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Compatibility Study of Protective Relaying in a Grid-Connected Fuel Cell

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ACRONYMS, ABBREVIATIONS, AND INITIALISMS

CT	current transformer
DER	distributed energy resources
DG	distributed generation
DR	distributed resources
DOE	Department of Energy
EPS	electric power system
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IFC	International Fuel Cells
IGBT	insulated-gate bipolar transistor
i-grid	web-based distributed power monitoring and notification system provided by SoftSwitching Technologies
i-sense	a monitor produced by i-grid
kVar	1000s of volts amps reactive (reactive power)
LCUB	Lenoir City Utilities Board
ma	milliamps
NTRC	National Transportation Research Center
ORNL	Oak Ridge National Laboratory
PF	power factor
PLL	phase locked loop
PT	potential transformer
RPR	reverse power relay
RMS	root mean squared
SEL	Schweitzer Engineering Laboratories
TVA	Tennessee Valley Authority
UPS	uninterruptible power supply
UT	University of Tennessee
UTC	United Technologies Company

EXECUTIVE SUMMARY

This DOE- and TVA-sponsored study considered the protective relaying system of a fully commercialized fuel cell power plant, which uses "synthesized" protective relays. The project's goal was to characterize the compatibility between the fuel cell's interconnection protection system and the local distribution system or utility grid. ORNL, with assistance from the Electric Power Research Institute–Power Electronics Applications Center (EPRI-PEAC) in Knoxville, Tennessee, monitored and characterized the system compatibility over a period of 6 months.

The 200-kW fuel cell was produced by International Fuel Cells (IFC), a United Technologies Company. This fuel cell was installed at an ORNL facility where it provided electrical power to a number of offices and experimental laboratories where engine research is conducted.

Distribution utility engineers are uncomfortable with the protective relaying and hardware that is generally provided in distributed generation (DG) systems. This is because the protective relaying circuitry (1) comes from sources other than those that normally supply instrumentation to the utility, (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, utilities will install a reverse power relay at DG sites to ensure that the integrity of the grid safety and protective relaying systems is preserved.

This study collected grid disturbance electrical data and event-related, building-load electrical data. An analysis of the data revealed that in installations where the power factor is poor, operating a DG system with a real power output close to the real power load can lead to potential problems. In such cases the grid will be meeting all the reactive power demand but providing little, if any, real power. This situation may cause I to lag V by almost 90^{o} at the building meter, create high current levels, and result in high power factor charge penalties from the utility. This situation does not arise if the DG system is able to supply adequate levels of reactive power.

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. The many and varied reasons that load tracking was problematic became a source of several lessons learned. Apart from these types of events, there were 6 events that are considered important and with high potential applicability to other DG sites.

Of the 6 events, 2 were desirable (i.e., normal responses of the fuel cell's internal protective relaying) and 4 were undesirable. The grid played a medium-to-high role in causing events in less than half of the cases. Of the 4 undesirable interruptions, the fuel cell hardware, settings, and/or software are the causes in each case. 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, may decrease over time as fixes are made by the manufacturers and the systems mature.

The recommendations that came from this study are summarized below:

1. If possible, choose a DG system that has operated for years and proved itself. Speak with technical representatives at the company to 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 reverse power lockout relay manual resets to gain assurance that 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.
5. Do not underestimate the need for reliable load tracking. Install surge protection on the system, and thoroughly check out the load tracking system at startup.
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 DG system is fast enough for the reverse power time interval permitted by the reverse power relay system.
8. Know the DG system control software and all the features and functions that it controls.
9. In installations where the power factor is poor, avoid selecting a generator with a real power output that will routinely be close to the real power building load.
10. At least initially, consider installing a data logger with continuous data sampling of the building load.

The state of fuel-cell-to-grid compatibility based on the results of this six-month study is considered to be good. This study produced valuable lessons that should be helpful to any organization that is contemplating the operation of grid-connected DER. 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 in this study.

1. INTRODUCTION

A 200-kW fuel cell produced by International Fuel Cells (IFC), a United Technologies Company, began operation at the National Transportation Research Center (NTRC) in early June 2003. The NTRC is a joint Oak Ridge National laboratory (ORNL) and University of Tennessee research facility located in Knoxville, Tennessee. This research activity investigated the protective relaying functions of this fully commercialized fuel cell power plant, which uses "synthesized" protective relays. The project's goal is to characterize the compatibility between the fuel cell's interconnection protection system and the local distribution system or electric power system (EPS). ORNL, with assistance from the Electric Power Research Institute–Power Electronics Applications Center (EPRI-PEAC) in Knoxville, Tennessee, monitored and characterized the system compatibility over a period of 6 months.

Distribution utility engineers are distrustful of or simply uncomfortable with the protective relaying and hardware provided as part of distributed generation (DG) plants. Part of this mistrust is due to the fact that utilities generally rely on hardware from certain manufacturers whose reliability is well established based on performance over many years or even decades. Another source of concern is the fact that fuel cells and other types of DG do not use conventional relays but, instead, the protective functions of conventional relays are simulated by digital circuits in the distributed generator's grid interface control unit. Furthermore, the testing and validation of internal protection circuits of DG are difficult to accomplish and can be changed by the vendor at any time.

This study investigated and documented the safety and protective relaying present in the IFC fuel cell, collected data on the operation of the fuel cell, recorded event data during EPS disturbances, and assessed the compatibility of the synthesized protective circuits and the local distribution system. The project also addressed other important and timely issues. For instance, the study includes an evaluation of the effectiveness of the fuel cell's synthesized relay protection scheme relative to the recently issued IEEE 1547 interconnection standard. Together, these activities 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.

Although more grid-connect fuel cell interruptions were encountered in this study than originally anticipated, and the investigation and findings became quite complex, every effort was made to clearly summarize the interconnection causes and issues throughout the report and especially in the summary found in Sect. 4.

ORNL's funding of this study is sponsored equally by (1) the Department of Energy's (DOE's) Office of Distributed Energy Resources and (2) the Distributed Generation Technologies program of the Tennessee Valley Authority (TVA).

2. SYSTEM AND SUBSYSTEM DESCRIPTIONS

This section describes several systems critical to this study. These include the operation of the IFC fuel cell, the protective relaying in the fuel cell, the local distribution system to which the fuel cell is tied, and the configuration of the monitoring system that was installed for the purposes of this study.

To prepare the reader for the discussion of grid-connect interruptions in Sect. 3, this section also presents information on two other areas: (1) barriers that prevented making the load tracking system operational and (2) the interaction of power factor (PF) and power system dynamics.

2.1 OPERATION OF THE IFC FUEL CELL

IFC, a United Technologies Company, of South Windsor, Connecticut, manufactured the 200-kW, phosphoric acid Model PC25C fuel cell shown installed and operating at the NTRC in Fig. 2.1. Hundreds of these fuel cell models 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%.[1]

Fig. 2.1. Fuel cell in operation at the NTRC in June 2003.

The NTRC is a well-suited load and test bed since the facility consists of both laboratories (laboratories make up 80% of the NTRC's space) and offices for University of Tennessee staff involved in transportation programs and ORNL staff primarily from the Engineering Sciences and Technology Division. The $20 million+ facility is a high-tech building as well as an energy-intensive building. The fuel cell installation at the NTRC will include provisions for combined heating and power by providing building heat during both winter and summer. During winter months, high-grade heat supplements the building heating system; during summer months, high-grade heat reheats 55°F conditioned air to temperatures selected via thermostats throughout the building.

[1] At the same time the fuel cell was being installed, a SEMCO enthalpy recovery system was installed on the roof of the NTRC to recover enthalpy from exhaust air and control the humidity of supply air in selected areas.

When the local utility, the Lenoir City Utilities Board (LCUB), was approached regarding interconnection of the fuel cell with the local EPS, their two greatest concerns were (1) the adequacy of the fuel cell's protective and safety relaying and (2) the potential for power to flow into the EPS, which is not allowed by TVA except from sources of green power.[2] LCUB required that a reverse-power lockout relay be installed not only to ensure that TVA requirements are met but also to gain added assurance that safety for LCUB repair crews would be maintained by the relay, which must be manually reset by LCUB.

Table 2.1 provides detail on the PC25C's main two operating modes. In the standard grid-connected operating mode, the typical PC25C provides power to the local distribution system and/or local facilities at a preset, desired output. The fuel cell can also be operated in a grid-connected/grid-independent mode, where it operates in either grid-connected or independent modes and can switch between them automatically or by manual command. The fuel cell can be switched in 2–3 sec to grid-independent mode when EPS power is lost. This dual-mode operation was not used during this test.

Table 2.1. Fuel cell operating mode and general characteristics

Fuel cell operating mode	Building electrical load	Characteristics
1. Standard grid-connected operating mode	Any load level[1]	The fuel cell provides constant level power as selected (e.g., 180 kW) in parallel with, and synchronized to, the grid. The fuel cell tracks the building load using a power dispatch signal (4–20 mA) from the main breaker panel B power monitor, which features analog output channels for general control functions.
2. Grid-connected/grid-independent operating mode	Any load level[1]	Synchronized, parallel operation with grid. Load tracking is enabled, as above. When switched, either manually or automatically to the grid-independent mode, the fuel cell can supply power to critical loads.

[1] Assuming that the load tracking system is functioning; otherwise, load should at least match the selected, fixed output of the fuel cell.

During this 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 Service B loads were low enough that the total load fell below the fixed output power level setting of the fuel cell. This resulted in episodes of reverse power flow into the EPS beyond allowed limits which caused trips of LCUB's protective relaying.

Technical representatives at IFC state that the fuel cell's ability to track falling loads is limited to a maximum rate of 20 kW/sec (of course, this is assuming that load tracking is operable). If the building load drops faster than this rate, power generated in the fuel cell may flow into the power EPS increasing the risk of a RPR trip. The local utility, LCUB, has agreed to set the limit of the RPR at 50-kVA for 5 sec in order to reduce the likelihood that the RPR will trip and cause a lockout. LCUB must manually reset trips of the RPR.

[2] Currently, fuel cells are not part of TVA's Green Power Switch program and are not eligible for reverse power and net-metering.

2.2 FUEL CELL INTERFACE AND PROTECTIVE CIRCUITRY

To understand the operational responses of the fuel cell, it is necessary to have a full understanding of the interface to the NTRC's internal wiring and distribution system. This section will present such details along with information on the fuel cell's internal protective circuitry.

2.2.1 Fuel Cell System Wiring to the NTRC

The PC25C fuel cell is wired into one of three main service transformers, the Service B transformer, at the NTRC. The Service B transformer, manufactured with wye-wye windings, normally supplies higher power levels than the other two NTRC service transformers. Figure 2.2 shows several key elements of the wiring scheme, beginning with the Service B transformer on the left-hand side of the sketch. The fuel cell is represented by the large box on the right-hand side of the sketch. The red line represents the main, 3-phase power path interconnecting the fuel cell inverter, the power grid, and the NTRC loads. The transformer secondary is connected to the NTRC building circuits/loads shown immediately below the transformer. At the top of the NTRC box is a data logger that was used to record the building's electrical load data. This was perhaps the most important source of data in the study. Just below and to the right of the Service B transformer are two circled numbers representing the reverse power sensor and the lockout relay. Many other protective relays are shown in the fuel cell portion of the figure of this simplified representation. More details and discussion pertaining to the protective relays are provided in Section 2.2.3.

Continuing with Fig. 2.2, power from the fuel cell inverter first reaches the main fuel cell relay, MCB001. This relay is closed in normal operation. The relay switches the fuel cell "on" or "off" by manual commands or by protective circuits. The output of the relay connects via MCB002, switch MD1, and a 400-A fuse to the local electric grid (i.e., transformer secondary). Relay MCB002 is normally closed during grid-connect operation unless there is a EPS outage or the fuel cell is placed in the grid-independent mode. In either of these cases, MCB002 opens, permitting fuel cell power to feed only emergency electric panels (via MD3 and MD4); however, the wiring to the emergency panels was not completed during this study. As indicated by a note, MD1, MD2, and MD3 are in the positions shown unless the fuel cell is turned off and placed into a maintenance mode.

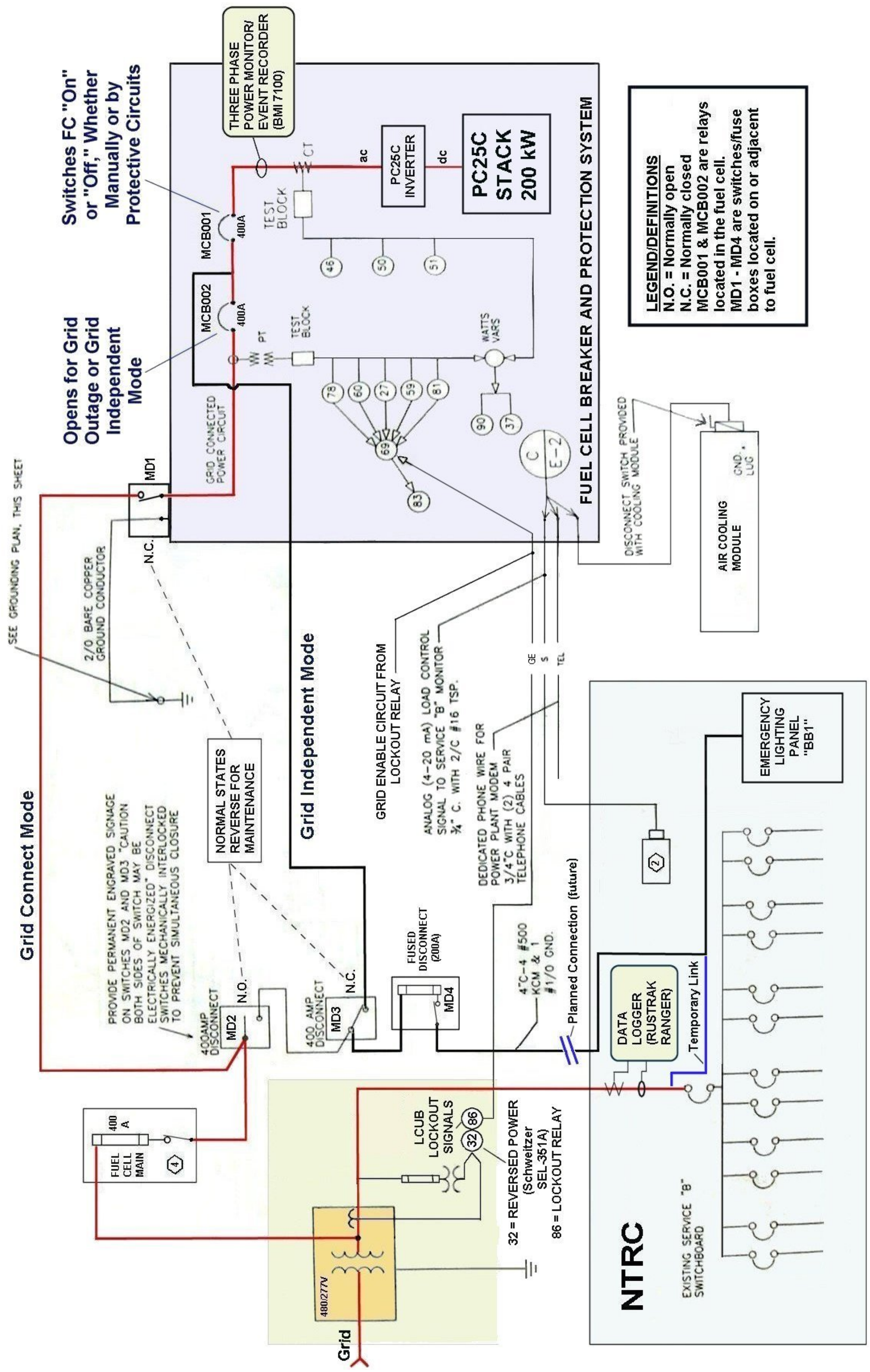


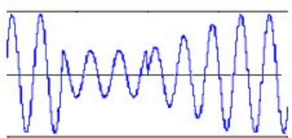
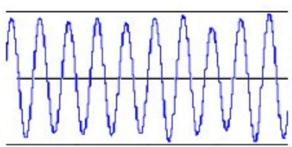
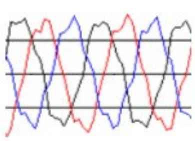
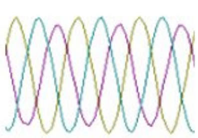
Fig. 2.2. Fuel cell and transformer wiring to the NTRC electrical system.

2.2.2 Power Quality [1]

Before discussing in detail the different types of protective relaying, it would be useful to review the power quality conditions that protective relaying is designed to protect against. There are several different types of power quality conditions that may exist at a specific location. They include transients, momentary, and long-duration conditions. The frequency of occurrence and the types of events typically seen at any given location depends on several factors, including prevailing weather conditions, utility maintenance practices, and local system loads to name a few.

Table 2.2 summarizes six types of power quality conditions that are some of the most common in commercial, industrial, and residential distribution systems. The table shows examples, terminology or identification, some possible sources of the conditions, and the effects that the problems may cause for end-use equipment. The effects of voltage sags and voltage interruptions can be quite significant.

Table 2.2. Power quality problems and potential effects

Example of waveform or RMS variation	Identification	Sources	Effects
	Voltage sag waveform (single phase)	- Remote system faults - Motor starting	- Motors stalling, overheating - Computer failures
	Voltage flicker waveform (single phase)	- Intermittent loads - Switching circuits - Motor starting - Arc furnaces	- Lights flickering - Annoyance
	Harmonic distortion waveform (three phase)	- Nonlinear loads - System resonance - Large computer systems - SCR-based inverters	- Overheating transformers and motors - Protective circuit trips - Meters misoperate - Failure of instrumentation
	Voltage unbalance waveform (three phase)	- Grid phase faults	- Motors experience high I unbalance - Motor failure
	Undervoltage or overvoltage (a steady-state RMS disturbance)	- Wrong transformer tap - Load dropping - Loading on long feeders - Lack of V support	- Motor life shortened - Light filament failure - May adversely affect some electronics
	Voltage interruption (an RMS disturbance)	- Grid protection - Protective relays - Fuses - Maintenance activities	- Loss of production - Equipment shut downs - Controller trips - Computer reboots - Costly process restarts

More quantitative definitions of power quality conditions are readily available [1]; for instance, voltage sags or dips are defined by IEEE as reductions in voltage for less than 1 minute but more than 8 milliseconds (0.5 cycles). The reduction in magnitude may range from 10 to 90% of the nominal RMS voltage. Some power quality conditions occur on a regular (cyclic) basis, while others, like voltage sags generally occur on a random-occurrence basis. In contrast to the random conditions, sustained undervoltage or overvoltage conditions may require hardware changes or corrections before the condition is resolved.

Most power quality conditions shown in Table 2.2 were encountered at some time during this study. Other power quality conditions, such as impulse and oscillatory transients, are not listed since they were not problematic in this study.

2.2.3 Fuel Cell Protective and Safety Relaying

An understanding of the operations and features of the fuel cell protective and safety relaying circuits is crucial to understanding and interpreting responses to power quality conditions and other types of power variations. The types of protective relays used in generators are fairly standard and well documented [2].

Figure 2.3 is an expansion of the earlier representation of this circuitry with the addition of refinements and additional protective device details. On the right-hand side of the drawing is a rounded rectangle showing one of several monitor/event recorders used in this study. Current transformer (CT) and potential transformer (PT) connections to all three phases provide the necessary data. The monitor is placed at the output of the fuel cell stack and 3-phase inverter before any relaying so that a full picture of power flow from the fuel cell is obtained. Any downstream relay openings can be clearly seen in this current flow.

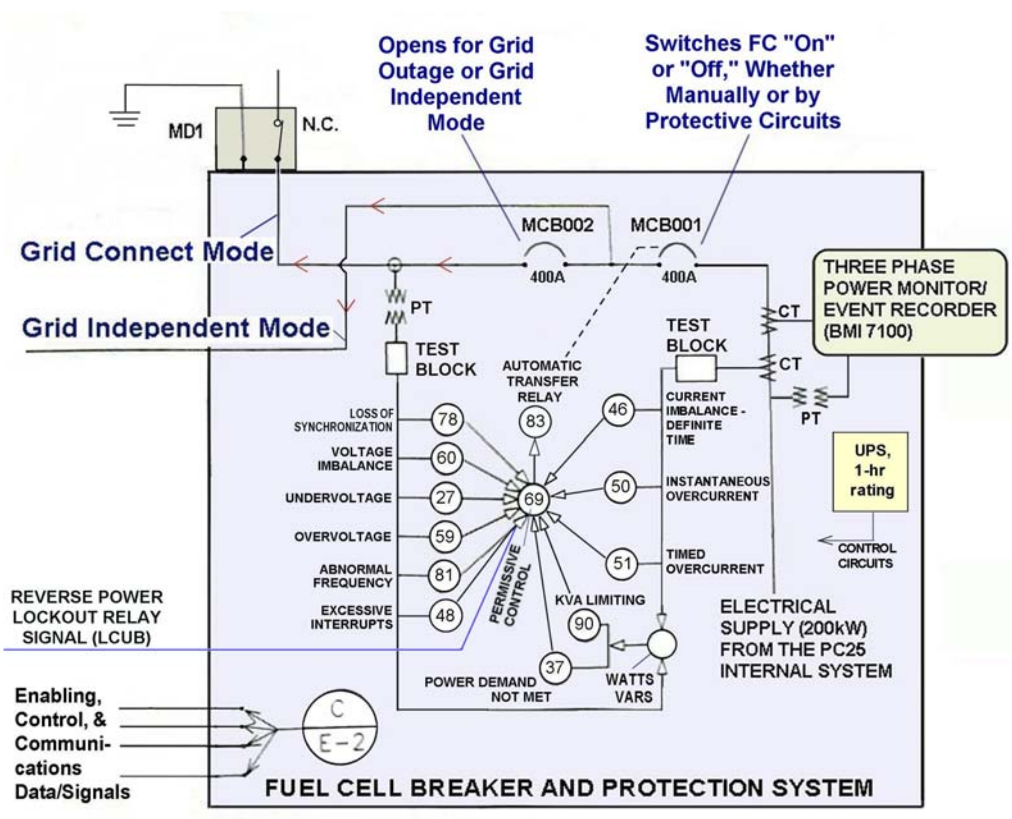


Fig. 2.3. Fuel cell protective and safety relay circuit.

Figure 2.3 shows at the lower, left-hand side the RPR permissive line. This external relay produces a signal that feeds into the permissive control, as do the other protective devices that are internal to the fuel cell. This is the only external relay that feeds into the PC25C protection circuitry. As indicated in the right-hand portion of the figure, a battery-powered uninterruptible power supply (UPS) is provided in the fuel cell to supply power to control circuitry during certain switching operations and EPS outages when control power is briefly interrupted. The UPS has a rating of one hour.

The fuel cell protective functions, their limits, and their responses are listed in Table 2.3 for those functions designed to protect the grid and in Table 2.4 for functions designed primarily to protect the fuel cell. As will be seen in Sect. 2.3, the number and types of safety and protective relays are far more extensive than those in the local utility substation. The specified functions are all equivalent to ANSI C37.2. Of the different types of overcurrent protection listed in Table 2.4, one of critical importance for the purposes of this study is #51. This protection will be of special interest later in this study in a discussion of fault current (see Sect. 2.3.4).

When any one of the protective devices (listed in Tables 2.3 and 2.4) that signals for a disconnect sends a permissive to the control system, it begins a rapid, two-stage process. The first stage is referred to, in fuel cell vernacular, as an "I55" interrupt that shuts down the inverter for 0.5 sec. If the permissive goes away, an "I50" run state results; however, if the permissive remains, an "I52" disconnect results and the fuel cell disconnects from the EPS.

