interruptions do not cause the building occupants to suffer a loss of power, aside from possibly the brief EPS voltage variation itself. This is an important advantage of parallel operation in the grid-connected operating mode. If the EPS returns to normal after the fuel cell is forced into the idle mode, resynchronization and reconnection takes place based on a user-selected protocol plan.

III. INTERACTION OF POWER SYSTEM DYNAMICS

In order to understand many of the interruption events, it is important to understand the interaction of the sources of real and reactive power and power factor (PF) at the line transformer and in the building. The fuel cell provides primarily real power, although a small amount of reactive power can be produced for partial correction of PF. At the site used in this study, PF levels were frequently poor (i.e., below 0.8).

Figure 2 shows a block diagram of the electrical system, comprising the EPS grid, line transformer for the building, fuel cell, and the building load. The main 3 electrical monitors are also shown. This diagram is useful in considering how different types of power can interact as viewed at the line transformer, which is the EPS energy use metering location.

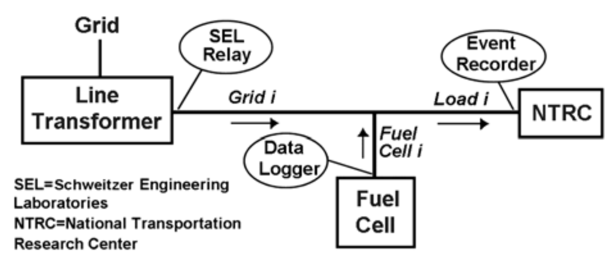

Fig. 2. Major current sources/loads in the grid-fuel-cell-building system.

Figure 3 depicts building load plot for an event where the real power dropped to ~150 kW and the reactive power to ~210 kVar. (Erratic line plots seen earlier in the day due to dynamometer operation in the building do not enter into this event.) Based the information at the time of the event, Figure 4 depicts the loads at both the line transformer and the NTRC. As indicated, the building load dropped well below 200 kW while the fuel cell continued to produce 200 kW. As a result, ~50 kW and ~215 kVA of power fed back into the EPS for >5-sec causing a RPR trip. Since this is a lock-out relay function, the EPS provider had to come to the site to manually reset the relay.

[2] The EPS-provider-imposed limit for reverse power was 50-kVA or greater with a current lag angle between 90° and 270° for >5 sec. The reverse power “window” was narrowed in early November to 120° to 270°.

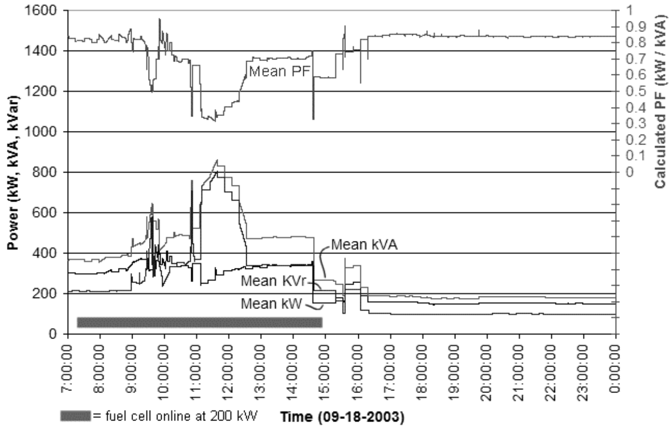

Fig.3. NTRC building load electrical data for 17-hr period on September 18.

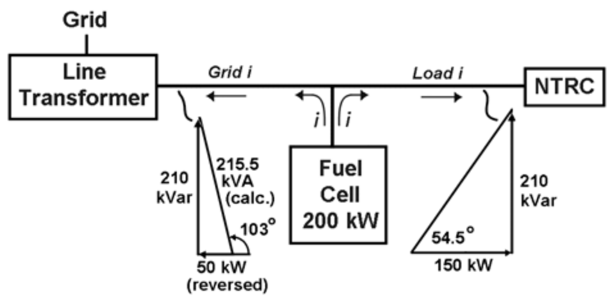

Fig. 4. System view of a September 2003 event with reverse power flow.