Table 2.3. PC25C protective functions primarily for protection of the grid

No.	Title	Limits
37	Power demand not met	Loss of grid phase as detected by power or VAR demand not met. Action: interrupt 10 sec after integral control reaches max error correction
78	Loss of synchronization	Degree of loss not specified. Action: disconnect from grid
90	kVA limiting	Applies to grid voltage higher/lower than 5% above/below nominal. Action: limits kVA output linearly to 85% of rated at grid voltages of +10% or –20%
27	Undervoltage	Grid voltage lower than –20% of nominal. Action: inverse time interrupt, infinite at 10% and decreasing to one cycle at 100%
59	Overvoltage	Grid voltage higher than 10% of nominal. Action: inverse time interrupt, infinite at –20% and decreasing to one cycle at –100%
60	Grid voltage imbalance	Limit is >5% for 100 msec. Action: interrupt
81	Abnormal frequency	Limit is ≥ ±3 Hz from nominal for 0.5 sec. Action: interrupt
48	Excessive interrupts	Limits are >3 interrupts in 15 sec and >6 interrupts in 2 min. Action: disconnect from grid and remain disconnected

Table 2.4. PC25C protective functions primarily for protection of the fuel cell

No.	Title	Limits
46	Excessive interrupts	Loss of grid phase, detected by ac current unbalance >75%. Inverse time interrupt, infinite at 75% to one cycle at 100%
50	Overcurrent	Either (1) grid overcurrent >160% of rated or (2) instantaneous inverter pole output current (peak or 175% rated) >700 A. Action: instantaneous interrupt
51	Timed overcurrent	Grid overcurrent greater than rated. Action: inverse time interrupt, infinite at 110% of rated and decreasing to 1 cycle at 120% of rated
51/52	Motorized circuit breaker thermal/magnetic overcurrent trip	Action: disconnect from grid and remain disconnected

This interrupt process functions most often in response to a grid voltage variation or transient. If a grid disturbance is detected, the fuel cell is designed to ride it out using the I55 interrupt. Breaker MCB001 remains closed, and the insulated-gate bipolar transistors (IGBTs) in the inverter stop passing current. This is referred to as an "interrupt state." As described earlier, if the voltage variation or transient remains after 0.5 sec, the protective circuitry transitions from the interrupt state to the idle state (i.e., MCB001 remains open). In the idle state, the fuel cell is still able to power internal equipment such as blowers and pumps to both protect the stack and remain ready for a resumption of operation. It is important to note that as long as the grid is still energized, the occupants of the NTRC should not suffer a loss of power, aside from the voltage variation itself, simply because the fuel cell goes into the idle mode. This is an important advantage of parallel operation in the grid-connected/grid-independent operating mode.

If the grid returns to normal while the fuel cell is in the idle mode, resynchronization and reconnection takes place based on a user-selected protocol plan. This plan may call for the PC25C to resynchronize and reconnect automatically or only via a manual command. If automatic reconnection to the grid is selected, the reconnect takes place based on an adjustable timer with a default period of 30 sec. If the grid does not return to normal after longer periods (e.g., 2 min), a second timer is used to require manual reconnection.

As indicated earlier, in Table 2.3, the excessive interrupt count (protective function 48) idles the fuel cell if there are >3 interrupts in 15 sec or >6 interrupts in 2 min. A less common event, called the "excessive *disconnect* count" functions in a similar way based on longer events. In this case transients exceed 0.5 sec, and the MCB001 breaker opens and closes each time as each transient passes. The excessive *disconnect* count feature will place the fuel cell in the idle mode on the third event that causes an interrupt >0.5 sec within a 5-min-and-5-sec period.

Anti-islanding circuit protection ensures that, in the event of a grid outage, the fuel cell does not attempt to supply power to a portion of the local grid and result in a hazard to electricians who may be attempting to restore power. The PC25C incorporates an anti-islanding protection scheme through the use of voltage (fastest protection), frequency, and power monitoring. These methods, and other secondary methods, are used as follows:

- Voltage—The fuel cell inverter output operates using current control whenever grid-connected. In reality, the current control always involves some level of voltage control. If islanding begins, voltage changes cause the control system to drive current in an unstable manner unless there happens to be a near-perfect match of current to the load. In such a case, current excursions would merely be delayed.

- Frequency—A phase-locked loop circuit matches frequency to the grid by shifting the phase angle (i.e., similar to controls for generators). However, when there is no grid, the circuit begins to shift frequency relative to the fuel cell's own generated frequency, causing the frequency to "run away."

- Device 37, power demand not met—Protection device 37 monitors power. When a grid outage occurs, the circuit may detect that the power demand or VAR demand is not being met and cause a disconnect.

Although not a part of the fuel cell protective relaying system, the specially installed RPR may be viewed as an additional layer of anti-islanding protection. For example, detection of 50-kVA or more of reverse apparent power over a 5-sec duration will cause the circuit to send out a permissive, via a lock-out relay, to the PC25C control circuit. This action puts the fuel cell into the idle mode until the lock-out signal is manually reset by LCUB. The power is determined to be reversed if the i-angle falls outside preset bounds (see Sect. 2.3.4).

2.3 LOCAL ELECTRICAL DISTRIBUTION SYSTEM—DESIGN AND ISSUES

This section will describe the switchyards at the Solway substation and discuss those issues that LCUB has raised regarding the safety of fuel cell operation while the fuel cell is connected to the grid.

The NTRC is located on a feeder that originates at the Solway substation, less than 1 mile from the building. Therefore, the NTRC is one of the first connections to this feeder, and the voltage conditions at the substation will be nearly identical to that at the primary of the Service B transformer.

The Solway 161-kV substation consists of three distinct switchyards, one for each of the following voltages:

- The 161 kV (primary) – transmission connection to TVA
- The 69 kV – transmission connection to other LCUB substations
- The 13 kV (multiple service feeds to surrounding areas) – distribution connections to local loads

The substation is schematically represented in Fig. 2.4 in a single-line diagram. The red line represents the secondary circuit to the Breaker 254 feed for the NTRC and other customers east of the substation. Two data monitors are shown in the lower right-hand corner of the figure, one installed by TVA for its own monitoring purposes and one installed for this project but seldom used (or needed) to provide insight into interruptions to the fuel-cell-to-grid connection.

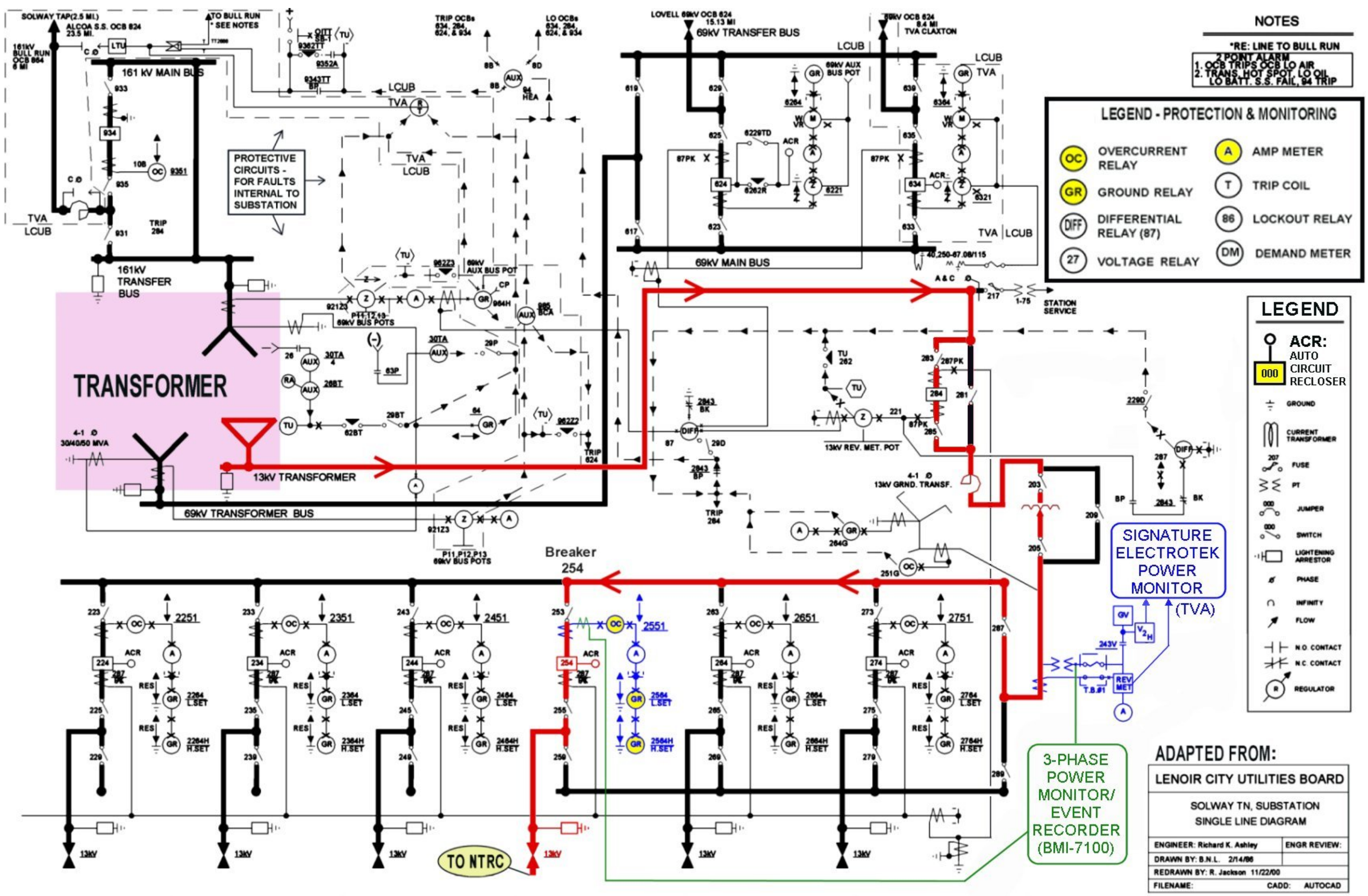


Fig. 2.4. Solway substation single-line diagram.

2.3.1 Switchyard for 161 kV

The 161-kV infeed switchyard receives 161-kV power from TVA via one or more lines. The power comes into the substation through a line trap that provides circuitry for transfer trip signals to TVA in case of a substation breaker failure or for problems in the areas of the substation that are unprotected by the station's circuit breakers.

The 161-kV switchyard includes station arresters, disconnect switches, and a tertiary 161-kV transformer with a 69-kV wye secondary and a 13-kV delta secondary.

The protection for the 161-kV switchyard includes three relaying schemes:

1. Line carrier transfer trip—activated by the main substation transformer bank's protective relays and the 161 kV–69 kV–13 kV differential zone.

2. 161 kV–69 kV–13 kV differential zone—The 161-kV protection is provided by a 3-relay circuit. The "differential zone" compares the inflow and outflow of electric power within the bounds of the zone. The zone of protection covers many bus or transformers faults; these faults are sensed by a differential relay.

3. Overcurrent, impedance, and thermal protection—The switchyard provides numerous protective relays for protection, including phase overcurrent, distance impedance, backup distance impedance, carrier ground directional, backup overcurrent ground, transformer hot spot, and transformer sudden pressure.

2.3.2 Switchyard for 69 kV

The 69-kV switchyard contains breakers, disconnects switches, station arrestors, and 69-kV taps. This area is protected by the same 161 kV–69 kV–13 kV differential zone described above. The system also includes 69-kV breaker impedance and overcurrent relays.

The 69-kV circuit breakers will actuate in response to any 69-kV line faults, including any internal breaker fault. Such faults are sensed by the directional distance impedance and/or ground relays. Breaker 624 serves the Lovell line and Breaker 634 serves the Claxton Line. These are both operated by their respective impedance distance relays (6221 and 6321).

2.3.3 Switchyard for 13 kV

The 13-kV switchyard provides service to six distribution lines serving customers in the Solway area (i.e., between Knoxville and Oak Ridge) and includes portions of northwest Knoxville. This switchyard includes the following 13-kV equipment: bus breaker, grounding transformer bank, disconnect switches, regulator, station arresters, and distribution circuit breakers. The area is protected by phase overcurrent and ground overcurrent relays and 13-kV line-protection relays.

Breaker 284 serves or interrupts all 13-kV service to the bus and six distribution circuit breakers. This breaker can be tripped out of service by the phase overcurrent relays, 13-kV back-up distance relay, the grounding bank's phase overcurrent relays, and the grounding bank's 13-kV backup ground relay.

The 13-kV distribution circuit breakers are 224, 234, 244, 254 (area served includes the NTRC), 264, and 274, each with the following protective circuits:

- Phase overcurrent 51
- Low ground overcurrent 64
- High ground overcurrent 64H

When a fault occurs on a distribution line, one or more of the overcurrent relays will operate and will open a distribution circuit breaker. The automatic closing relays or "reclosing relays" are programmed to provide immediate or instantaneous reclosures, followed by two or three preset intervals with reclosures, until the breaker either stays in service because the fault has cleared or goes into "lock-out." In the event of lock-out, the fault must be located and removed by a line worker, followed by manual relay and breaker operations to restore service.

2.3.4 Technical and Safety Concerns of LCUB

This section will discuss a number of important issues that LCUB raised regarding the safety of fuel cell operation while the fuel cell is connected to the grid, and that ORNL raised pertaining to fuel cell operability in the grid-connected mode. Some of these issues are related to broader concerns addressed in the recently issued interconnection standard for distributed resources (DR), IEEE 1547. In short, the IEEE interconnection standard states that DR systems must disconnect from the grid in the event of an interruption (i.e., the DR must not attempt to fill in the void or continue to energize the area EPS). For additional information on DR issues related to IEEE 1547, see Sect. 4.2.

The following subsections discuss various safety and protection issues.

<u>Purpose of the Reverse Power Relay</u>

TVA does not presently permit DG to feed power into the grid unless the DG is part of its Green Power Switch program. Fuel cells have not yet received this classification, although there is no emission-related reason why it should not. An RPR protective system—comprising a Schweitzer Engineering Laboratories (SEL) Model SEL-351A distribution protection relay and a lockout relay (located in a locked cabinet accessible only by LCUB) —was installed at the NTRC for four reasons: (1) the TVA non-reverse power requirement, (2) LCUB's desire to rely on the use of equipment of known reliability, (3) LCUB line repair personnel safety, and (4) to avoid compromising the protective schemes used at the Solway substation.

<u>RPR Settings</u>

On the advice of SEL, LCUB decided to use the Load Encroachment feature of the Model SEL-351A relay [3]. In this report, the RPR and reverse-power protection are used to refer to this protection scheme even though, to be precise, the installed protection is based on impedance rather than power. The LCUB settings for impedance measured by the SEL relay are based on a calculated maximum 3-phase current [(3)(277V)I=50,000 VA or I=60.2A] that is used in the impedance formula: Z=V/A=277V/60.2A=4.6 Ω. Any lower impedance (i.e., higher current) in the NTRC circuit will trip the RPR. When it is stated that LCUB programmed the SEL relay to permit reverse apparent power of up to 50-kVA for no more than 300 cycles (5 sec), only the magnitude and time settings are being defined. There are also settings that precisely define "reverse" power. For the first several months of operation, reverse power was defined by a phase angle of the line current in a range from 90º to 270º (with respect to the phase voltage).

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 standard reverse (real) power function (Device 32) is employed. This protection can be described as a CT-based, directional power measurement on a 3-phase or single-phase basis. The protection scheme used in this study was based on a maximum reverse *apparent* power 50 kVA with no limit on how small *real* reverse power may be; however, the Device 32 protection would have been used to place a maximum limit on reverse *real* power, such as 50 kW.

When difficult-to-explain events were encountered with unusually low PF (e.g., below 0.6), ORNL considered whether the Device 32 type of reverse power protection might be helpful. ORNL acknowledged that with a severe lagging current and high fifth harmonic content, there would be reverse harmonic currents that could cause trips even in a Device 32 protection scheme. In consultation with personnel at SEL, LCUB decided not to experiment with what it considered to be a technically inferior protection scheme. Instead, LCUB decided to modify the permissible phase angle in the load-encroachment scheme. At ORNL's request, LCUB allowed an additional 10º (for a total of 100º) in an effort to reduce the number of unexplained trips, but that did not seem at the time to be quite sufficient. LCUB was hesitant to extend the permissible current phase angle further, since it is under contract with TVA not to allow any customer to generate power onto the grid. As indicated in Fig. 2.5, it was not until early November that LCUB made a further adjustment in the settings to allow a lagging current phase of 120º. 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 (assuming normal levels of reactive power).

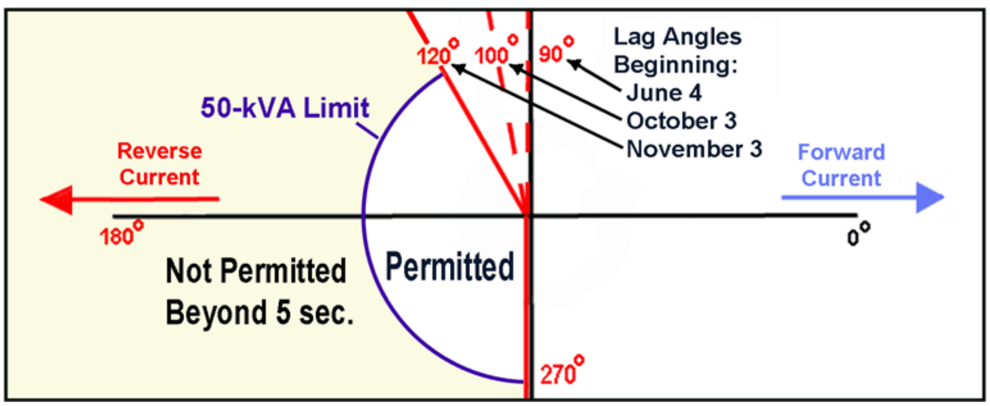


Fig. 2.5. Allowable lag angles in the grid-connected mode at full power generation.

Early in the project, ORNL had also discussed with LCUB the possibility of lengthening the 5-sec interval for reverse power. LCUB responded that the request would be granted only if a test were conducted on the fuel cell to verify the operation of all protective relaying schemes. This test would require 3-phase current sources and, based on the test procedure and past tests of this kind (per IFC's recollection), it would require a full day of testing. Since the extension of the 5-sec timed interval was of limited interest, ORNL never pursued this verification test.

Fault Current

The following paragraph is an excerpt from a letter from LCUB to ORNL [4] addressing fuel cell "fault current" (i.e., current into the grid) resulting, in part, from a lack of load tracking:

> "In the beginning I [LCUB representative] had anticipated that the fuel cell would have fault protection and would disconnect from the grid in the event of a fault on the grid. To date this has not happened. We are greatly concerned that LCUB's protection scheme [at the Solway substation] is compromised since the operating philosophy is to interrupt power flow to the fault and reclose quickly (less than a second) in an attempt to clear the fault. The hope was that the fuel

> cell would possess time current characteristics quicker than those at our substation Breaker 254 and would disconnect from the grid prior to our breaker operating. This would allow a momentary fault to clear (such as a lightning flash, tree limb, animal, or impact such as a car). Since the fuel cell has not cleared until the reverse power relay trips it after 5 sec, which is much too long under fault conditions, this means the momentary fault never de-energizes since the fuel cell feeds the fault during our breaker operations…. The present situation is unsafe and unacceptable for our line workers."

As a result of this situation, LCUB views the initial sub-second recloser action at the substation as ineffective (or less effective) in eliminating fault current. Of course, the underlying premise is that the continued presence of current tends to hold temporary fault paths in place. This situation necessitates greater reliance on the *second recloser* period, which is considerably longer than 5 sec, giving ample time for the RPR to send a permissive to the fuel cell protective circuitry. Thus, in LCUB's perspective the second recloser operation would completely interrupt the fault current for the first time.

During the design phase of the fuel cell project, LCUB requested that 200-A fuses be located at the fuel cell disconnect switch to provide protection against high fault currents [5]. However, the project electrical design contractor assured LCUB that the fuel cell protective circuitry would provide adequate fault current protection. This assurance, combined with pressure to reduce project cost, resulted in the elimination of the fuses.

As presented in Sect. 2.2.2, the overcurrent protection is provided by the following two protection features:

1. **Overcurrent (#50) —**Either (1) grid overcurrent >160% of rated or (2) instantaneous inverter pole output current (peak or 175% rated) >700 A will result in an instantaneous interrupt.
2. **Timed overcurrent (#51) —**Grid overcurrent greater than rated will result in an inverse time interrupt, based on "infinite" at 110% of rated and decreasing to one cycle at 120% of rated.

This timed overcurrent (#51) protection allows no more than 110% of rated current (163A) on an inverse time interrupt. Hence, the more current exceeds the 110% threshold, the shorter will be the allowed time before interrupt. This span of "managed-duration current" is quite short. At 120% of rated, which is 195.6 A, the allowed time has already shortened to a mere cycle. Thus the overcurrent protection specifications appear to be well suited for eliminating high currents, including fault current, in the reverse direction following grid outages. However, this did not appear to be the actual case based on LCUB data presented in Sect. 3.2.5 that show reverse current during/following transients of over 250 A.

Further investigation into the PC25C overcurrent protection specifications led to the discovery that the timed overcurrent (#51) is intended by the manufacturer to apply to "bolted faults" during otherwise normal grid-connected operation. It is a calculated average based on inverter overcurrent protection (#50) and, as such, should *not* be interpreted as a peak current specification. This level of detailed information was not available in the PC25 design and application guide [6].

Based on information obtained from a knowledgeable IFC consultant [7], the PC25C fuel cell has limited potential for producing peak reverse current exceeding 200 A per phase. In fact, if *all* building loads were suddenly lost as a result of a transient tripping various building control systems, the maximum current that would feed into the grid would be 240 A[3] in the case of unity PF or 282 A[4] for 0.85 PF. This current will span the 5-sec interval until the SEL relay generated a permissive, assuming that no internal

[3] Based on (277V)(I)+ (277V)(I)+ (277V)(I)=200,000W
[4] Based on (277V)(I)(0.85)+ (277V)(I)(0.85)+ (277V)(I)(0.85)=200,000W

permissive was generated by the voltage transient. Carrying this to a more extreme case, if *all* of the building loads were suddenly lost, there could be a very short (1 cycle) period in which 452 A[5] could feed into the grid before the internal current protection for the PC25C inverter would cause an interrupt. Because of the short duration of this 1-cycle-overcurrent event, it cannot be considered significant during the timed interval of the first recloser operation. Only the 240-A (max) reverse current can be considered attributable to the fuel cell over significant periods of time. If one assumes a more reasonable scenario in which only half the load in the NTRC is tripped, then the maximum reverse current attributable to the fuel cell over a period of seconds is reduced considerably, and load tracking may provide a complete elimination of the current within the 5-sec timed interval.

In a broader view, the IFC consultant considers currents only in the range of 1000s and 10,000s of amps as "fault currents" and did not agree with applying the term "fault current" to excursions of a few hundred amps into the grid.

LCUB cited currents well above 300 A (into the grid) for certain events and indicated that the currents lasted seconds until the SEL relay actuated the RPR to place the fuel cell into the idle mode. The source of the current, at the time, was not entirely clear; however, there are other potential sources beyond the fuel cell. Any induction motor that suddenly loses grid power can act as a generator during coast down as long as there is a residual field. The induction motor listing for the NTRC is summarized in Table 2.5. See the text box for further discussion of this investigation and the potential for dynamometers to have created this current.