To understand certain events, it is essential to understand that between the building load data logger and the SEL relay at the transformer, the fuel cell injects real power, leaving the entire reactive power burden for the EPS to supply. The fuel cell was not programmed to provide reactive power compensation until after most of the interruption events.

In another event during August 2003, unbalanced "reverse currents" of 1261, 1342, and 1374 A were recorded for the 3 phases by the SEL relay at the end of the 5-sec timed trip interval. These data are problematic because the fuel cell is not capable of producing such high levels of current in excess of what the NTRC was consuming. This data alarmed the EPS provider. At the time of the event, the building's reactive power level was 750 kVAR as indicated in the Figure 5 building load plot. The high reactive power level was due to the fact that dynamometers in the engine research labs were dumping excess power from regenerative braking into the grid in a less-than-optimal fashion. This causes the PF to plummet to as low as 0.2. Although the 750 kVAR was measured in the building, it also applies to the line transformer location (see Figure 6), because the fuel cell was injecting only real power. The building was consuming 250 kW, of which the EPS was supplying only 50 kW. This produced current phase angles at the transformer and in the building that were lagging voltage by 86.2º and 72º, respectively.

Another effect of dynamometer operation is the production of very high levels of harmonic distortion (especially the fifth harmonic). Thus it is postulated that the RPR trip occurred because the monitor made a ~4º phase error for 5 sec because of the harmonic currents and interpreted the 86.2º lag as >90º lag. This explained the high reverse currents into the power grid that the fuel cell could not have produced; they were actually forward currents, and they were high because of the high levels of reactive power during dynamometer operation.

This event is of high interest because of how system dynamics play a key role in causing the interruption in fuel cell operation and because no plausible explanation can be found without considering system dynamics. Although the dynamometer operation makes the applicability of the event to other DG locations very low, understanding the underlying principles is helpful in gaining an understanding of other events that occurred in the study.

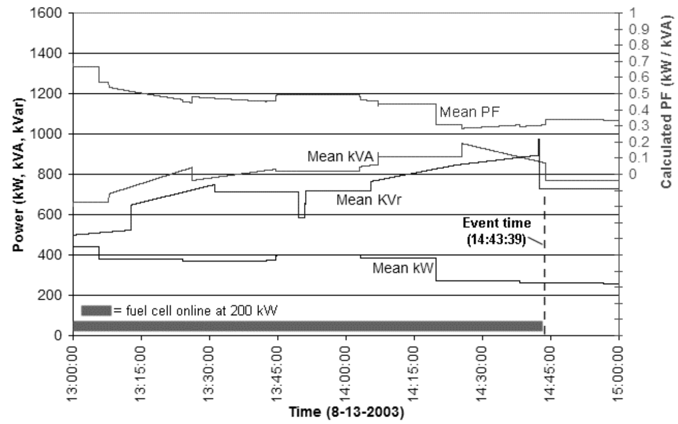

Fig. 5. NTRC building load electrical data for 2-hr period on August 13.

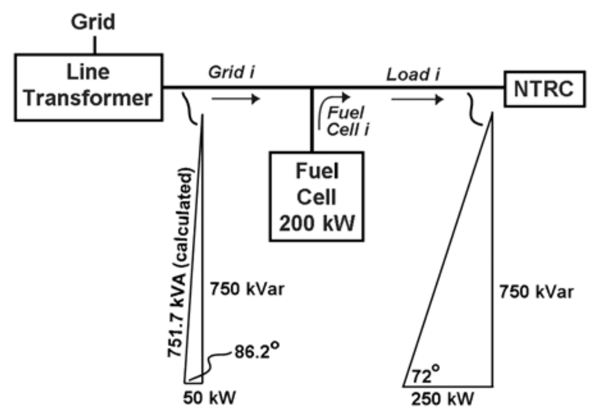

Fig. 6. System view of the August 2003 event during high reactive power demand.

A significant effect of bringing the fuel cell to full power is the negative impact it has on the PF or current angle phase shift from voltage as seen at the line transformer. This effect would be reduced significantly if the DG could generate more reactive power compensation and/or reactive power demand in the building was much less. Reactive power becomes high in general industry as a result of the operation of large motors that are oversized for their application. As already mentioned, this site has an unusual cause of low PF – the operation of dynamometers with regenerative braking systems.