Table 2.5. Induction motor applications in the NTRC

Motor application	Total hp available
Roof top supply fan motors	180
Roof top return fan motors	41
Supply fans for the air unit	190
Non-fractional-hp exhaust fans	100
Pumps	210
Cooling water tower	55
Hydraulic system – packaging lab	unknown
Hydraulic system – composites lab	unknown
Chiller compressor motor	220 hp (est. based on 240 A, measured)
Total known hp	996

Analysis at the end of the study pointed to 3 likely sources of high reverse current, (1) effects of power system dynamics in an environment where reactive power is high (see Sect. 2.6), (2) dynamometer power dumping operations (see below), and (3) instrument error where forward current is misinterpreted as reverse current (see Sect. 3.2.5 and 3.2.7) because poor power quality can compromise the accuracy of electrical phase angle measurements. The summary section (Sect. 4.1) considers the 2 highest "reverse current" events and presents further reasons why high fault current does not appear to be a serious issue.

[5] Based on 160% of rated current at 0.85 PF (1.6 ×282A × 0.85), which is a setting to protect the IGBTs in the inverter circuit.

Current Producing Capability of Motors and Dynamometers

The NTRC has large ventilation fans, chiller compressor motors, an air compressor motor, hydraulic systems, and pumps and fans supporting cooling towers. Of the 996 hp total for available motors in the building, it can be assumed that 50% to 70% is generally in operation (about 500 hp to 700 hp). Theoretically, these are capable of feeding into the grid immediately following a grid interruption. An electric utility would usually not record such an event occurring at a particular customer's site; however, the SEL relay routinely measures and records voltage and current waveforms when the RPR protection trips. Therefore, it was postulated during the six-month study that the higher electric current levels seen during certain events are likely a combination of the fuel cell and induction motor currents. Working strongly against this theory is the presence of elevated reverse current at the end of the 5-sec timed interval when a reasonably well-loaded motor would have coasted down to (or near) a full stop.

The NTRC engine testing laboratories use a number of large dynamometers (600hp, 500hp, 300hp, 175hp). In most cases, a controller operates the dynamometers and grid outages have little effect other than possibly producing a dc power surge that the controllers/capacitors must absorb. However, three of the larger dynamometers in the engine testing labs use an inverter to convert the dc voltage into 3-phase, 480 Vac. The controller then "dumps" this power (in a non-optimized manner) into the grid (also known as regenerative braking). Because the dynamometers are driven by gasoline- or diesel-powered engines, it is conceivable that one or more of these systems could produce power and feed the grid for the entire 5-sec period following a voltage sag or outage while also causing severe plunges in PF to a range from 0.15 to 0.65. This theory was not fully explored.

Service B Transformer Thermal Considerations

Later in the study―when it was fully understood that the dynamometers were capable of creating severe PF degradation, and the fuel cell's supplying 200 kW of real power tended to worsen the PF, as reported by the SEL relay ―LCUB was concerned about the effect a very poor PF would have on the Service B transformer. During periods of poor PF, the NTRC Service B transformer had to supply higher current; and during fuel cell operation, most of the current was due to high reactive power levels that the grid alone supplied. With a 0.25 PF, the loading on the transformer may have reached ~2200 kVA at times, but the transformer rating was 1500 kVA. In response to LCUB's concern, close attention was paid to data obtained during periods of low PF, especially during dynamometer operation. The data showed that dynamometer operation was more brief in nature than thought (e.g., typically a small portion of an hour) over a period of several weeks. It was also recognized that if the engine research in the NTRC changed so that long-duration dynamometer operation became common, the issue would become quite significant. Fuel cell operation alone did not seem problematic during this study, especially since a lack of load tracking was restricting power generation levels.

2.4 CONFIGURATION OF ELECTRICAL MONITORING SYSTEMS

The original data collection concept of EPRI-PEAC and ORNL called for BMI-7100 PQNode data monitor/event recorders to be installed at the local electrical substation and at the fuel cell. It was anticipated that the responses of the fast relaying in the fuel cell would be captured in the buffer of the event recorder, and the data from the substation and fuel cell recorders could be matched and analyzed. It was not anticipated that the RPR would be a significant component requiring analysis. The RPR was viewed as nothing more than a safety requirement of the local electric utility.

After the first few events involving an external permissive from the RPR, it became clear that the event recorders were not adequate because their buffers could hold data from only a small portion of the 5-sec interval permitted for reverse power. The recorder's buffers were even more limited in capturing data (i.e., cycles) immediately *preceding* the triggering of the event recorder. It was necessary to capture the transient or initiating event. In retrospect, it is clear both that the data monitoring function was too coarse (i.e., providing a data point every 15 min) and that the event recorder function provided data that were too fine (i.e., consuming the limited buffer with detailed waveform data). In the end, the main purpose of the fuel cell monitor/event recorder became the determination of whether the fuel cell was on line and verification of power level, VARs, kVARs, etc.

The most important improvement made to the data collection system was EPRI-PEAC's addition of a Rustrak Ranger data recorder to the main Service B breaker panel in the NTRC, as shown in Fig. 2.6. This improvement, made in early July 2003, provided the actual voltages and currents for all three phases, revealed fluctuations in the building loads (unlike the monitor located in the fuel cell), and provided continuous data feedback during the study. From the data, real power, apparent power, reactive power and PF plots were generated for many of the events.

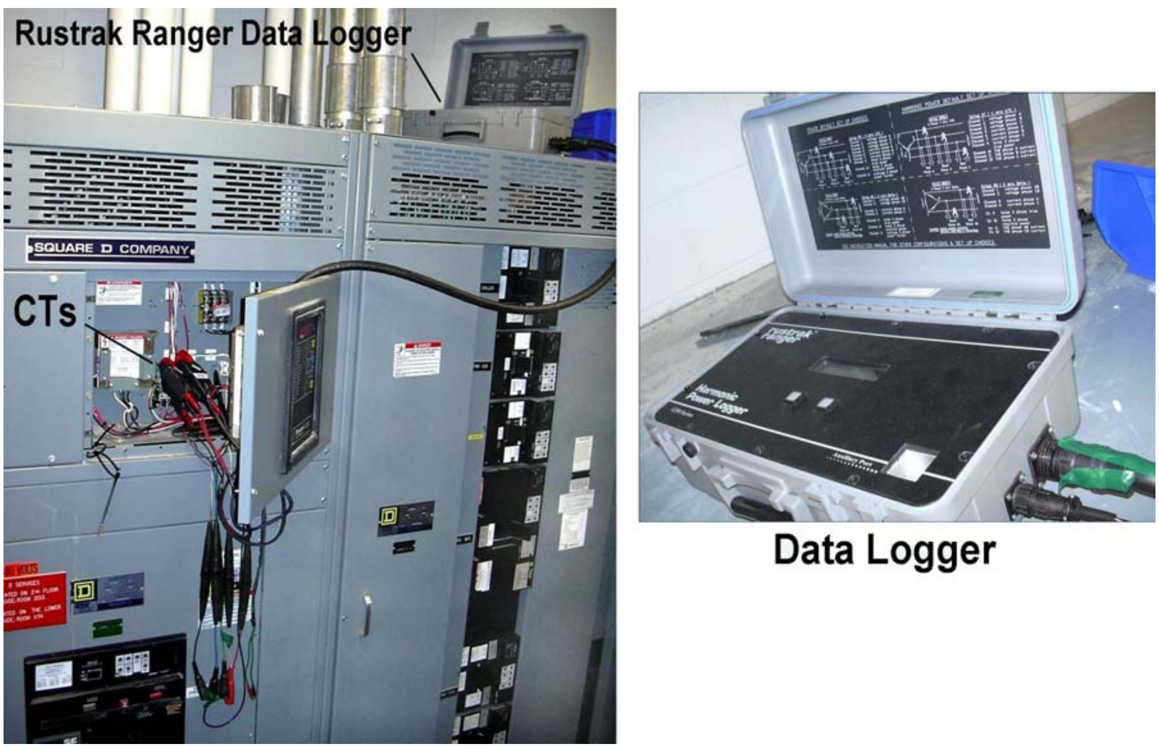


Fig. 2.6. Main breaker panel for Service B with data logger installed.

The second most important source of data was the SEL relay's waveform and electrical parameter recording capabilities (hence, the instrument is more than just a "relay"). The SEL relay is shown in Fig. 2.7 mounted in a cabinet adjacent to the Service B transformer. The lockout relay is shown immediately above the SEL relay. The SEL relay provided data only for the events in which it generated the permissive that placed the fuel cell into the idle mode. The instrument captured 3-phase voltage and current waveform data, 3-phase current magnitudes at the time of interrupt, time, and other data. From the waveform data, PF can be estimated.

Fig. 2.7. SEL relay and lockout relay in cabinet adjacent to the Service B transformer.

An “i-grid” system monitor, referred to as “i-sense,” was also installed in the cabinet near the Service B transformer as shown in Fig. 2.7. I-grid is a web-based distributed power quality and reliability monitoring and notification system provided by SoftSwitching Technologies. The i-sense unit captures 3-phase, 480-Vac transients on the grid and transmits the data to the i-grid web site. ORNL and other i-grid site users are then able to download the voltage transient data.

Important note: It is *essential* for analysis and understanding of the results of this study that the reader understand that the Rustrak data recorder monitored the building load; the SEL relay recorded data at the Service B transformer; and, between these two locations, the fuel cell injected real power, leaving the entire VAR burden for the grid to supply.

Ideally, this project would have relied upon a 12-channel data recorder (typically priced at $20K to $30K) located in the Service B transformer cabinet providing 3-phase voltage waveforms and 3-phase current waveforms for (1) the grid contribution to the NTRC (Service B), (2) the fuel cell contribution, and (3) the NTRC load (Service B). Such a system was briefly realized near the end of the study (in November) during a demo-trial period for a Gould/Nicolet DAstar power monitor. Data were obtained for reverse power events during November that resulted from low building load without load tracking (i.e., a common, low-interest event). The interaction of the building load, fuel cell, and grid are as expected (see Sect. 3.2.11).

2.5 BARRIERS TO ESTABLISHING LOAD TRACKING

Due the TVA reverse-power rules and the RPR protection scheme, load tracking is important for ensuring that fuel cell power generation automatically scales back when the building load becomes low. The rate at which the fuel cell power level adjusts to drops in load is important in the event that major pieces of equipment (e.g., chillers) trip off because of voltage transients. Load tracking does not occur and is not necessary when the building load is consistently greater than the power production capability of the grid-connected fuel cell.

During this study, load tracking was not operational beyond perhaps a few days midway through the study. The reasons for this are many and varied, as will be discussed. Since grid connectivity is the prime focus of this study, the issue of load tracking is of critical importance. It is perhaps fortuitous that many obstacles arose over the course of this fuel cell study for a subsystem that is so basic and that should be readily implemented in PC25C installations. The lessons gained will likely help others to ensure that load tracking is not taken for granted, no matter what projections they may have for stable loads and/or loads well in excess of the fuel cell's capabilities.

Although some of the reasons that load tracking remained elusive at the NTRC were uncommon in general commercial and industrial settings, most have broad applicability. In the interest of thoroughness, the listing of obstacles, errors, and setbacks will include a broad scope of events that are human-related, administrative, acts-of-God, and purely technical.

The events over a six-month period that effectively prevented the use of load tracking are as follows.

1. *Miscommunication*—The fuel cell operators and researchers were aware that another organization had successfully tested the load tracking control signal just before fuel cell operation began. This control signal was connected to the fuel cell per the manufacturer's instructions. The system was therefore believed (erroneously) to be operational.
2. *Underestimation of Need*—Early in the study, fuel cell operators and researchers paid little attention to load tracking because the around-the-clock electrical load at the NTRC was well in excess of the fuel cell production capability.
3. *Inadequacy of electrical monitors*—Using the initial electrical monitor/event recorder system (in June and July 2003), it was not clear from early interruptions of grid-connect operation that load tracking was not functioning. For instance, event recorders had small data buffers that did not span periods of seconds.
4. *Complex interface software*—The fuel cell Rockwell interface software comprises numerous screens. On one screen, a cryptic message for "dispatch" provides options for "local" and "external." An IFC contact alerted ORNL to the fact that the "dispatch=local" command meant that the system was not programmed to operate using load tracking. External dispatch allows for load tracking using the NTRC building load control signal.
5. *Multiparty miscommunication*—In further discussions with an IFC contact, ORNL learned that if an active circuit is used to generate the load control signal, as opposed to a watt transformer, then a particular module must be used in the fuel cell. This was not previously communicated among IFC, ORNL operators, and the construction contractor. Since ORNL was using a Square D, programmable power monitor and an analog I/O module to generate the 4-20mA load control signal, IFC saw that it was necessary to send ORNL a replacement module and precision resistor to be installed in the fuel cell.
6. *Act of God*—An electrical storm on June 16 destroyed a power supply for the Square D power monitor, which also supplies power to the i/o module. Because this equipment is owned by the NTRC building owners (i.e., not by ORNL), replacement of the power supply was coordinated and completed by that party.
7. *Lack of surge protection*—A lack of voltage surge protection in the main breaker panel was evidently a second cause of the power supply failure mentioned in item 6.
8. *Volatile memory*—Repeated attempts to turn on the load tracking (dispatch = external) resulted in the fuel cell power immediately falling to zero. This problem was traced back to the I/O module, which was not producing a control signal. This signal had previously been verified as good. This was investigated as time allowed. Ultimately, ORNL determined that the particular model Square D power monitor in use was produced just before Square D adopted a non-volatile memory in its power monitors. The power monitor had not been set up to produce an analog output corresponding to power output since the failure of the power supply caused a loss of all settings of this type.

9. *Administrative delays*—ORNL requested of NTRC management that the Square D power monitor be repaired so that it produced the required analog output. Excessive delays were encountered; therefore, ORNL obtained necessary information and performed the needed programming.
10. *Intermittent and gradual failure of monitor*—About the time that it appeared all was set for implementing load tracking, the Square D monitor was seen occasionally displaying reboot messages; and, in the days and weeks following, it was occasionally seen completely blank, as if fully de-energized.[6] As long as these events were very infrequent, there was some question whether the failure was real and whether electricians called in for repair would be able to take effective action. Gradually, the frequency of these events increased; and a month later, the monitor appeared fully de-energized at all times.
11. *Ownership and cost issues*—The manufacturer had discontinued the model of the power monitor that failed, and a replacement would require a different cutout and mounting scheme in the 480-Vac, Service B, main breaker panel. Replacement and installation would cost well over $4000. Although ORNL had a project-related interest in a power monitor replacement, the building owners did not see any benefits that would justify the cost. This decision process took nearly 2 months.
12. *Limited alternatives in market*—ORNL surveyed the market for a less expensive alternative that would produce an analog signal, one that could be paid for with a research project account. Because of poor power quality, a more expensive watt transformer (or transducer) was necessary, and was selected, that would tolerate any PF. Because the building load on Service B is small relative to most commercial and industrial building loads, the watt transducer ORNL selected had to be special-ordered with custom-made transformers. This resulted in a 4- to 6-week delivery, and installation would take place after completion of the six-month study.

Regarding item 2 above, as the project proceeded, the importance of load tracking became more apparent. Not only could certain transient-related interruptions in fuel cell grid-connected operation have been avoided if load tracking had been in use, but also the building load late in the project (i.e., beginning early in November) began to fall below 150 kW regularly during off-hours. In the absence of load tracking, the fuel cell had to be operated at 110 kW during the final 2 months of the study in order to avoid feeding more than 50-kVA into the grid and causing an RPR lockout.

Many of the problems described could have been minimized had the organization that was operating and evaluating the fuel cell had full ownership of the load tracking control signal system. The entire load tracking system should be viewed as part of the fuel cell, and full ownership and control is essential. This and other lessons learned are presented in Sect. 4.3.

2.6 INTERACTION OF PF AND POWER SYSTEM DYNAMICS

To understand many of the events described in Sect. 3, it is important to understand the interaction of PF and the source of real power, especially in instances where significant levels of reactive power exist. The fuel cell provides primarily real power, although a small amount of reactive power can be produced for partial correction of PF. At the NTRC, PF levels are frequently poor (i.e., below 0.8), and the PF correction provided by the fuel cell is small (increasing the PF by only a few hundredths); therefore, this section will use the simplifying assumption that the fuel cell provides only real power. This is not to suggest that such an assumption is generally recommended or appropriate, but it will be helpful in gaining a clearer understanding of certain events encountered in this study.

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[6] It is hypothesized that the root cause of this failure is either a latent affect of the earlier lightning-induced damage or very poor power quality during dynamometer operation. Neither can be proved.

Figure 2.8 shows a block diagram of the electrical system, comprising the grid, transformer, fuel cell, and load in the NTRC. In this section, we will consider how different types of power can affect the PF as viewed by the utility (i.e., at the main Service B transformer).

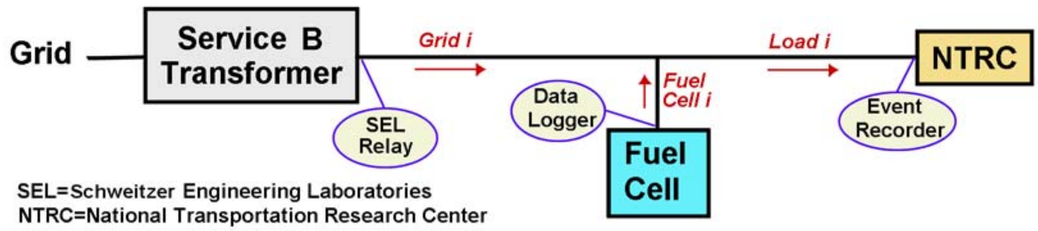

Fig. 2.8. Major current sources/loads in the grid-fuel-cell-NTRC system.

Figure 2.9a shows the general relationship between real, apparent, and reactive power levels in a facility such as the NTRC, where the reactive power level is high. Since the fuel cell is idle, the grid is supplying all real and reactive power. Figure 2.9b shows the same relationship; however, in this case, the fuel cell is contributing 100 kW of real power. Because of this generation, the grid supplies a reduced level of real power, and the grid is now supplying mostly reactive power. Another consequence is that the power factor changed from 0.8 to 0.57 as seen by the grid (i.e., at the building transformer). The corresponding current lag angles increased from 37 to 55º. Taken another step further, if the fuel cell generation level is increased to the full 200-kW level and the real power demand in the NTRC remains very close to the fuel

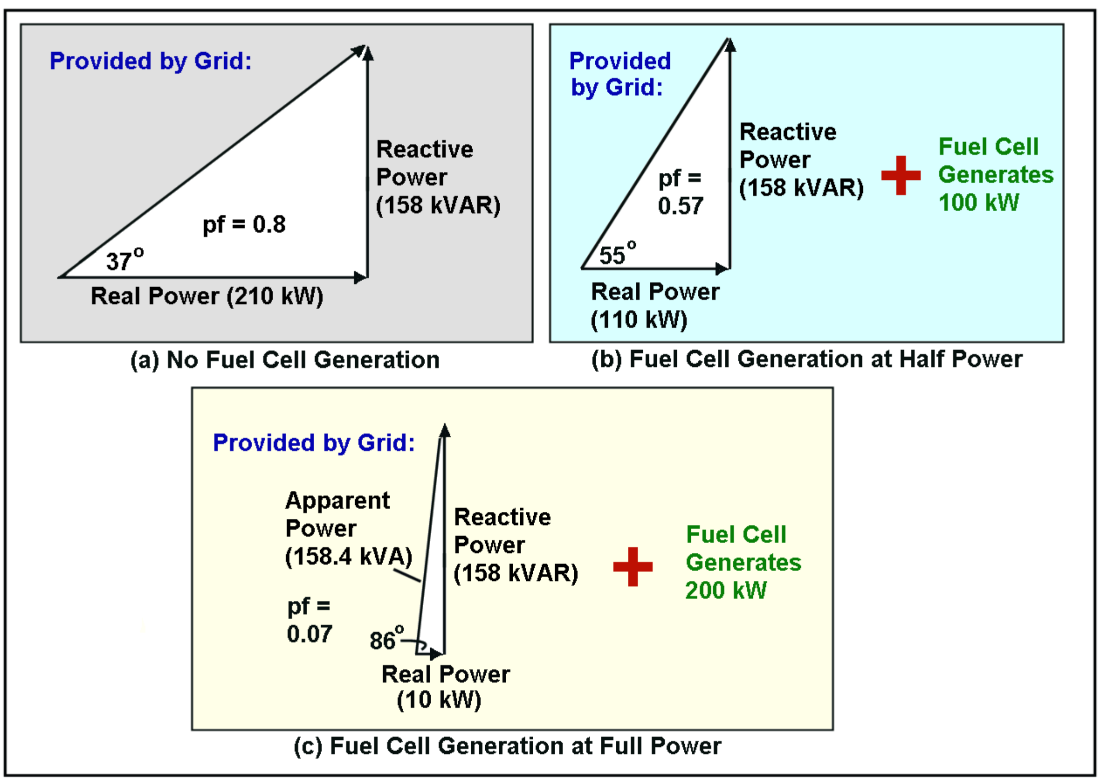

Fig. 2.9. Effects of meeting real and reactive power demand with a progressively greater fuel cell contribution.

cell's full generation capacity, the result is evident in Fig. 2.9c. With the grid supplying only 10 kW of real power and the same reactive power as before, the PF is now extremely low (0.07) and the current lag angle is 86º. Under these circumstances, the apparent power has decreased to become numerically very close to the reactive power. If this general trend continued, this time due to an 11-kW decrease in the building load, the current-to-voltage phase lag would be >90° and the apparent power would be well over the 50-kVA limit, thus resulting in a RPR trip after 5 sec.

Throughout the study, reactive power remained well above 50 kVAR. Thus, it is clear how the type of reverse power protection used in this study could cause a trip even when the reverse *real* power was near zero (as it would be just above 90° lagging). In effect, crossing the 90° limit for >5 sec guaranteed a trip.

A major result of bringing the fuel cell to full power is the negative effect it had on the PF or current lag angle as seen at the building transformer. This effect would have been significantly less in each case had the reactive power demand in the building been much less. Reactive power becomes high most frequently as a result of the operation of large motors that are oversized for their application. In addition, the NTRC has a unique situation in which the PF is severely worsened by the operation of dynamometers in research labs (see Sect. 2.3.4). The effect of dynamometers dumping power into the grid has been observed to change the PF from 0.8 to as low as 0.2 and to greatly increase harmonic distortion.

3. DATA DESCRIPTION AND ANALYSIS

This section provides the data collected during the six-month study of fuel-cell-to-grid connectivity. First, an overview is provided to give the reader some sense of the kinds of events that will be discussed. Then the events are discussed in detail, beginning with those that involved a reverse power lockout relay actuation and followed by those that did not.

Power production data for the fuel cell over the full six-month period are provided in Appendix A in a series of plots.

3.1 OVERVIEW OF EVENTS DURING GRID-CONNECT OPERATIONS

The interruptions to fuel cell grid-connect operation are initially divided into two groups, those events that involve an external permissive (i.e., actuation of the lockout relay) and those that do not. Table 3.1 lists the events in which a reverse-power lockout relay actuation took place. The table provides time, date, and information provided by the SEL relay such as phase current levels, qualitative waveform plot characterization, and approximate phase lag angles. In addition to showing currents for each phase, the current to ground, I_G, and the residual current (sum of all three phases), I_Q, are provided. Note that when the current unbalance is high, the I_Q is also high. The initiating events are briefly stated, based on knowledge of coincident electrical storm systems, trips of major electrical equipment in the NTRC, etc. The last column indicates what anomaly may have been listed in the fuel cell event log.

Table 3.2 lists the events that did not involve an external permissive from the lockout relay. The table provides date, time, fuel cell event log information, and initiating events. The SEL relay data that were available in Table 3.2 are not available for these events because these events did not create an external permissive, which is a necessary condition for the SEL relay to archive a set of data for later retrieval by LCUB.