During the study, the EPS provider expressed concern over "fault currents" from the fuel cell compromising their substation safety systems. The events with the two highest levels of recorded reverse current occurred on August 13th and September 18th as indicated in Table I. However, both events have little or no significance in regard to fault current in general DG applications. The other lower-current, reverse power events of the study pose little danger in fault situations and can be almost fully mitigated with an effective load tracking system.

TABLE I
Summary of the highest two reverse current events

Date and Iavg	Conclusion	Justification
8/13 1300 A	Not believed to be an actual reverse power event	Suspect SEL relay phase error of ~4° in high harmonic environment caused by dynamometer operation
9/18 300 A	Event believed to have low global applicability to other DG sites	Building load was 150 kW; reverse current was high due to reactive power from dynamometer

The fuel cell protective relaying system does not provide fault current protection other than overcurrent and timed overcurrent protection that are designed primarily to protect the fuel cell inverter. The protective relaying system of the fuel cell would not be able to detect a fault current unless major modifications were made including the installation of sensors on grid lines well removed from the fuel cell system. The lack of fault current protection is the reason why EPS providers insist on the use of a reverse power relay system.

The reverse power protection scheme[3] used by the EPS provider was based on a maximum reverse *apparent* power (50 kVA) with no limit on how small reverse *real* power might be. IFC is aware of ~25 other installations of its fuel cell where the local utility requires an RPR protection scheme. In *all* of these installations, a conventional Device 32 reverse power function is employed. Device 32 is a CT-based, directional real power measurement on a 3-phase or single-phase basis. The Device 32 protection is used to place a maximum limit on reverse *real* power, such as 50 kW.

In early November, at ORNL's request, the EPS provider changed the phase differential window settings in the SEL relay from 90°-270° to 120º-270° lagging current to narrow the window on what is considered reverse power. The limit of apparent power remained at 50 kVA. In effect, this change created a protective system that not only required >50 kVA reverse apparent power, but also a significant amount of reverse *real* power. Prior to this change, in September, there was an event where a trip occurred based on the SEL load encroachment logic for reverse impedance while the Device 32 reverse power function, if set for 50 kW, would *not* have tripped since only 5 kW was flowing into the EPS (the 90° phase angle limit had barely been passed).

IV. CONCLUSIONS

Generally, the electrical data was used in analyzing events in which the fuel cell was forced from grid-connect operation to the idle mode or, in a couple of instances, to a complete shutdown. There were 17 such events but 9 are considered nuisance trips due to the fact that the fuel cell's load tracking system could not be made operational during the study.

[3] To be more precise, a reverse *impedance* protection system was used. The selected impedance limit is consistent with a maximum of 50 kVA and the phase differentials described in the text.

An analysis of the events led to the 6 shown in Table II that are considered important with global applicability to other DG sites assessed at either medium or high. The table provides the date, whether the power grid acted as an initiator, whether the power grid initiator played a major role in the event, whether a full shutdown of the fuel cell occurred (i.e., requiring nitrogen purging), whether the interruption-to-grid-connect operation was desirable, and the global applicability. If load tracking had functioned properly during the test period, very conceivably these 6 events would have been the full outcome of this study.

TABLE II.
Summary of all high/medium global applicability fuel cell events

Date	EPS initiator/ contribution	Desirable interruption? (with justification)	
8/31	Yes/High	Yes	Normal protection
9/28 FS[1]	Possible/ Low	No	Hardware failure (UPS)
10/14	Yes/Low	No	Timer setting error
11/4 FS[1]	Possible/ Low	No	Spurious trip (UPS-related)
11/28	Yes/High	Yes	Normal protection
12/14	Yes/ Medium	No	Software flaw

[1]FS = full shutdown of fuel cell instead of a mode change to idle

Of the 6 events, 2 were desirable (i.e., normal responses of the fuel cell's internal protective relaying) and 4 were undesirable. The power grid played a medium-to-high role in the event in less than half of the cases. Of the 4 undesirable interruptions, the fuel cell hardware, settings, and/or software are the causes. Thus if there is any significant problem with fuel-cell-to-grid connectivity, this study tends to point to miscellaneous equipment/software problems that, in general, should decrease as fixes are made by the manufacturers and systems mature.