Table 3.1. Fuel cell trip events in which a reverse power lockout relay actuation took place

Date (2003)	Time[1]	3-phase I (amps)	I_G	I_Q	Waveform plot characterization	Lag angle	Initiating event	Fuel cell event log information
6/14	*06:40:22*	*~200 per phase*	*Occurred before 6-mo study period*			*Unknown*	*Not apparent*	*No grid anomaly*
6/16	*13:25:59*☼	*~300 per phase*	*Occurred before 6-mo study period*			*Unknown*	*Electrical storm, Feeder 254 reclosure*	*Grid unbalanced, grid undervoltage*
7/15	16:12:13.6☼	225,188,157	20	70	Severe—I step and unbalance	120^o	Not apparent	No grid anomaly
7/28	18:25:46.6	130,126,197	12	60	Severe I unbalance with a drop in I	160^o	Electrical storm	Grid unbalanced, grid undervoltage
8/13	14:43:38.9☼	1261,1342,1374	18	128	I unbalance, very high I	90^o	Not apparent	No grid anomaly
8/28	20:09:47.5	241,250,249	10	29	Slight I unbalance and distortion	100^o	Unknown	No grid anomaly
9/3	13:51:44.4☼	270,275,272	12	13	Slight I unbalance	90^o	Minor storm system	No grid anomaly
9/10	19:23:26.1	241,248,236	13	23	Moderate I unbalance	120^o	Unknown	No grid anomaly
9/18	15:06:51.4☼	296,296,302	16	16	Normal	90^o	Chiller trip	No grid anomaly
9/24	19:19:46	154,141,145	19	5	Normal	210^o	Not apparent/chiller shutdown?	No grid anomaly
11/1	02:11:36	166,151,163	14	20	I unbalance with a drop in I	220^o	Low building load—no load tracking	No grid anomaly
11/4	02:09:99	160,154,166	8	23	Large drop in I and unbalance	220^o	Low building load—no load tracking	No grid anomaly
11/14	23:18:24	Not available			Not available	Not available	Low building load—no load tracking	No grid anomaly

(1) ☼ = during work hours when common transients and possible dynamometer operation may have adversely affected power factor.

Table 3.2. Fuel cell trip events not related to reverse power

Date (2003)	Time[1]	Fuel cell event log information	Initiating event
8/31	19:22	3 interrupts for unbalanced grid voltage for >0.5 sec resulted in an "excessive disconnect count" permissive	Severe electrical storm
9/28	10:01 (weekend)	Fuel cell event data for this event lost due to a "controller reboot." The controller reboot itself was a strong indication that the uninterruptible power source (UPS) had failed	Grid voltage sag
10/14	16:25☼	Grid under voltage and voltage unbalance conditions lasting in excess of allowed time caused the fuel cell to enter the idle mode	Voltage sag in grid (possibly weather related)
11/4	12:19:07☼	Controller reboot and total shutdown.	Unknown UPS anomaly
11/28	05:25:19	Interrupt >0.5 sec followed by unbalanced grid voltage transients	First V unbalance lasting >0.5 s
12/14	15:36:38	Grid voltage unbalance >0.5 sec	V unbalance lasting >0.5 s

(1) ☼ = during work hours when possible dynamometer operation may have adversely affected power factor.

3.2 DETAILS PERTAINING TO LOCKOUT RELAY TRIPS

The primary goal of this section is to present event data and, based on the data, present a likely and/or postulated cause for the event. In some cases, the cause will not be clear and the cause may have to be partially inferred from similar events for which more is known.

A secondary goal is to provide the reader with some sense of the difficulty that was encountered in sorting out events that were often perplexing and that often appeared to be like other events but were not. For instance, it was not known during the early months in how many different ways the PF could be brought below 0.7 or 0.6. During early months, NTRC operation in the 250–370 kW range seemed to provide a comfortable buffer where load tracking of the fuel cell would be of limited value. A gradual reduction of load over months, with a sudden onset of chiller cycling during night hours late in the study, changed that reality. Other complex phenomena, such as the presence of high fifth harmonics during certain hours and voltage transients during electrical storms, may have caused fuel cell interruptions that will never be clearly linked to the cause.

Another difficulty encountered in the study was the widely accepted description of the RPR protection scheme. Beginning during the fuel cell site construction process, LCUB, the contractors, and all participants in the research consistently spoke of a "50-kW limit" that would be placed on reverse power. It was not until 2 months *after* the study that EPRI-PEAC discovered that the SEL reverse impedance scheme actually resulted in a 50-kVA limit. As described in Sect. 2.3.4, this difference had important ramifications.

Data collection activities and data processing were provided by EPRI-PEAC. Data logger operation did not provide immediate feedback on operation. Data would be collected over several days, manually downloaded, and stored for processing as time and other priorities allowed. This study was conducted based on limited resources. The data provided by EPRI-PEAC were extremely useful in performing the analysis toward the end of the six-month study, but the data summary plots were not always available on either a weekly or monthly basis to provide a full understanding of what was occurring in the grid-connected system. This "understanding lag" resulted in some unnecessary reverse power events during the study, but is not believed to have significantly affected the final analysis or findings provided in Sect. 4.

This section begins with the discussion of two events in June that are "pre-study events." The events proved useful in determining what kind of electrical data recording instrumentation would be needed; however, the types of monitors in place at the time did not provide answers on probable causes for the events. Therefore, the beginning of the six-month study period was moved to July 1.

3.2.1 Event of June 14 (Preceding the Six-Month Study)

The fuel cell had been operating at 200 kW since the initial startup date of June 4. The June 14 event proved to be unique over the next several months in that it occurred during an early hour (i.e., 6:40 a.m.) of the day: however, the initiating event was never determined. LCUB reported that, based on SEL relay data, the reverse power detection scheme reportedly sensed about 199 A of reverse flow in each phase for at least 5 sec and sent a permissive to the fuel cell, causing it to go into the idle mode. The cause of the reported reverse flow event was unknown. Data also suggest a current imbalance in the power produced by the fuel cell, but this may have been due to an early electromagnetic interference (EMI)-induced problem with the instrumentation leads in close proximity to transformers.

Table 3.3 shows the specific events recorded in the fuel cell event history log. The disconnect sequence begins with an external permissive (i.e., the RPR) causing an "I52 disconnect" and an "I26 idle" state. Note that the precise order of events in the event log may be misleading (e.g., the first two events occurred in reverse order from what is shown). Event messages as they appear in the log may not necessarily reflect the actual order or time in which they occurred, but rather the order and time in which they were *reported* to the internal data logger. The "AIO board reset" simply indicates that the dc bus had dropped to zero volts, necessitating resets for the inputs and outputs. The disabled grid "ok" flags indicate that the fuel cell cannot be placed online again until the grid external permissive is cleared (i.e., the lockout relay reset). The entire event was over in about 5 sec. The SEL relay's 5-sec timed interval trip for reverse power would have preceded the external permissive.

Table 3.3. Event log for event of June 14, 2003

Date	Time	Message
6/14/2003	06:40:22	Entered I52 disconnect
6/14/2003	06:40:22	External grid connect permissive
6/14/2003	06:40:23	Entered I26 idle
6/14/2003	06:40:24	AIO board reset (callout)
6/14/2003	06:40:24	GRIDOK flag disabled
6/14/2003	06:40:24	GRIDOK flag disabled in idle (I26)

At the time of the event, it was believed that a grid outage event occurred and that the SEL relay performed as intended. A subsequent review of this event months later failed to produce any conclusions or suspected scenarios because this early event lacked adequate data.

3.2.2 Event of June 16 (Preceding the Six-Month Study)

The fuel cell had been idle since Saturday, June 14, and this event occurred shortly after a restart attempt. The initiating event was weather-related (e.g., lightning); during the event, a substation fault occurred, resulting in a reclosure on substation Feeder 254. A power supply for an ABB meter, located in the main breaker panel for Service B inside the NTRC, was destroyed (confirming the severity of the event). The fuel cell went off line and into idle. The RPR caused the shutdown of the fuel cell after reportedly sensing approximately 300 A in each phase for at least 5 sec.

Table 3.4 shows the fuel cell event log in which the first seven events pertain to the fuel cell sequence for establishing a grid-connect operating mode. This is followed about a half-hour later by the first interrupt due to grid voltage unbalance, and then, 3 min and 49 sec later, by an undervoltage condition. After 25 sec more, the SEL relay tripped, generating a permissive to the fuel cell protection circuitry. A normal sequence of messages followed as the fuel cell entered the idle mode. Finally, two more grid events were generated.

Table 3.4. Event log for event of June 16, 2003

Date	Time	Message
6/16/2003	1213:41	445 GRIDOK flag enabled
6/16/2003	1248:11	445 Operator selected power reset
6/16/2003	1248:43	445 Operator selected idle
6/16/2003	1249:02	445 Operator selected grid connect
6/16/2003	1249:02	445I Entered I30 idle G/C
6/16/2003	1249:03	445I Entered I48 connect 1
6/16/2003	1249:03	445I Entered I50 run G/C
6/16/2003	1321:45	446I Entered I55 interrupt
6/16/2003	1321:45	446I Utility grid voltage unbalanced
6/16/2003	1325:34	446I Entered I55 interrupt
6/16/2003	1325:34	446I Utility grid under voltage
6/16/2003	1325:59	446I Entered I52 disconnect
6/16/2003	1325:59	446I External grid connect permissive
6/16/2003	1326:00	446 GRIDOK flag disabled
6/16/2003	1326:00	446I Entered I26 idle
6/16/2003	1327:50	446I Utility grid under voltage
6/16/2003	1327:50	446I Utility grid voltage unbalanced

At the time of the event, it was believed that a grid outage event occurred and that the SEL relay performed as intended. A subsequent review of this event months later failed to produce any conclusions or suspected scenarios because this early event lacked adequate data. There were no observations or electrical data supporting the existence of a grid outage of 5 sec or more during which a reverse-power event may have conceivably occurred.

These two initial events, both involving the RPR, made it clear that additional data collection instrumentation was needed before the six-month study could actually begin. The limited buffer of the triggered event recorder on the fuel cell output circuit was not providing answers. Initially, the utility-required RPR was considered to be no more important than a fuse box to ensure that safety standards are satisfied. However, it was now clear that the data collection system would have to have an added capability to capture these 5-sec events for later analysis. Early in July, a data logger was connected to the NTRC's main breaker panel B to continuously monitor the building voltage and load. The sample rate for the Rustrak data logger is dynamic in that it is dependent on the rate at which electrical current is changing—the sample rate varied from approximately 1 point every 2 sec to several points/second. The sample rate also depends on the frequency of manual data downloads.

3.2.3 Event of July 15

The July 25 event occurred at 4:08 p.m. without any known initiating event. This is the first event of the six-month study. As shown in Table 3.5, the fuel cell event log indicates that the grid disconnect resulted from an external permissive, and subsequently the fuel cell went into the idle mode. There is no grid anomaly shown in the event log.

Table 3.5. Event log for event of July 15, 2003

Date	Time	Message
7/15/2003	16:08:22	Entered I52 disconnect
7/15/2003	16:08:23	External grid connect permissive
7/15/2003	16:08:24	GRIDOK flag disabled
7/15/2003	16:08:24	Entered I26 idle

The building power and PF plot from 3 to 6 p.m. (Fig. 3.1) shows that all three power curves (i.e., real, apparent, and reactive power) fluctuated for unknown reasons at about the time of the event. These are postulated to be coincident times; however, one must allow 5 min of clock error between the fuel cell clock and the Rustrak data recorder. The real and apparent power and the PF fluctuated for approximately 15 min following the event.

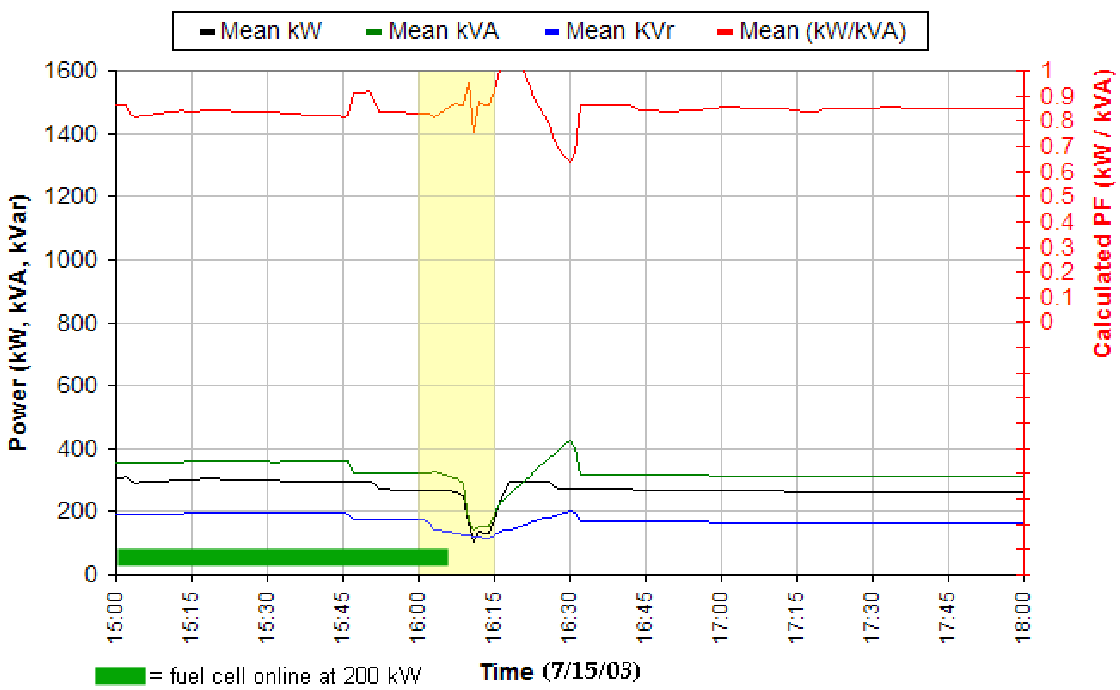

Fig. 3.1. NTRC building load and PF data for July 15, 2002.

At the end of the SEL relay's 5-sec reverse-power time delay, the SEL relay's trip summary data, shown in Fig. 3.2, indicates that the current phase angle was approximately 120º lagging and the "reverse currents" for the three phases were 225, 188, and 157 A. Since the waveforms changed at the end of the 5-sec timed interval as evident in the figure, the improvement of the current phase angle from 120º lagging to 20º lagging was a byproduct of the lockout relay trip. At the same time, the current increased as shown because the grid was assuming the full NTRC load. There was considerable current unbalance (phase C current being 30% less than phase A) that was due to unknown causes.

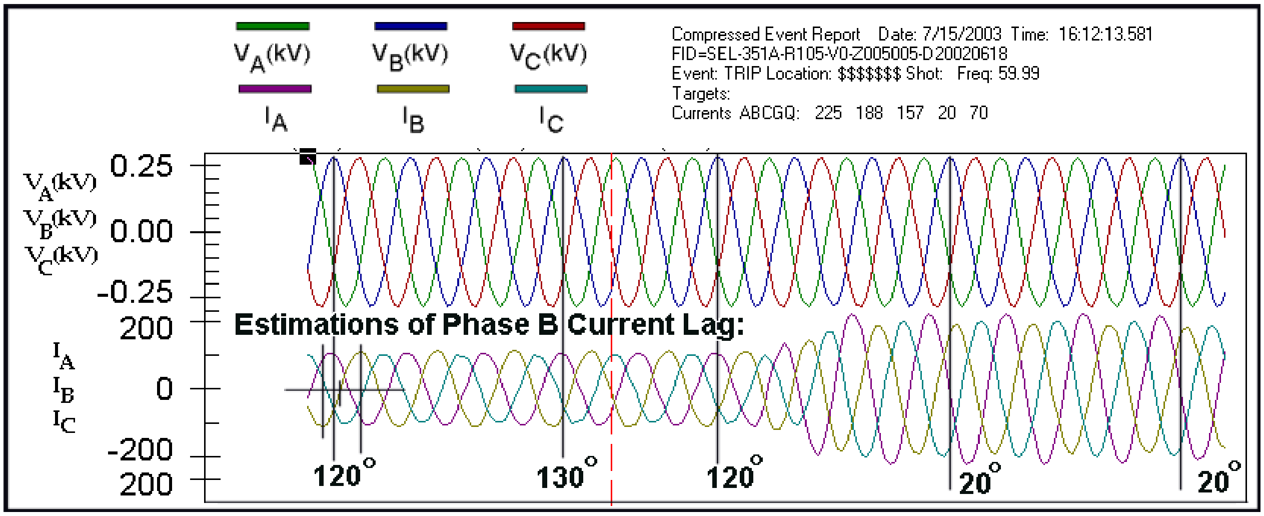

Fig. 3.2. SEL relay data showing voltage and current waveforms at time of trip.

After careful analysis of the system and the power plot data, it became clear that a reverse power flow occurred during the time when the apparent power was dropping from ~320 kVA to ~120 kVA. Since the fuel cell power generation was fixed at 200 kW and only ~100 kW load existed, it is reasonable to assume a reverse power situation existed. The ~110 kVAR reactive power level assures that the apparent power was >50 kVA as the 90° phase angle limit was crossed. It is unlikely that this event would have occurred if the load tracking system in the fuel cell had been operational.

3.2.4 Event of July 28

A storm system was present in the local area on July 28, causing a minor interruption around 12:48 p.m., and a more significant event occurred hours later. Minor interruptions, lasting seconds, are not normally discussed in this study; but an exception will be made here briefly to illustrate a routine aspect of the operation of the fuel cell's internal protective relaying. As shown in the first nine rows of the event log (Table 3.6), a utility grid voltage unbalanced condition resulted in a disconnect and interrupt because the unbalanced condition exceeded 0.5 sec. This placed the fuel cell in an idle state. Because the grid returned to normal within a prescribed period of time,[7] a grid-reconnect sequence automatically began that placed the fuel cell in the run mode 7 sec after the event began.

As will be seen in later events, if the grid had not returned to normal within the prescribed period, the fuel cell would have been left in the idle mode. It will be shown in later months of the study that this automatic reconnection feature was lost for a period of several weeks up to the end of the study period.

The more significant July 28 event occurred at 6:20 p.m. Both an electrical storm and its effects on the grid comprised the initiating event. As shown in the second part of Table 3.6, the fuel cell event log indicates that the grid voltage became unbalanced and an undervoltage condition was detected 1 min later. These events occurred 7 to 8 sec before an external permissive from the SEL relay caused the "disconnect" (i.e., caused the fuel cell to go into the idle mode). The lockout relay function resulted in the disabling of the "GRIDOK" flag.

[7] A fuel cell setup parameter that is usually set by the operator at about 5 sec.

Table 3.6. Event log for event of July 28, 2003

Date	Time	Message
7/28/2003	1248:12	1453I entered I52 disconnect
7/28/2003	1248:12	1453I entered I55 interrupt
7/28/2003	1248:12	1453I utility grid voltage unbalanced
7/28/2003	1248:13	1453A AIO board reset (callout)
7/28/2003	1248:13	1453I Interrupt duration > 0.5 seconds[1]
7/28/2003	1248:14	1453I entered I26 idle
7/28/2003	1248:18	1453I entered I30 idle G/C
7/28/2003	1248:18	1453I entered I48 connect 1
7/28/2003	1248:19	1453I entered I50 Run G/C
7/28/2003	1820:32	1459I utility grid voltage unbalanced
7/28/2003	1820:33	1459I entered I55 interrupt
7/28/2003	1820:33	1459I utility grid under voltage
7/28/2003	1820:39	1459I entered I52 disconnect
7/28/2003	1820:40	1459I external grid connect permissive
7/28/2003	1820:41	1459 GRIDOK flag disabled
7/28/2003	1820:41	1459I entered I26 idle

[1] The original event log message states “0.3 seconds”; however, IFC has assured ORNL that the interval is, in fact, 0.5 sec. Thus a blanket correction has been made in all event log tables.

The top plot of Fig. 3.3 shows the building power and PF plot from 9 a.m. until the end of the day. The external permissive from the SEL relay presumably occurred during a large dip in all three power plots and instability in the PF plot. With the variable, dynamic sampling rate of the data recorder, it is not certain how many data points would have been recorded during the 5-sec timed interval for reverse power. For this reason, and because Fig. 3.3 provided insufficient resolution, more detailed plots were generated. The second plot in Fig. 3.3 is the first zoomed-in view, and the third plot is the final expanded view. Only by examining the third plot does it become clear that conditions were adequate for an RPR trip. The real power fell to ~140 kW for 5 sec which satisfies the condition for a reverse power flow of adequate duration. The plots indicate that apparent power remained well above 50 kVA assuring that the power requirement for a RPR trip was met. Recall that the SEL relay threshold is -50-kVA with a current phase angle (relative to the phase voltage) > 90º and < 270°over a 5-sec, continuous[8] timed interval.

As seen in Fig. 3.4, the SEL relay provided waveform data at the end of the 5-sec period (when the relay tripped) indicating a ~160º phase angle for the phase current. This was reasonable based on the end of the 5-sec interval shown in the Fig. 3.3.

[8] It should be noted that had the current phase angle dropped below 90º (or the reverse power <50-kVA) at any time during the 5-sec interval, an immediate return to >90º (or >-50-kVA) would have restarted the clock at time zero. LCUB verified this clock reset function when the SEL was installed and tested.

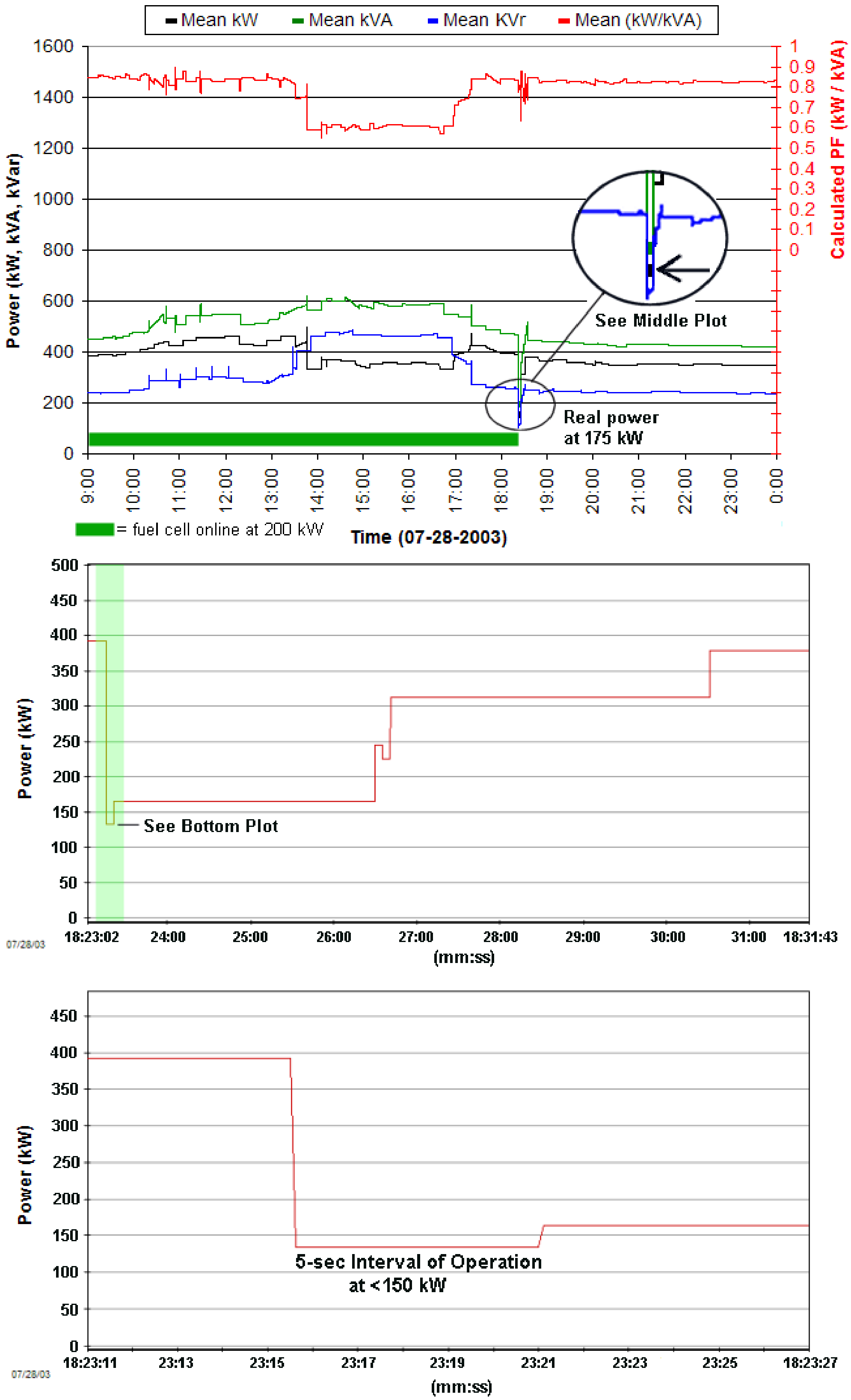

Fig. 3.3. NTRC building load and PF data for July 28, 2002.