The state of fuel-cell-to-grid compatibility based on the results of this 6-month study is considered to be good. There are valuable lessons learned, discussed in Sect. V, that should be helpful to any organization that is contemplating the operation of grid-connected DG. If these recommendations are followed, the fuel-cell-to-grid compatibility experience should be good to excellent, rather than "assessed as good" or "theoretically good" as has been the experience at the NTRC.

V. RECOMMENDATIONS FOR IMPROVED DG SYSTEMS

The recommendations produced by this study for improving the performance of grid-connected DG systems come from (1) the general management of the PC25C fuel cell, (2) operational lessons learned, (3) experience gained with power system dynamics, (4) delays due to organizational barriers, and (5) analysis of electrical and event log data. Of course, there is some overlap in these areas or sources of learning, but it is important to recognize all of the different sources of information. The recommendations provided below are not all based on experience gained in this specific study; some relate to anticipated or potential problems based on general knowledge of the fuel cell and other DG systems. For instance, although ORNL enjoyed a high level of cooperation from both the EPS provider and IFC, some recommendations allow for the possibility that this may not always be the case.

The following are the primary recommendations of this study.

1. If possible, choose a DG system that has operated for years and proved itself. Speak with technical representatives at the company to (1) assess the apparent level of cooperativeness and (2) learn of any operational issues that are not yet resolved.
2. If the DG system is not well proven in the field, a comprehensive service contract should be sought from the vendor/manufacturer.
3. Talk to a representative of the local utility that will provide RPR resets to assess the level of cooperativeness and ensure that manual resets, if needed, will be prompt.
4. Discuss with the local utility representative the type of reverse power protection that will be used, and review what settings may be involved. If reverse power is defined by a window of lagging current phase angles, request a reverse power window of 120º (or 110º) to 270º, rather than 90º to 270º. Generally, ~50 kVA coincident with this 120º - 270º window should be permitted since such a power level should not significantly jeopardize the safety of power grid protective relaying systems. In this installation, high levels of reverse power had to be tolerated for at least 5 sec to give the load tracking system time to compensate for large load drops.[4]
5. Do not underestimate the need for reliable load tracking even if projections for power demand far exceed the generation capacity. A downward variation in load need last only seconds for an RPR trip to occur; and sudden, deep drops in load do occur. Thoroughly check out the load tracking system at startup. Install adequate surge protection on the system electronics that produce the control signal.
6. Ensure that DG operators have ownership and management of the entire load tracking system including the source of the control signal.
7. Verify that the power ramp-down rate of the power generation system is consistent with the reverse power time interval permitted by the reverse power protection system.
8. Know the DG system control software and all the features and functions that it may control.
9. In installations where the PF is poor, avoid selecting a DG system with a real power output that will routinely come close to matching the load demand. Otherwise, the power grid will be supplying high levels of reactive power and little real power. This situation may create high current levels and result in high PF charge penalties from the utility. (Note: This recommendation does not apply if the DG system is able to supply adequate levels of reactive power for PF correction.)
10. At least initially, consider installing a data logger with continuous data sampling of the building load. The data may prove useful in assessing performance of the DG system during interrupt events. If the DG system has an event log, arrange for access to those data also. Review data soon after events to minimize the learning curve.

[4] This is in apparent conflict with IEEE Standard 1547-2003, which requires island detection in 2 sec. However, the load tracking system needs 5 sec to reduce generation by 100 kW based on the maximum rate of 20 kW/sec for this fuel cell system design.

VI. REFERENCES

1. R. H. Staunton, "Compatibility Study of Protective Relaying in a Grid-Connected Fuel Cell," Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/TM-2004/12, Mar. 2004.
2. "IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems," Institute of Electrical and Electronics Engineers Standards Board, http://standards.ieee.org, July 2003
3. B. Kennedy, *Power Quality Primer*, McGraw Hill, New York, 2000.
4. *SEL-351A Instruction Manual*, http://www.selinc.com/instruction_manual.htm, Schweitzer Engineering Laboratories, Inc., Pullman, Washington, July 14, 2003.
5. *PC25 Power Plant Design and Application Guide*, International Fuel Cells, South Windsor, Connecticut, 2001.