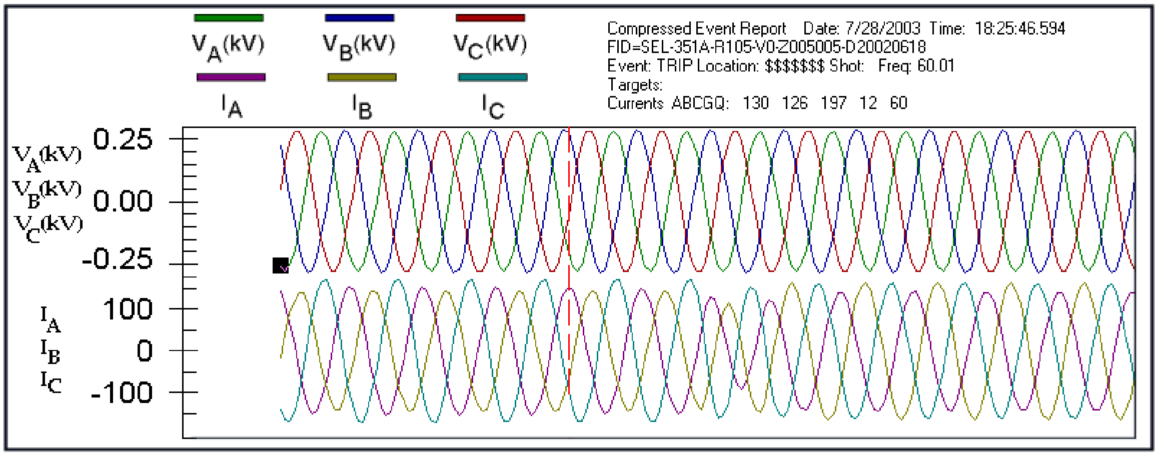

Fig. 3.4. Waveform data for the July 28 event provided by the SEL relay.

The event appears to be related to a substantial drop in power consumption in the NTRC. This may be due to the tripping of certain equipment in response to storm-related voltage transients. Given a large drop in power consumption, the fuel cell immediately assumed the entire real power load and began supplying power (~ 60 kW) to the grid. In the absence of load tracking, this could continue, in theory, for as long as the building load remained low.

3.2.5 Event of August 13

The cause of the August 13 SEL relay trip was initially unknown since there was no waveform anomaly, clear initiating event, or fuel cell event log information of significance. The fuel cell appeared to be simply taken offline as the result of an external permissive from the SEL relay. This event exhibited very high "reverse currents" recorded by the SEL relay for all three phases at the grid connection.

A review of the electrical data for the NTRC building loads provides considerable insight into this event. Figure 3.5 shows that the event occurred during the greatest drop in PF during much of August (the figure omits 10 days at the end of the month for better clarity). During the portion of the month depicted, and during the period when the fuel cell was grid-connected, the event coincided with the highest peak in reactive and apparent power. Figure 3.6 shows the data expanded to show details during the early afternoon of August 13. The event time is coincident with the half-hour period of minimum PF and the peak in reactive power.

The event occurred at a PF of 0.3 at the main breaker panel, indicating a lagging current of 72.5º. These severe conditions are the result of a dynamometer regenerating power back into the distribution system at the NTRC.

The fact that the SEL relay at the transformer generated a permissive indicates that the instrument interpreted a > 90º phase angle for at least 5 sec. This is confirmed by waveform data from the SEL relay showing a ~90º phase angle at the end of the 5-sec timed interval.

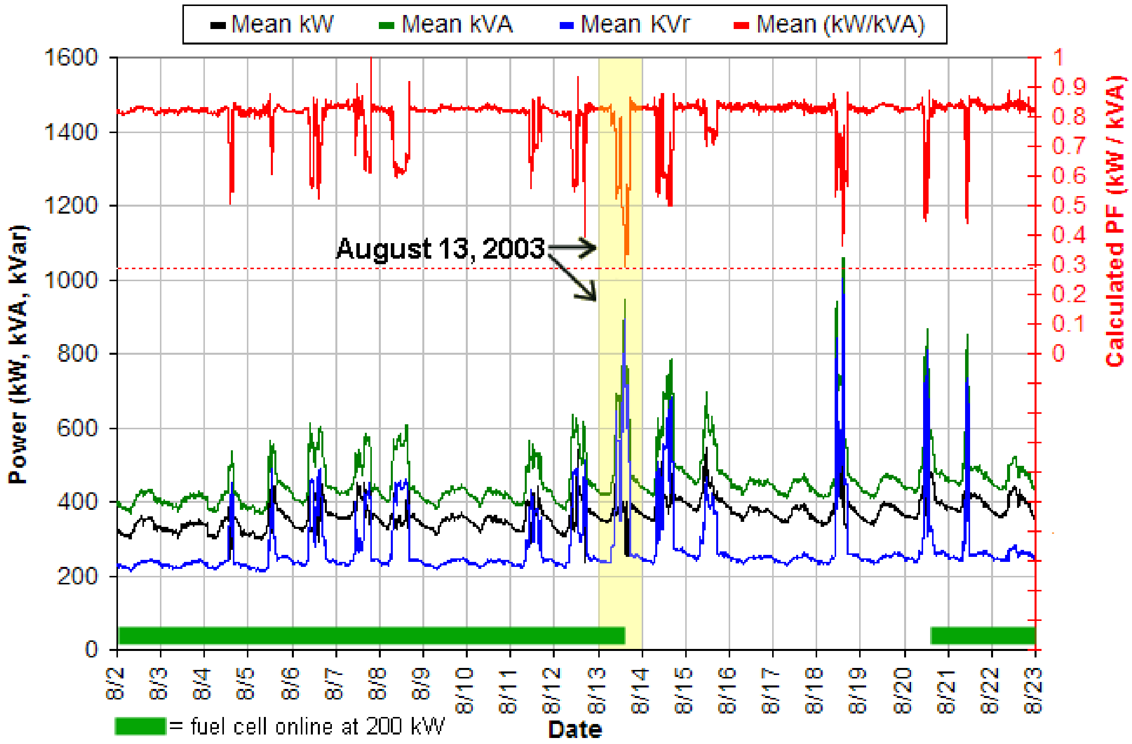

Fig. 3.5. NTRC building load electrical data (August 2003).

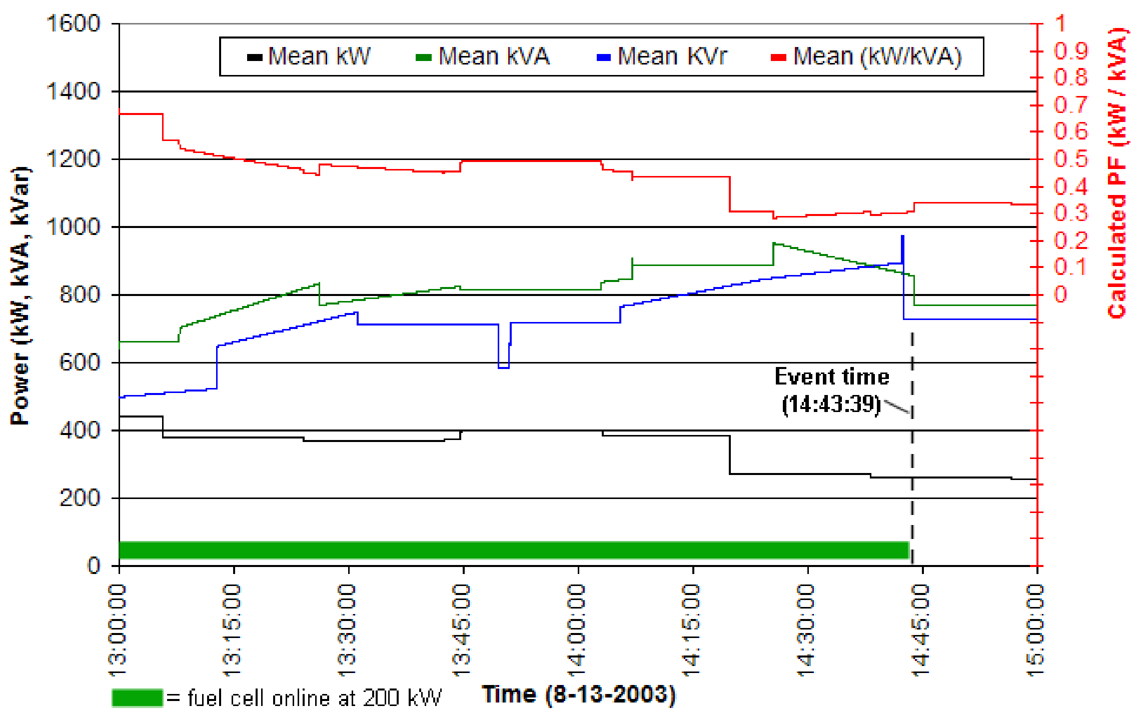

Fig. 3.6. NTRC building load electrical data for 2-hr period on August 13.

Unbalanced "reverse currents" of 1261, 1342, and 1374 A_{pk} (average RMS = 937 A) were recorded for the 3 phases by the SEL relay at the end of the 5-sec timed interval. These data are problematic because the fuel cell is not capable of producing such a level of current in excess of the NTRC demand.

Further analysis can be aided by looking at the overall system (Fig. 3.7). The power plot showed that the reactive power level was 750 kVar at the time of the event. Although measured at Panel B, it also applies to the transformer location, because the fuel cell supplies only real power. The building was consuming 250 kW, of which the grid was supplying only 50 kW. This produces lagging current phase angles at the transformer and NTRC of 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 SEL relay trip occurred because the monitor made an ~4º phase error for 5 sec because of the harmonic currents and interpreted the 86.2º lag as a ~90º lag. This solves the problem of the high reverse currents 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.

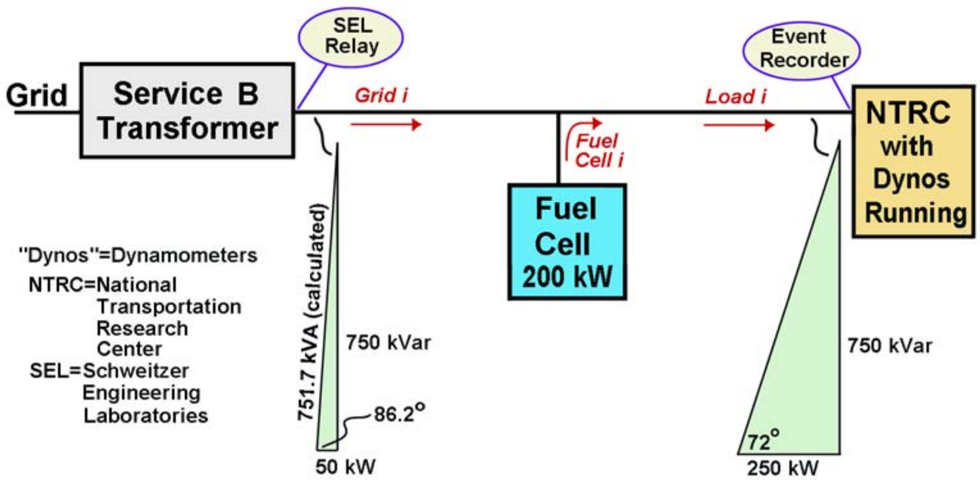

Fig. 3.7. System view of the August 13 event during high reactive power demand.

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 to other DER locations low, understanding the underlying principles was helpful in gaining an understanding of other events that occurred during this study.

3.2.6 Event of August 28

At about 8 p.m. Thursday, August 28, the NTRC building load plummeted to about 95 kW and remained there for almost 2 hours, as shown in Fig. 3.8. This created a reverse power situation that, in the absence of load tracking, caused the SEL relay trip.

The SEL relay produced waveform data (see Fig. 3.9) at the end of the 5-sec timed interval showing that the phase differential between the voltage and the current (as viewed at the Service B transformer) was >90º. The phase differential was due to the fuel cell's real output power level, which more than offset the real power demand of the NTRC loads. Thus, the excess real power flowed back into the LCUB distribution system.

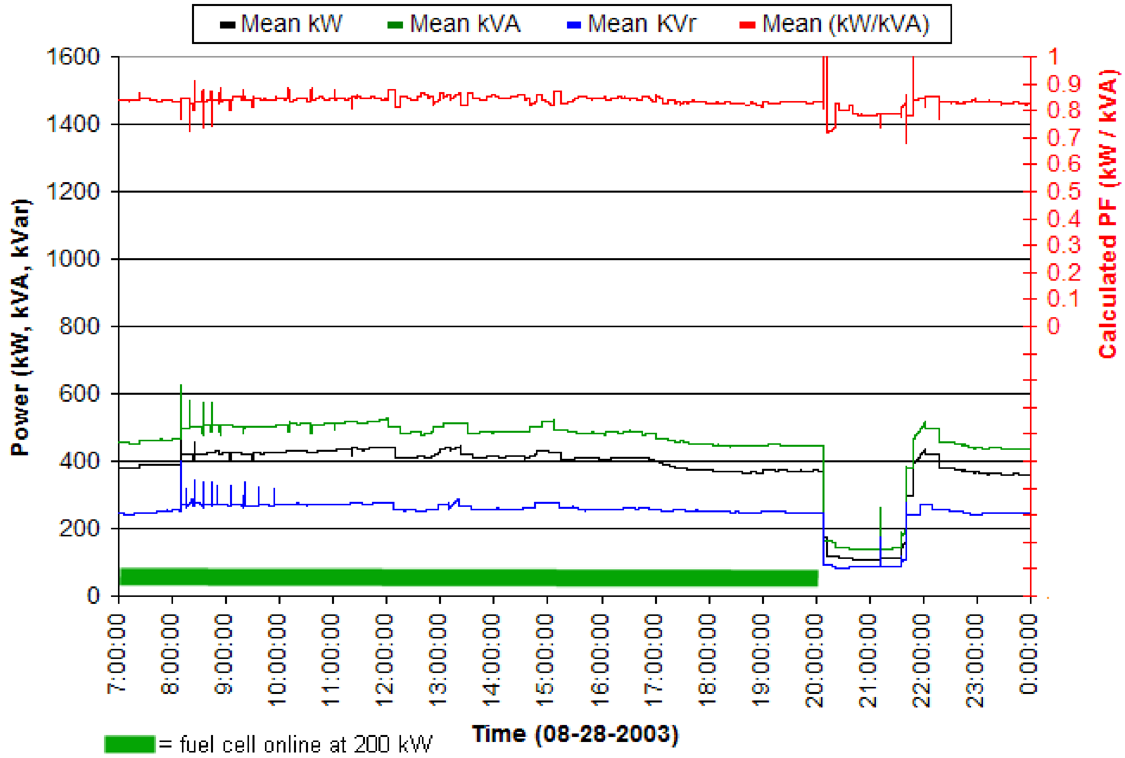

Fig. 3.8. NTRC building load electrical data for 17-hr period on August 28.

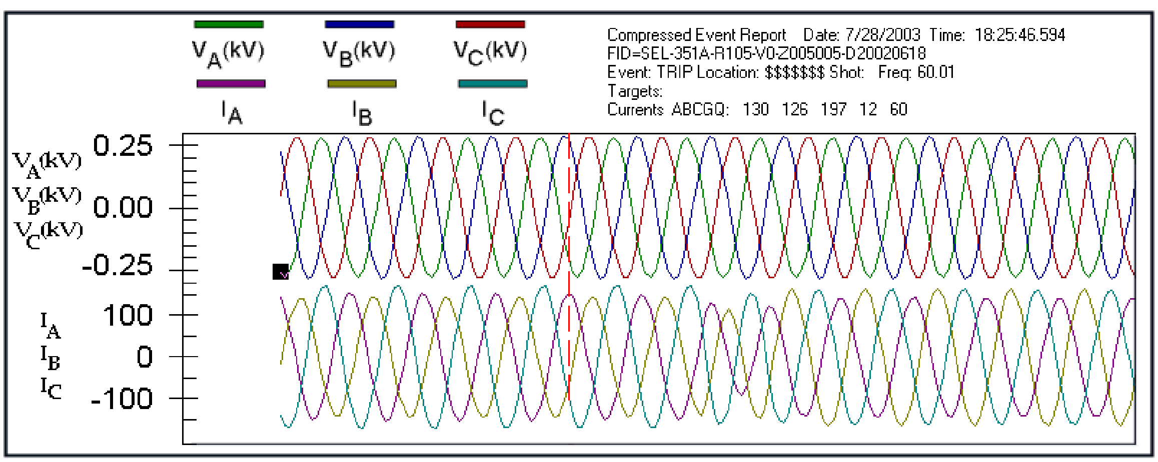

Fig. 3.9. Waveform data for the August 28 event provided by the SEL relay.

This event involved a reverse power situation in the absence of load tracking (which would normally be provided at a DG site). Load tracking, if operable in this system, would have reacted to the load drop by decreasing power generation at the rate of 20-kW/sec. Thus, in just over 2 sec, the fuel cell output would have matched the load's real power demand and the 5-sec reverse power trip condition would not have been met.

3.2.7 Event of September 3

September was an eventful month in which there were a number of severe PF excursions and severe drops in NTRC power levels, as indicated in Fig. 3.10. Note that, as expected, the low-PF excursions correspond to high peaks in apparent and reactive power. The four disconnect events for the month are highlighted in yellow. As indicated by the green bar at the bottom of the plot, the percentage of the month when the fuel cell was grid-connected and producing 200 kW was small. This situation was due to delays in getting a reset of the SEL and lockout relays from the utility and the continuing setbacks in efforts to get load tracking operable.

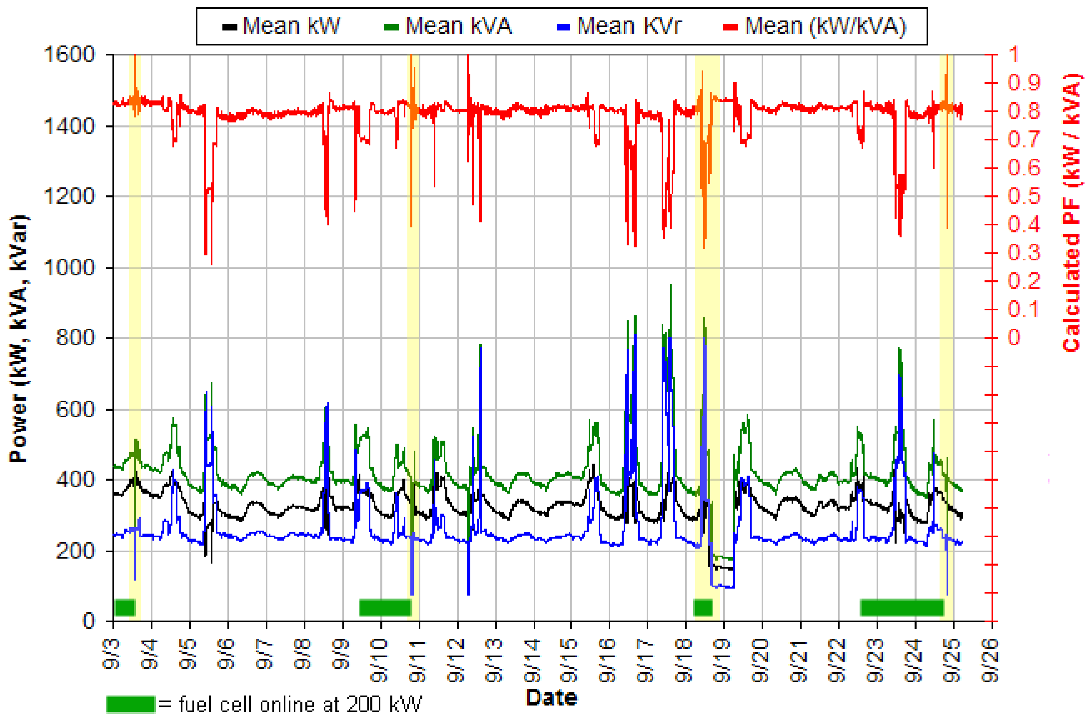

Fig. 3.10. NTRC building load electrical data (September 2003).

The month's first event occurred on September 3, and its event log is shown in Table 3.7. The sequence of events is quite standard for an external grid permissive event where no grid anomaly is evident (an unrelated voltage unbalanced message is listed in the table almost 2 h after the disconnect).

Table 3.7. Event log for event of September 3, 2003

Date	Time	Message
9/3/2003	1342:55	2342I entered I52 disconnect
9/3/2003	1342:55	2342I external grid connect permissive
9/3/2003	1342:56	2342I entered I26 idle
9/3/2003	1342:57	2342 GRIDOK flag disabled
9/3/2003	1527:54	2344I utility grid voltage unbalanced

The building load data for September 3 are shown in Fig. 3.11. The fuel cell was programmed to deliver full power, and the weather conditions were overcast and rainy with little or no lightning in the area. Just before 2 p.m., the real power, shown in black, dropped from about 400 kW to 195 kW for 10 min. This building load drop, as confirmed in a detailed review of the data, did not involve apparent power dropping any lower than 200 kVA but real power dropped to 195 kW which would have caused a small amount of reverse real power flow. As detailed in Fig 3.11, the SEL relay at the Service B transformer would have seen this small reverse power flow and a much higher amount of reactive power. By inspection, the diagram makes clear that the apparent power was over the 50 kVA trip limit by more than a factor of 3. Hence the power, time, and phase angle requirements were all met for a RPR trip.

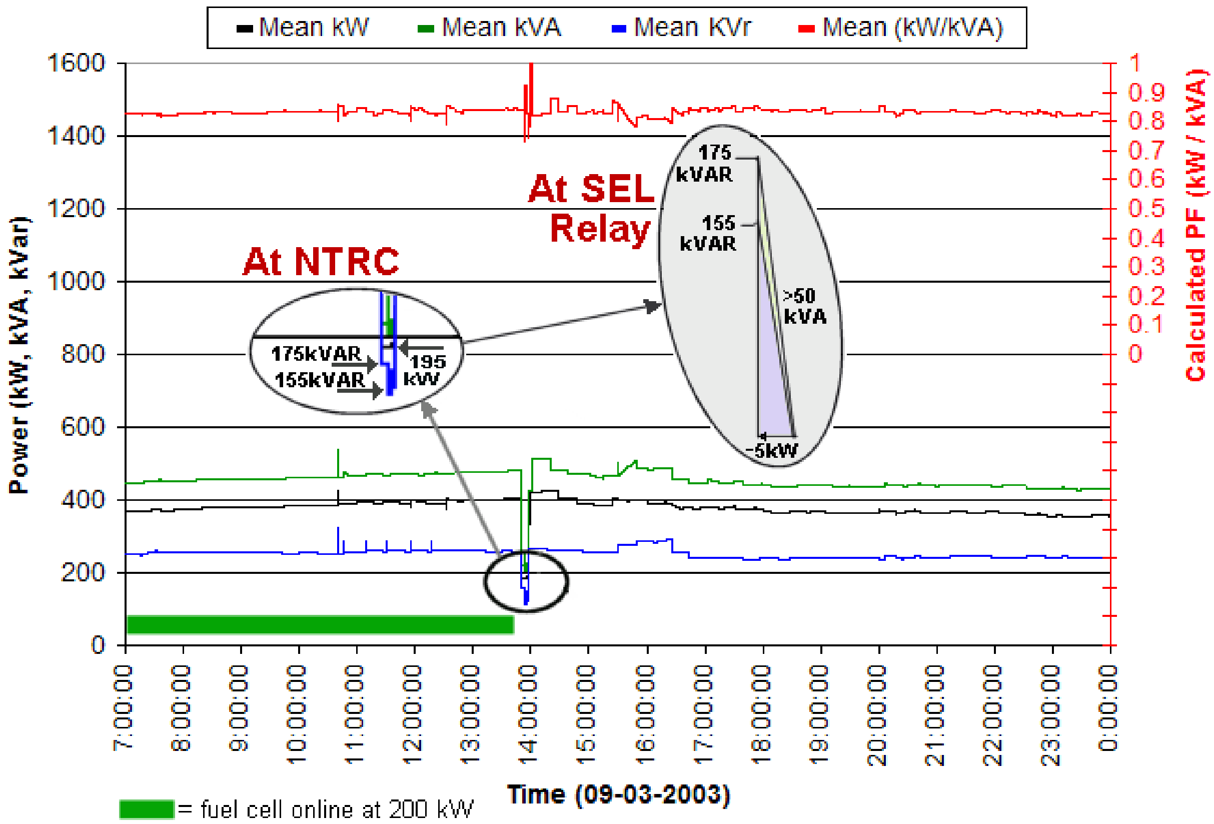

Fig. 3.11. NTRC building load electrical data for 17-hr period on September 3.

The actual SEL relay data for the event (see Fig. 3.12) showed a balanced current of about 272 A in each phase at the end of the 5-sec timed trip interval. The waveforms appear normal, but the current lagged voltage by roughly 90º. The SEL relay time was 13:51:44, which cannot be precisely correlated with the building load data. Based on both the building data and the SEL relay data, it appears that the SEL relay tripped the lockout relay during the building load drop.

This event is of special interest since it clearly shows how conditions were met for a trip based on the SEL load encroachment logic for reverse impedance while the more commonly used Device 32 reverse power function, if set for 50 kW, would *not* have tripped. In IFC's 25 other installations of its fuel cell where the local utility requires an RPR protection scheme, Device 32 is used. The protection scheme used in this study trips based on an apparent power limit with *no* limit on how small real reverse power may be.

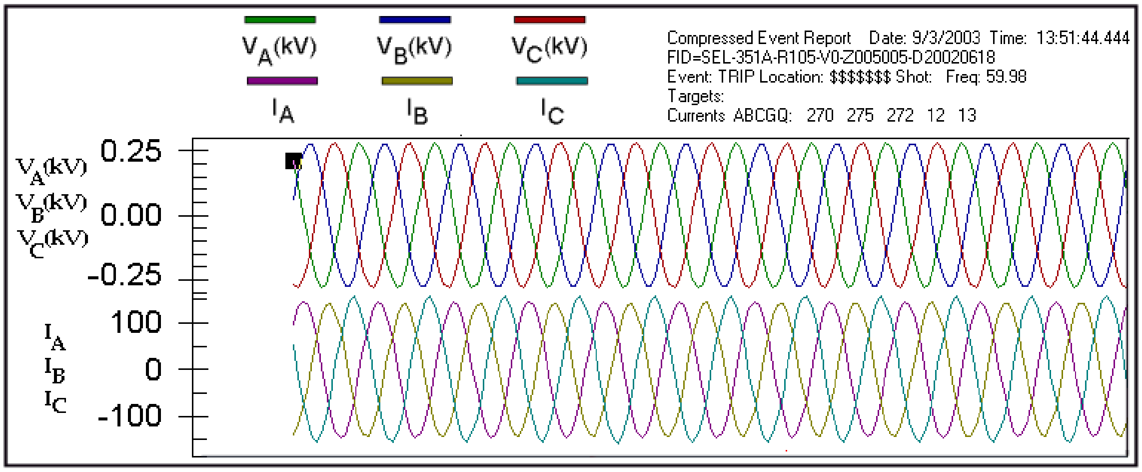

Fig. 3.12. Waveform data for the September 3 event provided by the SEL relay.

3.2.8 Event of September 10

The second September event occurred on September 10; its event log is shown in Table 3.8. The sequence of events is typical for an external grid permissive event where no grid anomaly is evident.

Table 3.8. Event log for event of September 10, 2003

Date	Time	Message
9/10/2003	1913:54	2516I entered I52 disconnect
9/10/2003	1913:54	2516I external grid connect permissive
9/10/2003	1913:56	2516 GRIDOK flag disabled
9/10/2003	1913:56	2516I entered I26 idle

The building load data for September 10 are shown in Fig. 3.13. The fuel cell was programmed to deliver full power. At about 7:13 p.m., the real power, shown in black, dropped from about 330 kW to 110 kW for almost 1.5 h possibly due to trips of the chiller and other building loads (unknown initiating event). The PF briefly dropped to 0.4 at the onset of this event. The drop in building load was sufficient (i.e., to a level <150 kW) to cause a reverse power condition because the fuel cell load tracking was not operable. There was roughly 120 kVA of apparent power in the reverse direction, more than twice the amount needed for a trip. The SEL relay recorded currents in the 3 phases of 241, 248, and 236 A with a 120º lagging phase angle at the end of the 5-sec timed interval. Waveforms appeared normal.

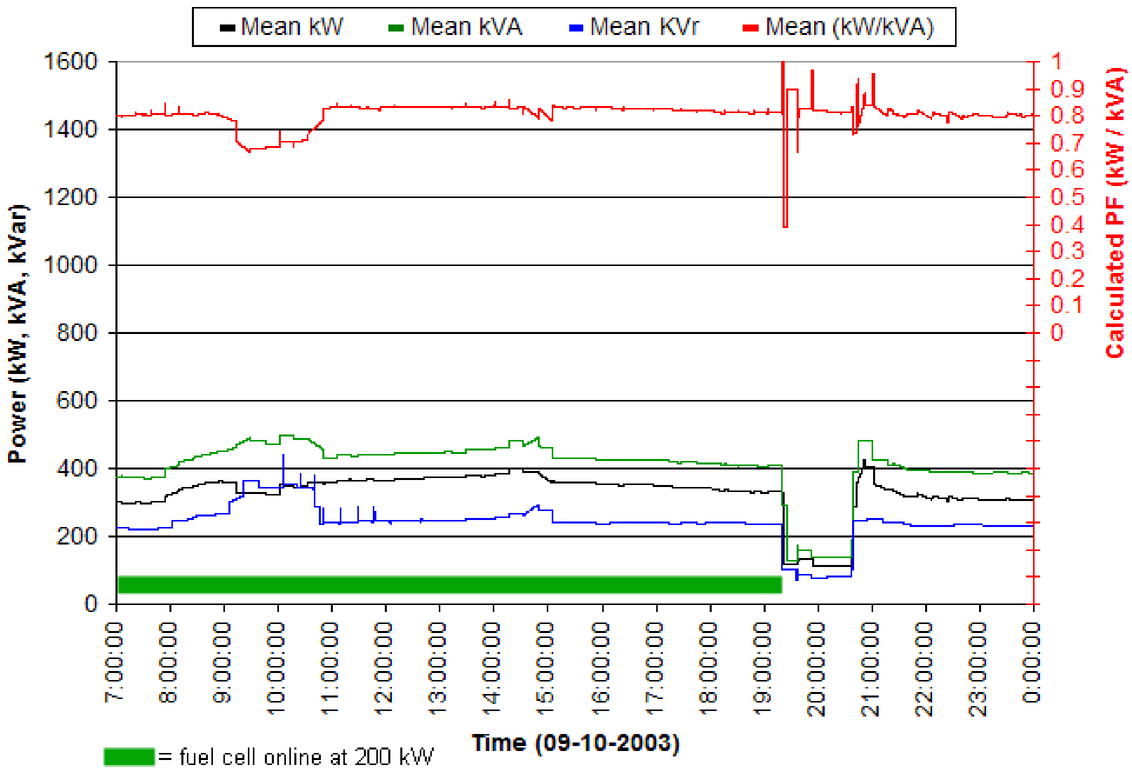

Fig. 3.13. NTRC building load electrical data for 17-hr period on September 10.

3.2.9 Event of September 18

The third event of the month occurred on September 18; its event log is shown in Table 3.9. The first part of the table indicates a test of the fuel cell's load tracking feature earlier in the day. The fuel cell was left in "external power dispatch," which means that an external load control signal was set to regulate the power level (i.e., load tracking was operable). In the second part of the table, the sequence of events is typical for an external grid permissive event where no grid anomaly is evident.

Table 3.9. Event log for event of September 18, 2003

Time	Date	Message
9/18/2003	1230:40	2701 external power dispatch selected
9/18/2003	1233:06	2701 local power dispatch selected
9/18/2003	1234:06	2701 external power dispatch selected
9/18/2003	1456:35	2703I entered I52 disconnect
9/18/2003	1456:35	2703I external grid connect permissive
9/18/2003	1456:36	2703I entered I26 idle
9/18/2003	1456:37	2703 GRIDOK flag disabled

The building load data for September 18 are shown in Fig. 3.14. The fuel cell was programmed to deliver full power. Effects of dynamometer operation are evident during the hours prior to the event. At about 3 p.m., the real power, shown in black, dropped from about 350 kW to 150 kW (with some variation) for about 1 h because of a chiller trip. The PF dropped to about 0.32 at the onset of this event (not remaining long enough to contribute to an SEL relay trip) and then took a step up to about 0.58, where it remained for most of an hour. There was likely some level of dynamometer operation during this hour. The power drop itself was to a low enough level that a >50-kVA reverse power situation resulted. It appears that the fuel cell was not able to load-track (for unknown reasons) and therefore an SEL relay trip occurred during the drop in load.

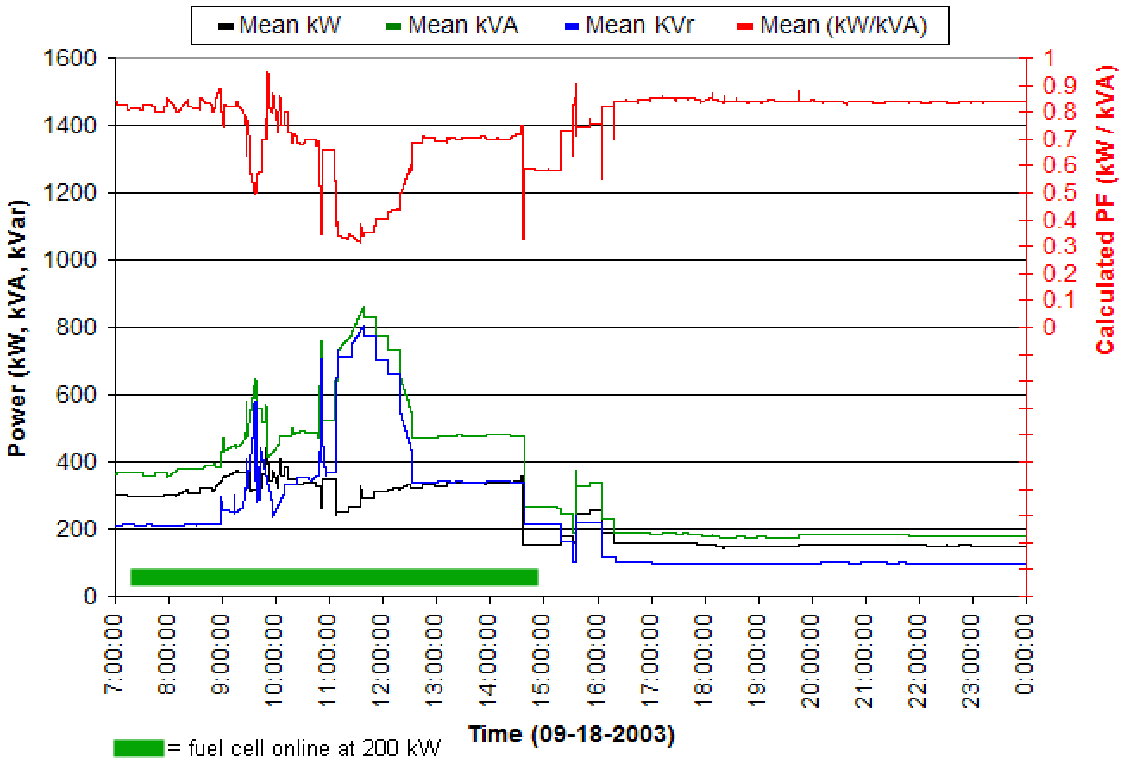

Fig. 3.14. NTRC building load electrical data for 17-hr period on September 18.

The SEL relay recorded currents in the 3 phases of 296, 296, and 302 A at the end of the 5-sec timed interval. Waveforms appeared normal. Figure 3.15 shows that the reverse power flow at the transformer resulted in a 103° current phase angle lag condition (13° into the reverse power region). Apparent power is calculated to have been 215.5 kVA at the SEL which is more than 4 times the amount required for a RPR trip. The high reactive power during the event, evident both in the building and at the transformer, was also a likely reason that the reverse current levels were higher than in nearly all other events, but its global applicability is reduced by dynamometer operation (see Sect. 2.3.4).

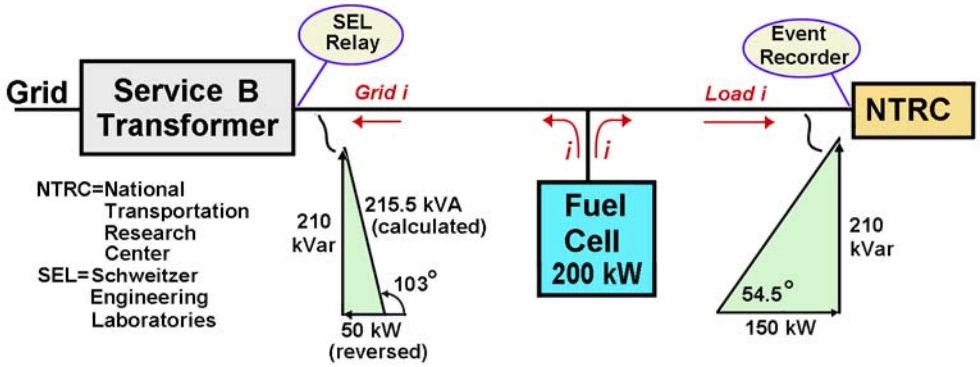

Fig. 3.15. System view of the September 18 event with reverse power flow.

3.2.10 Event of September 24

The September 24 event occurred 4 days before an event in which an internal fuel cell UPS inverter failure caused the fuel cell controller to reboot. This caused a loss of volatile memory; therefore, the event log for the September 24 event was lost. However, based on SEL relay data, clearly there was a lockout relay trip.

Based on the building load data shown in Fig. 3.16, the event occurred at about 7:15 p.m. when the PF plunged to 0.4 very briefly (i.e., less than 5 sec) and the real, apparent, and reactive power levels fell for a more significant period of time (i.e., about 10 min). During the power drop, the real power fell well below 200 kW, which, in the absence of load tracking, would have caused a reverse power situation. The apparent power remained above 100 kVA, easily satisfying the power requirement for the SEL relay trip.

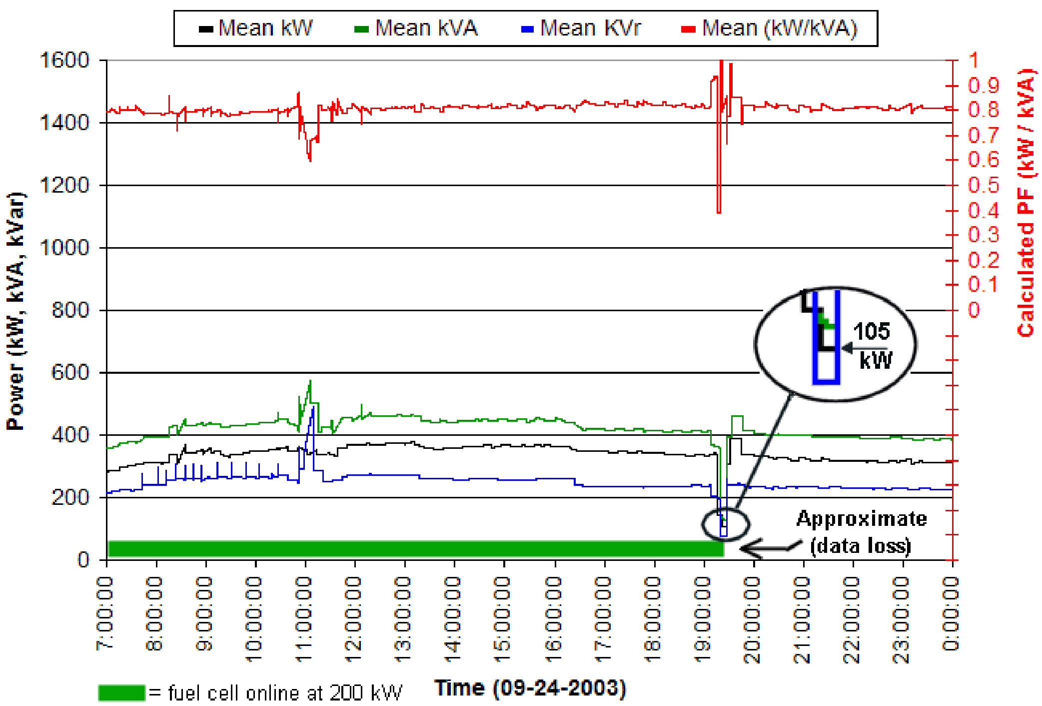

Fig. 3.16. NTRC building load electrical data for 17-hr period on September 24.

The SEL relay recorded currents in the 3 phases of 154, 141, and 145 A with an ~210º lagging current phase angle at the end of the 5-sec timed interval. Waveforms appeared normal. Since the reverse power was fairly substantial, approaching 100 kW, and the reactive power was in a very significant dip to less than 100 kVAR, the lagging current made a greater phase shift beyond 90º than in any prior event. The low reactive power during the event, evident both in the building and at the transformer, was also a likely reason that the reverse current levels were lower than in nearly all other events.

3.2.11 Grid-Connect Mode Transfer Attempt of October 3

On October 3, ORNL had a fortunate situation where, with dynamometers actively dumping power into the grid and PF at ~ 0.2 as measured at the Service B transformer, representatives from LCUB and IFC took part in an attempt to place the fuel cell online at 200 kW. As the fuel cell was placed under load, it became apparent that another SEL relay permissive would have occurred had LCUB not widened the permitted SEL relay impedance window from 90º to 100º lagging current just prior to the attempted grid-connect transfer. Even at the 100º setting, the system was on the verge of triggering an SEL relay permissive, so IFC reduced power to 125 kW and left it there.

Data archived for October 3 (see Fig. 3.17) show a "highly eventful" day of widely cycling power levels and PF. This plot is atypical of what is seen in commercial and industrial buildings similar in size to the NTRC. Other buildings may have large pieces of equipment cycle on and off, but to have equipment cycling combined with the presence of PF levels as low as 0.2 and high levels of harmonic distortion is quite unusual. The cause(s) of the steep changes in power level are not known. The near-90º angles reflect the fact that real power consumption in the NTRC had fallen to just below 200 kW. Months after the event, during a detailed review of the data, this was confirmed to be the likely case because the event log shows that these grid-connect attempts occurred at 1016, 1022, and 1426 hours: all three coincide with the periods in the plot when demand was below 200 kW.

When Schweitzer experts recommended to LCUB that it use the reverse impedance mode for protection at the NTRC fuel cell, they had no idea what kind of unusual PF the instrument would be seeing. Following this incident, ORNL proposed to LCUB that instead of relying on the reverse impedance load encroachment logic, a more standard RPR be adopted through new settings in the monitor. Based on what was known at the time, it was hoped that a protective scheme that did not interpret current-voltage phase difference and trip based on apparent power might produce fewer false permissives. Instead of pursuing another type of protective scheme, LCUB and ORNL began discussions with SEL experts and other experts in the field to identify the best measures. Ultimately, the SEL experts recommended continued use of the present protection scheme but with new settings providing greater allowances for current phase angles > 90º lagging.

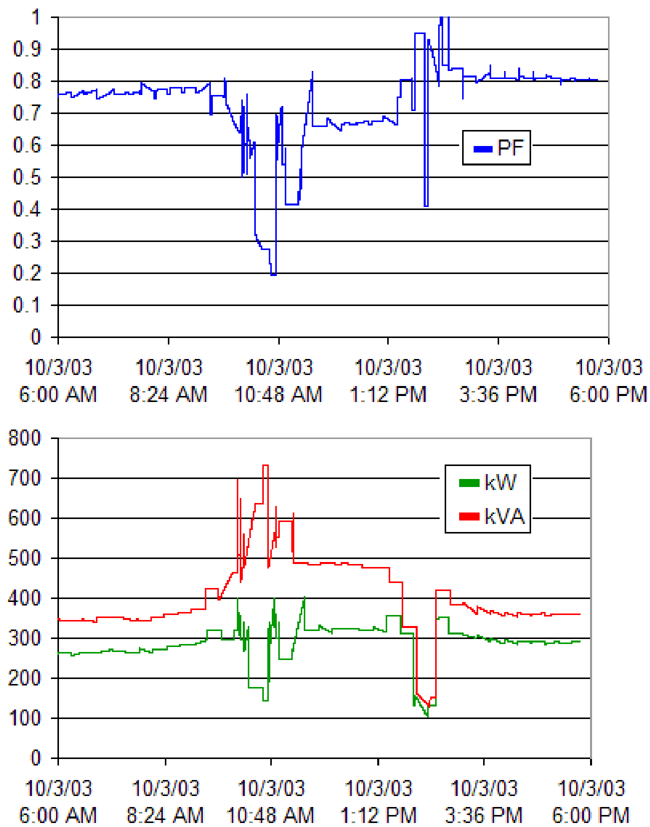

Fig. 3.17. NTRC electrical data for October 3, 2003.

Reducing the power level of the fuel cell to 125 kW on October 3 proved to be a prudent and effective measure, because operation at this power level did not result in any SEL relay trip events during the entire month. The reason is that the PF at the SEL relay improves when the grid supplies more real power (reactive power remaining constant). Of course, this lower power setting simply makes it less likely that a reverse power situation will develop. The power level was returned to 200 kW on October 31 because a new data collection system had been installed, and ORNL was interested in capturing data from an SEL relay reverse power trip event (as well as other types of events).

3.2.12 November Lack-of-Load-Tracking Events

In November, there were three lockout trip events that occurred as a result of excessive reverse current into the grid in the absence of load tracking. The events occurred on November 1, 4, and 14 at fuel cell power generation levels of 200, 150, and 125 kW, respectively. These are low-interest events that resulted from the ongoing delays in obtaining load tracking (see Section 2.5). The events were also intentional, because the fuel cell was adjusted from 125 to 200 kW on October 31 in order to generate events and record the data on a new 12-channel data logger that was installed in the Service B transformer cabinet.

This section will not present the very similar data from all three events but, instead, will present the detailed data of the November 14 event obtained from the 12-channel data logger. The event log for the November 14 event is shown in Table 3.10 and is quite typical for a reverse power lockout relay event.

Table 3.10. Event log for event of November 14, 2003

Date	Time	Message
11/14/2003	2318:24	3961I external grid connect permissive
11/14/2003	2318:24	3961I entered I52 disconnect
11/14/2003	2318:25	3961I entered I26 idle
11/14/2003	2318:26	3961 GRIDOK flag disabled
11/14/2003	2318:26	3961A AIO board reset (callout)

Figure 3.18 shows the plots of real power, apparent power, and PF at the time of the November 14 event. Note that the times indicated by the data logger are 1 h later than actual because the logger had not been updated from EDST to EST. The building load level (black plot line) dropped from ~80 kW to ~30 kW per phase (phase A being shown in the plots) because the building chiller was set to cycle off via a timer switch during the month of November. Once the building load dropped to ~30 kW, another device in the

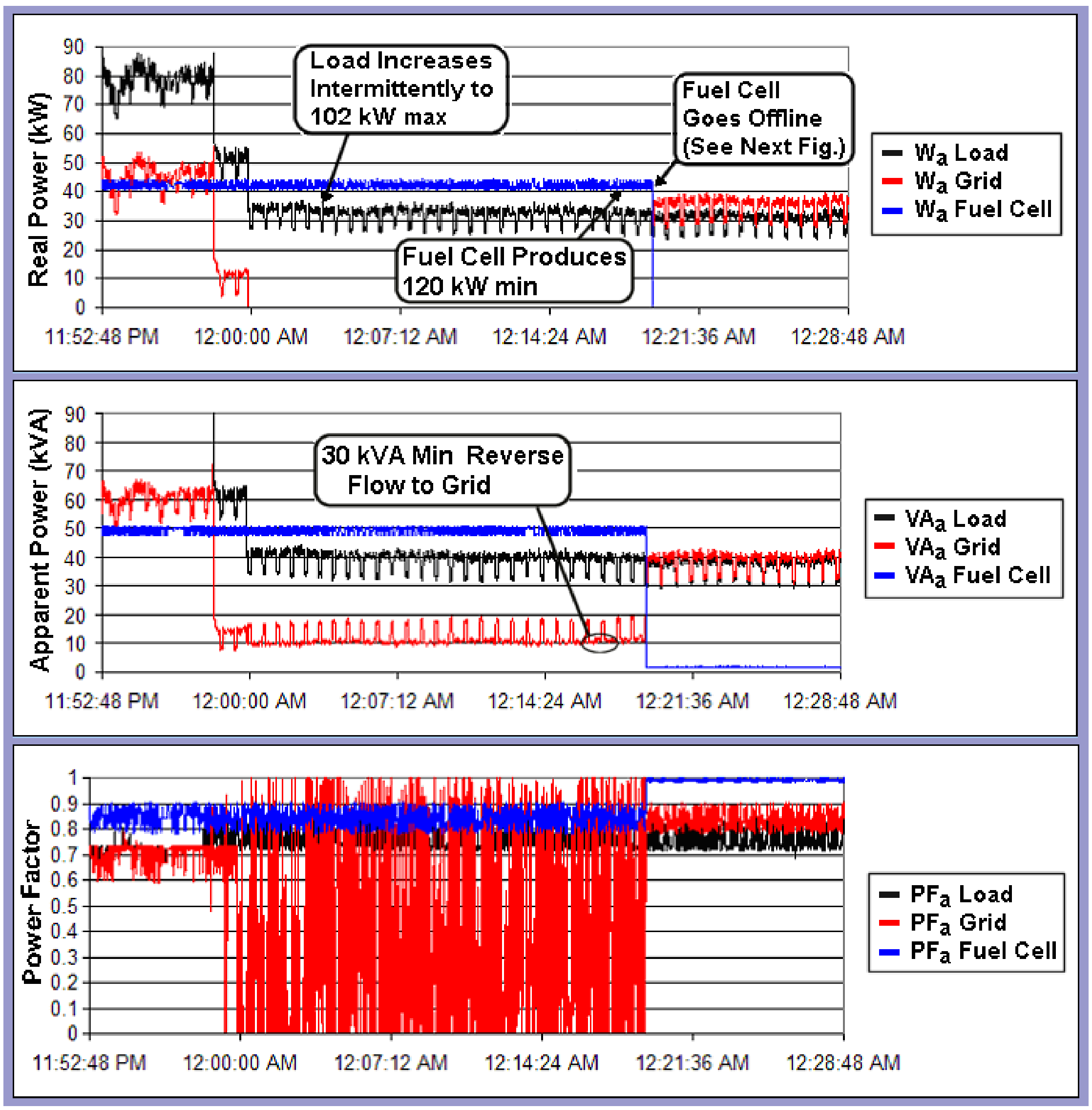

Fig. 3.18. November 14 event plots of real and apparent power and power factor.

NTRC evidently was cycling off and on more than 20 times every quarter hour. As indicated in the figure, the building load increased to 120 kW max and the fuel cell produced 120 kW min for a resulting reverse flow into the grid of 18 kW min. The second plot in Fig. 3.18 points out a min of 30 kVA into the grid. Together, 18 kW and 30 kVA will produce a current phase of 126° lagging. The 30 kVA and the 126° phase angle are both close to the 25 kVA limit and 120° limit (in effect on this date) and it was the fluctuation of each, occasionally below the threshold, that probably delayed the trip by several minutes until there was a period of 5 sec during which the limits were exceeded continuously.

The third plot of Fig. 3.18 shows the PF, which was originally very poor at 0.6 to 0.7. After the load dropped to a point where a reverse power condition existed, the PF plot became very erratic. In reality, the PF had passed into the negative range somewhere between 0 and –1. That the plot is so erratic is likely due to the presence of harmonic currents, as will be apparent in the waveforms presented later in this section. Once the fuel cell became idle, the PF improved to its best level in the plot, 0.8 to 0.9, because the grid was then performing its normal service, supplying high levels of real power.

Figure 3.19 is a zoomed-in portion of the first plot of Fig. 3.18 showing the precise real power conditions at the time when the reverse power trip limit was reached. The fuel cell was operating at a fixed output of 125 kW. It appears that a trip *may* have occurred even if Device 32 protection set at 25 kW was used.

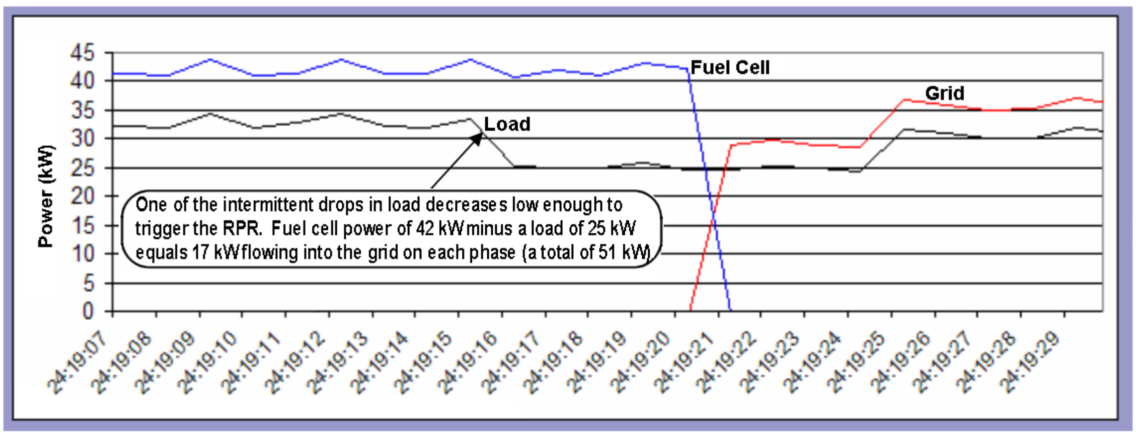

Fig. 3.19. Precise seconds at which the reverse power limit was reached.

Figure 3.20 shows the 3-phase waveforms for voltage and for current in all three lines of interest: NTRC, grid, and fuel cell. The voltage plot is normal both before the fuel cell trip and following it. The grid current in the second plot is very rich in harmonics prior to the trip, with reduced but significant harmonics following the trip. The third plot shows the drop in fuel cell current when the fuel cell was tripped off the grid-connect mode. The fourth plot shows the building load current, which remained steady throughout the event as it has through the great majority of events in this study.

The data for the other two reverse power trip events in November look similar to the data presented earlier in this section. The November 14 event came as a surprise because a fall of the building load to 75 kW would never have been predicted at the beginning of the study, when off-hour loads were well above 200 kW. The building HVAC is designed to make use of a chiller year-round because room temperature is adjusted by a cold-hot mixing scheme. Before November every effort was made to keep the chiller on line at all times, and it was unknown that this practice would soon change. However, early in November, the chiller began cycling off nightly at midnight via a timer switch. In response to the November 14 event, the fuel cell generation power level was adjusted from 125 kW to 110 kW, which prevented other reverse power events from occurring during the remainder of this study (a 1.5-month period).

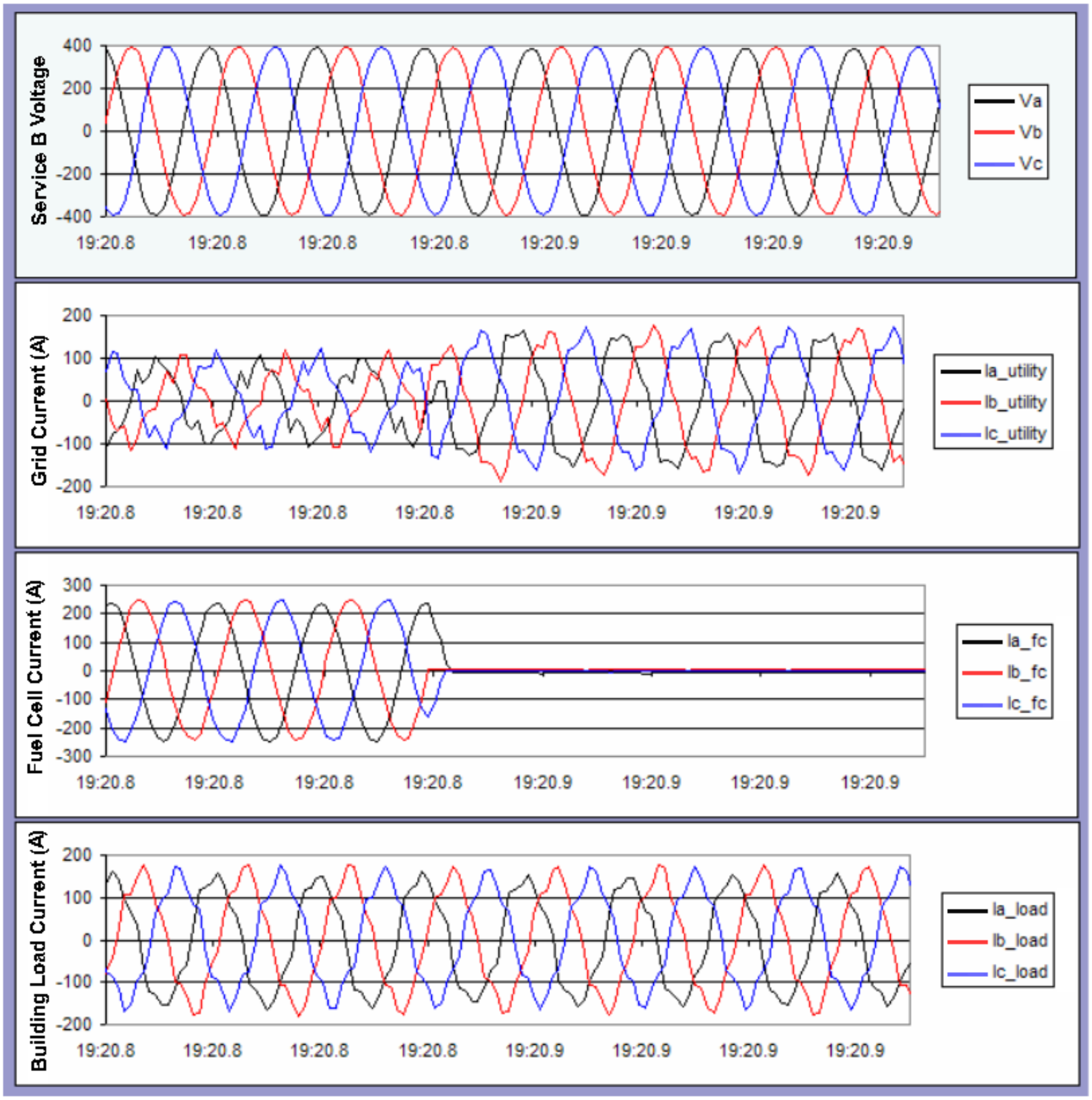

Fig. 3.20. Time plots of the Service B voltage and three corresponding currents.

3.3 DETAILS PERTAINING TO NON-LOCKOUT-RELAY TRIP EVENTS

The interruptions to grid-connect events described in this section are events of high interest that fulfill the original intention of this study. They have broad applicability to fuel cell grid-connect operation and, in some cases, to other types of grid-connected distributed energy resources (DER).

3.3.1 Event of August 31

An electrical storm on the evening of August 31 caused a number of voltage unbalance transient events that ultimately caused the fuel cell to be placed in the idle mode. This is the first event in this study that resulted from actions taken by the fuel cell's internal protective relaying system.

As indicated in the fuel cell's event log shown in Table 3.11, a grid voltage unbalance condition occurred at 1919:04 and lasted longer than 0.5 sec, causing a brief idle period followed by a reconnection (i.e., "Run G/C"). (Whenever the transients exceed 0.5 sec, the MCB001 breaker (Fig. 2.3) opens and then closes when the grid returns to normal.) Then, 23 sec later at 1919:27, a second grid voltage unbalance caused a similar idle period. Finally, 4 min and 39 sec following the second unbalance, a third unbalance caused an I52 disconnect due to an "excessive disconnect count."

Table 3.11. Event log for event of August 31, 2003

Date	Time	Message
8/31/2003	1919:04	2276I entered I55 interrupt
8/31/2003	1919:04	2276I utility grid voltage unbalanced
8/31/2003	1919:05	2276I interrupt duration > 0.5 seconds
8/31/2003	1919:05	2276I entered I52 disconnect
8/31/2003	1919:06	2276I entered I26 idle
8/31/2003	1919:10	2276I entered I48 connect 1
8/31/2003	1919:10	2276I entered I30 idle G/C
8/31/2003	1919:11	2276I entered I50 run G/C
8/31/2003	1919:27	2276I utility grid voltage unbalanced
8/31/2003	1919:28	2276I interrupt duration > 0.5 seconds
8/31/2003	1919:28	2276I entered I52 disconnect
8/31/2003	1919:28	2276I entered I55 interrupt
8/31/2003	1919:29	2276I entered I26 idle
8/31/2003	1919:33	2276I entered I48 connect 1
8/31/2003	1919:33	2276I entered I30 idle G/C
8/31/2003	1919:34	2276I entered I50 run G/C
8/31/2003	1924:06	2276I entered I55 interrupt
8/31/2003	1924:06	2276I utility grid voltage unbalanced
8/31/2003	1924:07	2276I interrupt duration > 0.5 seconds
8/31/2003	1924:07	2276I excessive disconnect count
8/31/2003	1924:07	2276I entered I52 disconnect
8/31/2003	1924:08	2276I entered I26 idle

This type of event should not be confused with the excessive *interrupt* count described earlier. The excessive interrupt count event is designed to idle the fuel cell if there are >three interrupts in 15 sec or >six interrupts in 2 min. These events are typically very brief (i.e., <0.5 sec). In contrast, the excessive *disconnect* count is an uncommon protective relay scheme that places the fuel cell in idle mode after the third event that causes an interrupt of >0.5 sec within a 5-min-and-5-sec period.

The electrical storm in progress at the time of the event is evident in the building load electrical data plot shown in Fig. 3.21. Based on the figure, it appears that the event occurred near the beginning of a series of electrical transients lasting at least 3 h.

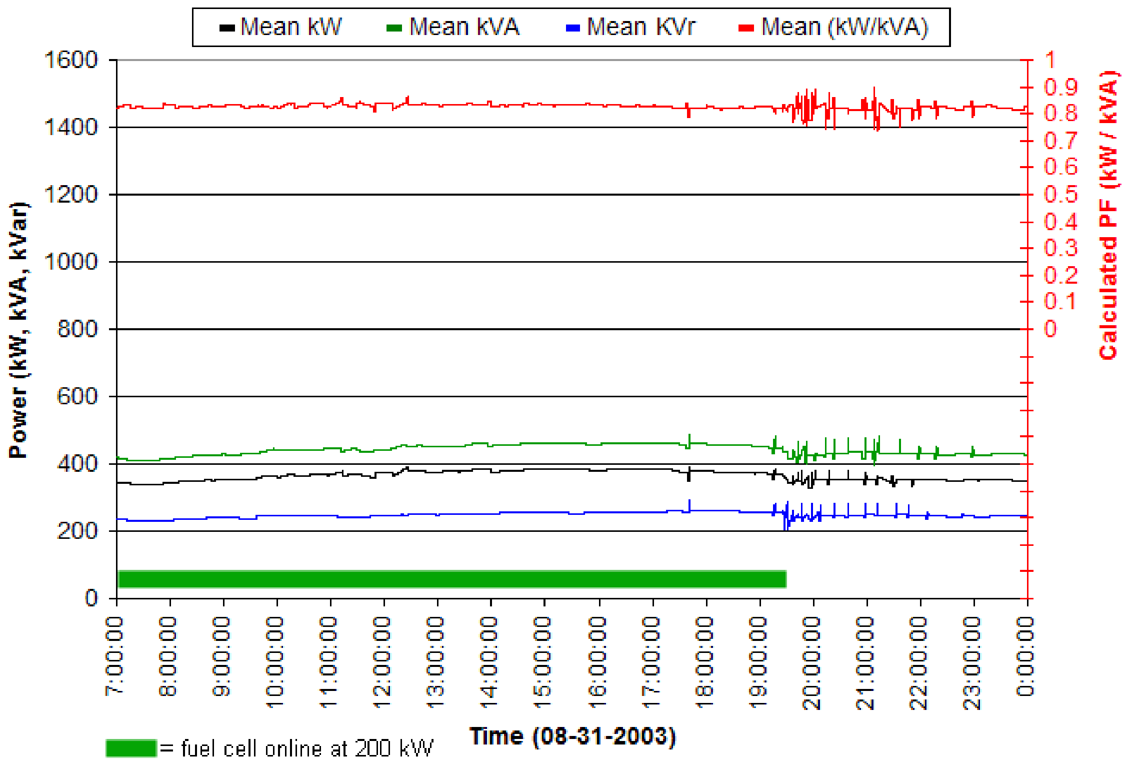

Fig. 3.21. NTRC building load electrical data for 17-hr period on August 31.

Figure 3.22 shows detailed voltage and current event data from the fuel cell monitor/event recorder. Note that the monitor clock was not synchronized with the fuel cell event log clock times. The left-column plots show three voltage unbalance conditions and are followed by a plot showing the transfer into the idle mode. The right-column plots show the corresponding current plots. The first two voltage unbalance plots are 23 sec apart, which corresponds exactly with the fuel cell event history times. The second and fourth pair of plots are 4 min and 40 sec apart, which corresponds within 1 sec to the second and third unbalance events in the fuel cell event history times. However, the third voltage unbalance plot occurs minutes before the third one seen in the event history. The current plot shows that an interrupt did not accompany this unbalance. Since the unbalance was greater than the 5% threshold, it is not known why the fuel cell did not recognize this voltage unbalance event. The third voltage unbalance that *was* recognized by the fuel cell occurred immediately before the bottom two plots. Its existence is partially confirmed by the current plot, which starts at 87 A. This abnormally low current corresponds well with the final current levels of the first two current plots.

An alternate explanation is that the fuel cell *did* recognize the third unbalance shown in the figure, but the event log was very late in reporting it. There are two problems with this alternate explanation: (1) a knowledgeable IFC contact [8] says it is not likely that the event log could be 4 min tardy[9] in reporting an event, and (2) the third current plot in the figure does not show any decay and thus does not match the beginning current level of the fourth current plot.

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[9] Event log times are reporting times that often, but not always, match the actual times. The fuel cell *inverter* log times may be more accurate; however, since they are not routinely saved and archived, they were not available for the analysis of this event.

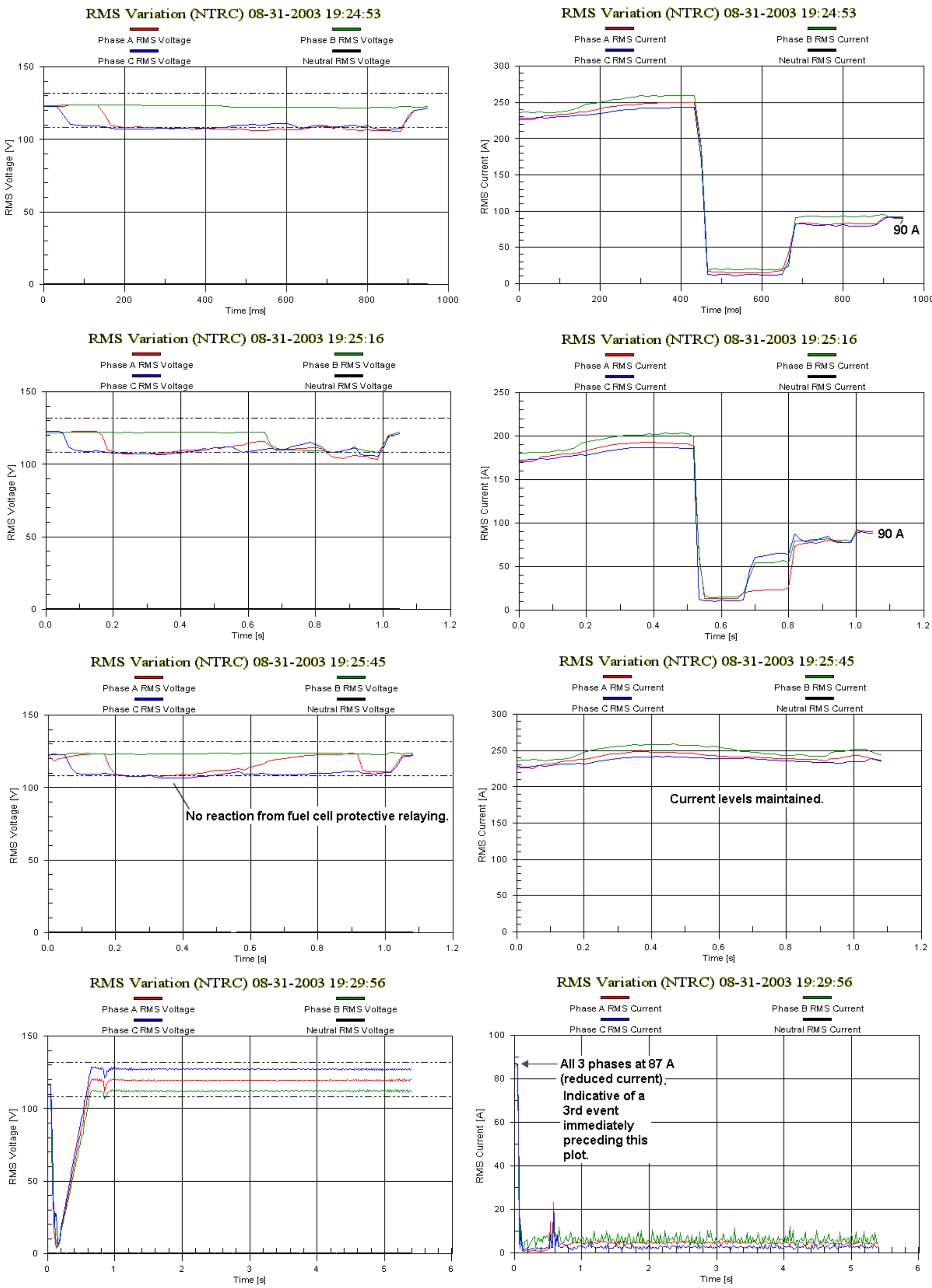

Fig. 3.22. Event data from fuel cell monitor showing three voltage unbalance events (left column) and shutdown. Corresponding current data shown on right.

Although there is some question pertaining to the voltage unbalance data, there is little question that the overall event was a normal response of the fuel cell's "excessive disconnect count" protective relay scheme to a series of >0.5-sec interrupts caused by an electrical storm.

3.3.2 Event of September 28

The September 28 event involved a full shutdown of the fuel cell with an accompanying reboot of the controller; therefore, the fuel cell's event log data were lost. The controller reboot is a strong indication that the fuel cell's UPS had failed, because the UPS is used to provide a power bridge to the controller during various brief interruptions such as those that occur when the fuel cell is switching between modes (e.g., inverter interrupt and normal). It is likely that a >0.5-sec transient in the grid necessitated the switching.

In response to this event, the fuel cell cabinet was opened, and the UPS was heard producing an audible alarm. The inverter fault light was illuminated on the front panel of the UPS. Once notified, IFC promptly shipped a replacement UPS and it was installed.

Figure 3.23 shows the inverter output waveforms recorded during shutdown as captured by the event recorder located in the fuel cell cabinet. These plots, as dramatic as they are, are provided only to emphasize the contrasting, continuous-power condition that prevailed in the NTRC. Events such as this one that occur with a normal grid are entirely *seamless* to the NTRC occupants and operations, since the grid picks up the load instantaneously.

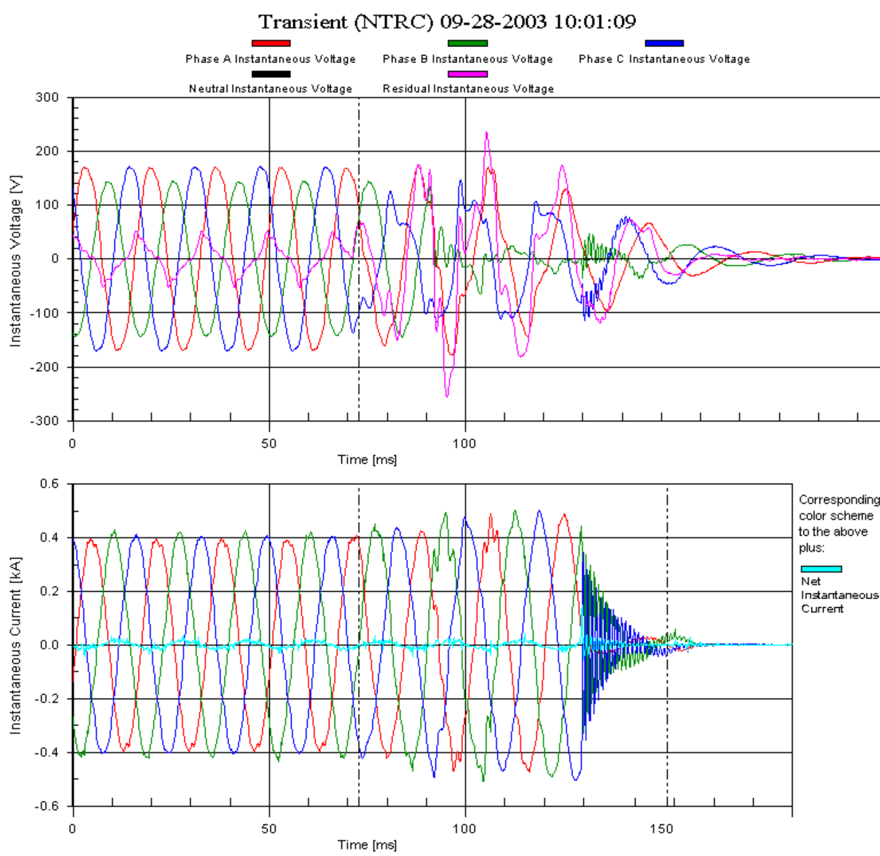

Fig. 3.23. Shutdown event V and I waveforms resulting from UPS inverter failure.

3.3.3 Event of October 14

The October 14 event was one of a very few during which the interruption to fuel cell operation coincided with a noticeable flickering of the lights in the NTRC. It was the first outage since the UPS replacement, quarterly maintenance, and the beginning of operation at reduced power (i.e., 125 kW). Wind gusts and a storm system were in the general area. The interruption to fuel cell operation occurred during a grid voltage variation and during resulting grid-induced drops in power and PF, as shown in the building power and PF plot in Fig 3.24.

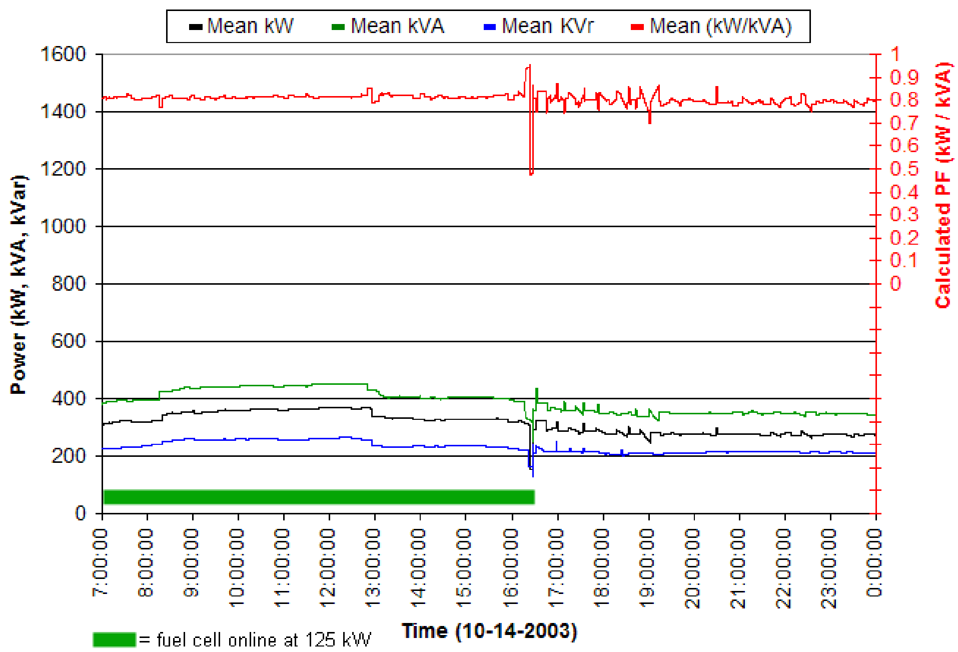

Fig. 3.24. NTRC building load electrical data for 17-hr period on October 14.

Table 3.12 shows the specific events recorded in the fuel cell event history log. The actual time was approximately 25:13, as was evident by observation of a flicker in NTRC lights, the fuel cell data logger, i-sense data, and a subsequent check of the fuel cell clock error. The grid voltage variation initiated standard interrupt messages and a message indicating that the grid anomaly exceeded 0.5 sec, causing the fuel cell to become idle.

Table 3.12. Event log for event of October 14, 2003

Date	Time	Message
10/14/2003	16:12:14	Entered I52 disconnect
10/14/2003	16:12:14	Entered I55 disconnect
10/14/2003	16:12:14	Interrupt duration >0.5 seconds
10/14/2003	16:12:14	Utility grid under voltage
10/14/2003	16:12:14	Utility grid voltage unbalanced
10/14/2003	16:12:16	AIO board reset (callout)
10/14/2003	16:12:16	Entered I26 idle G/C

Reconnection was supposed to occur after the internal timer reached the programmed setpoint of 5 sec, provided the grid was back to 480 Vac (+10%, –20%) and balanced. Based on what was known about the grid voltage variation, there is suspicion that the grid was fully restored well before 5 sec expired and that a reconnection should have been made.

Figure 3.25 shows that a single-phase voltage drop occurred in the NTRC grid power at 16:24:05, and the second plot in the figure shows a 3-phase voltage drop 1 sec later. Thus the entire event was over in approximately 2 sec. Data obtained from an i-sense voltage sensor located near the Service B transformer cabinet also indicated that the event occurred within 2 or 3 sec.

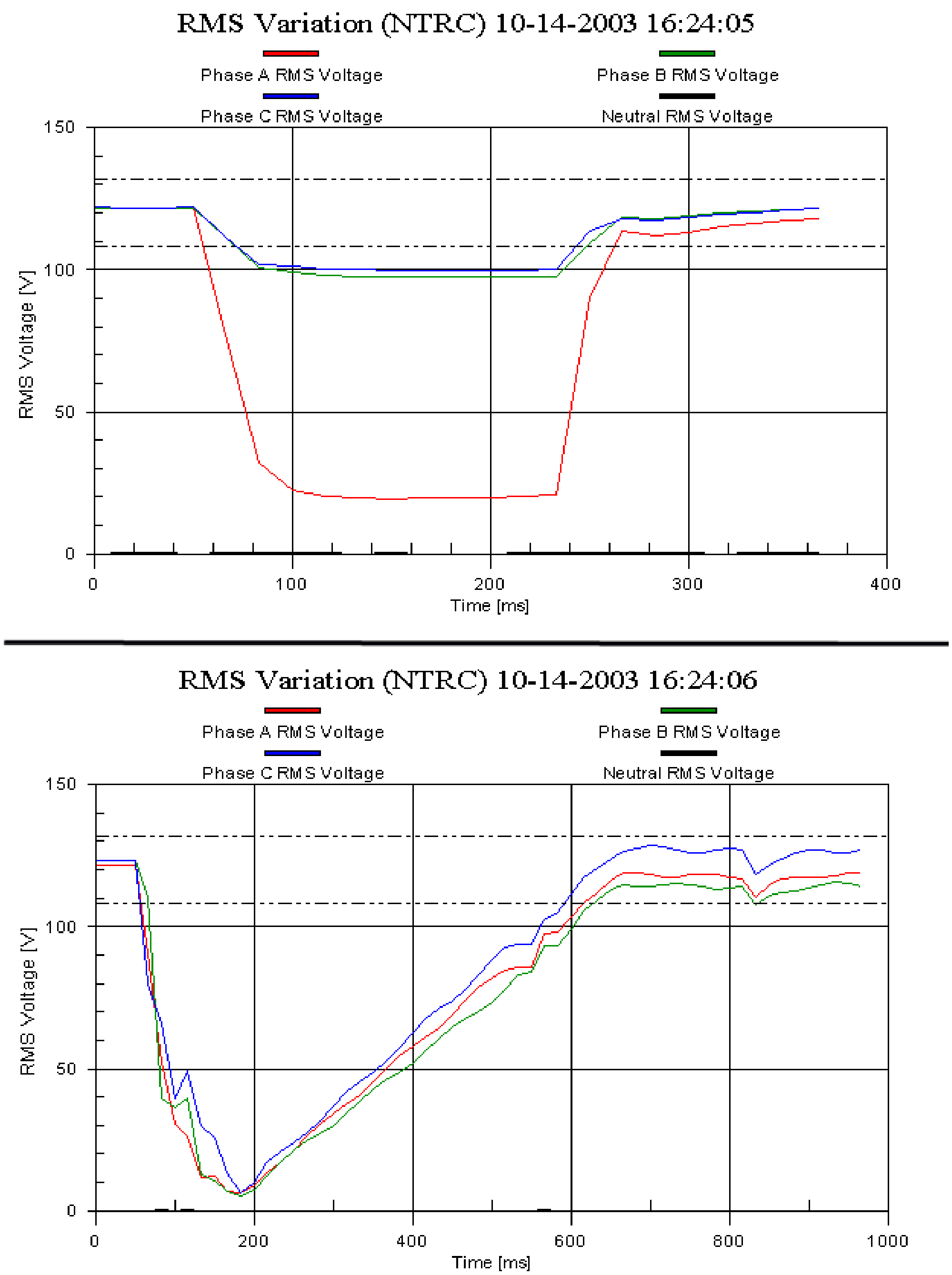

Fig. 3.25. NTRC building voltage data for October 14.

A technical contact [9] at IFC looked at the fuel cell timer settings and discovered that the timer that determines how long the fuel cell will remain in the standby grid-connect mode following a >0.5-sec voltage variation was set at 4 sec. A second timer that determines how long the fuel cell remains in the grid-independent mode was set at 5 sec, even though it is required that this time be shorter in duration. Suspecting a logic error caused by these timer settings, IFC changed the setting of the first timer from 4 sec to 10 sec.

Subsequent to this event, in early December 2003, a different technical contact at IFC notified ORNL that it was changing settings in the fuel cell to prevent automatic reconnection to the grid after inverter interruptions. The contact stated that there existed a software problem related to the UPS that necessitated this temporary change; otherwise, unnecessary full shutdowns of the fuel cell could result during certain grid-disconnect events. This raised suspicion that the timer settings were intentionally set to prevent reconnection for the same reason.

Thus it appears that the October 14 event should have been all but unnoticed, with a grid reconnection occurring within 3 sec when the grid was restored. Instead, because of incompatible settings in the fuel cell protective relaying system,[10] the protective circuitry placed the fuel cell into the idle mode and left it there.

3.3.4 Event of November 4

On November 4, while the fuel cell was operating at 175 kW, an event suddenly occurred that caused a full shutdown of the fuel cell. A comprehensive database of all events provided by IFC is shown in Table 3.13. The comprehensive database is presented instead of the fuel cell event log because the event log appears to have erroneous time data, based on comparisons with electrical monitors. The first three events in the database are normal inverter communication status messages. The first alarm message (see second column) is a routine communication message with the CPU in the controller. However, it is the three "inverter" messages at 12:02:26 a.m. that are indicative of the actual failure event. In these messages, it can be seen that the inverter's lockout relay resulted in the I200 shutdown of the fuel cell. (The remaining messages have to do with water temperature, a flow switch for a fan, and make-up water status.)

Table 3.13. IFC comprehensive database for event of November 4, 2003

Date and time	Type	Message
11/4/03 12:02:22 am		3713 COM3 8250 UART detected
11/4/03 12:02:22 am		3713 COM2 16550 UART detected
11/4/03 12:02:22 am		3713 COM1 16550 UART detected
11/4/03 12:02:23 am	Alarm	3713A Quarterly maintenance needed
11/4/03 12:02:23 am		3713 PCS/ARCNET failure (write)
11/4/03 12:02:26 am	Inverter	3713I External grid connect permissive
11/4/03 12:02:26 am	Inverter	3713I PCS lockout relay
11/4/03 12:02:26 am	Inverter	3713I Entered I200 shutdown
11/4/03 12:20:27 am	Alarm	3713A TE400FT high (P30EVENT and callout)
11/4/03 12:21:29 am	Alarm	3713A FS150 OFF
11/4/03 12:46:04 am	Alarm	3713A PMP451 on time alarm (callout)

[10] There is a possibility that the UPS software problem, mentioned earlier, is the root cause.

Figure 3.26 shows the low-resolution voltage and real power plots from the fuel cell monitor (inverter output) indicating the loss of generation only minutes into November 4. It also shows another outage late in the day that was an SEL relay trip event (see Sect. 3.2.12).

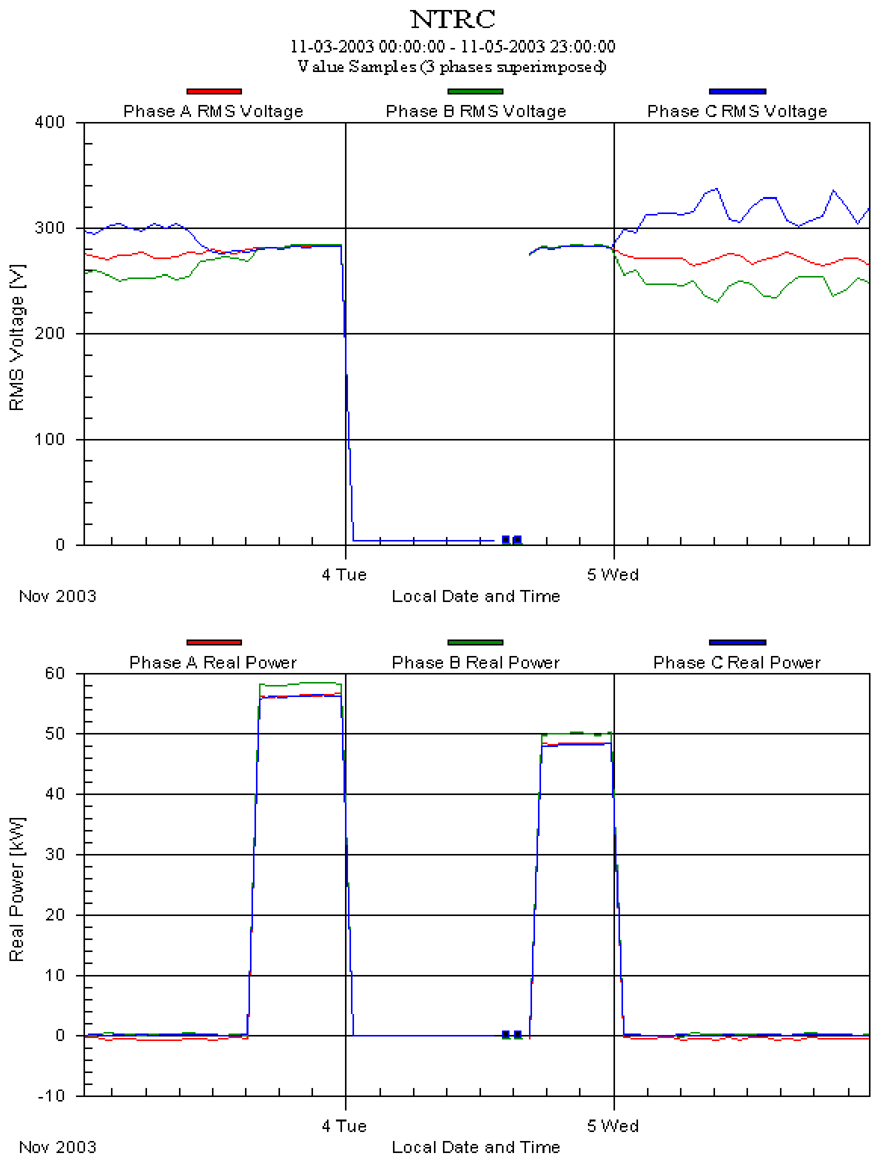

Fig. 3.26. RMS V and real power generated from fuel cell on November 3–5.

IFC analyzed all data available to it and determined that this event was due to the UPS inverter's interpreting an overcurrent condition and causing a full shutdown. This is the same UPS that was newly installed as a replacement in early October. The root cause is unknown, but IFC characterized this event as a malfunction of the UPS. No action was taken regarding the UPS. With only a partial cool down, the fuel cell was purged with nitrogen, placed in idle, and returned to grid-connect operation later in the same day.

3.3.5 Event of November 28

On November 28 at 5:25 a.m., the fuel cell transferred from grid-connect to idle as a result of a series of transients in which the voltage became unbalanced in one or more phases. Table 3.14 shows that a grid voltage unbalance lasting more than 0.5 sec caused the inverter to interrupt, and that two more unbalance transients followed within a 5-sec period. All three transients were captured by the i-grid monitoring system, and the data from i-grid are shown in Figs. 3.27–3.29. Based on the i-grid times, the duration of the events spanned a period of about 5.7 sec.

Table 3.14. Event log for event of November 28, 2003

Date	Time	Message
11/28/2003	0525:18	4279I interrupt duration > 0.5 seconds
11/28/2003	0525:18	4279I entered I52 disconnect
11/28/2003	0525:18	4279I entered I55 interrupt
11/28/2003	0525:18	4279I utility grid voltage unbalanced
11/28/2003	0525:19	4279I entered I26 idle
11/28/2003	0525:20	4279I utility grid voltage unbalanced
11/28/2003	0525:23	4279 GRIDOK flag disabled
11/28/2003	0525:23	4279I utility grid voltage unbalanced
11/28/2003	0525:24	4279 GRIDOK flag enabled

Event 1301 Summary

Serial Number:	0012-7071-9455	Name:	Service B Transformer
Location:	Knoxville, TN	Time:	Fri Nov 28 05:29:26.991 AM EST 2003
Classification:	Transient	Duration:	0.008 seconds (0.48 cycles)
Nominal RMS Voltage:	480.0	Frequency:	60.0 Hz

RMS Data:

Channel	Min	Max	Worst Case RMS as % of Nominal
1	469.1	479.1	97.7%
2	472.2	478.1	98.4%
3	474.7	479.2	98.9%

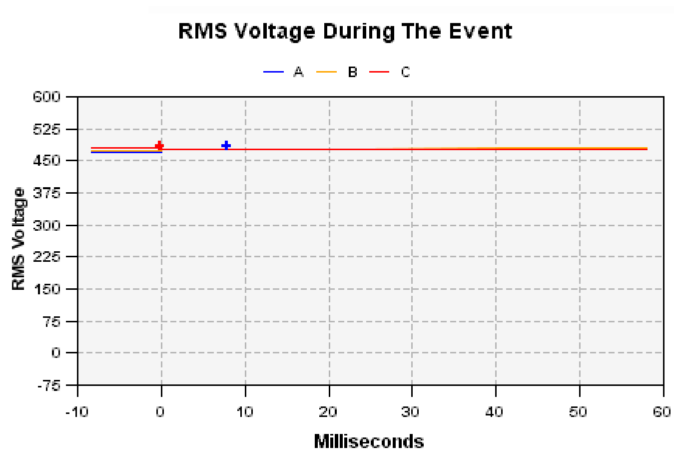

Fig. 3.27. Voltage transient data from i-grid for the first of three transients.

Event 1302 Summary

Serial Number:	0012-7071-9455	Name:	Service B Transformer
Location:	Knoxville, TN	Time:	Fri Nov 28 05:29:29.815 AM EST 2003
Classification:	Instantaneous Sag	Duration:	0.010 seconds (0.6 cycles)
Nominal RMS Voltage:	480.0	Frequency:	60.0 Hz

RMS Data:

Channel	Min	Max	Worst Case RMS as % of Nominal
1	427.9	479.6	89.1%
2	463.5	479.2	96.6%
3	472.3	478.5	98.4%

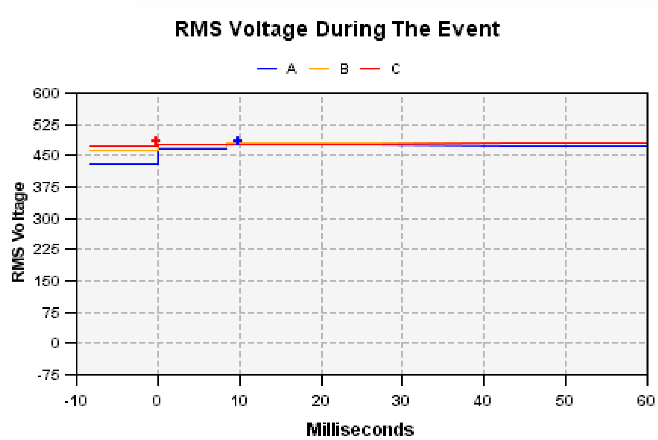

Fig. 3.28. Voltage transient data from i-grid for the second of three transients.

Event 1303 Summary

Serial Number:	0012-7071-9455	Name:	Service B Transformer
Location:	Knoxville, TN	Time:	Fri Nov 28 05:29:32.699 AM EST 2003
Classification:	Transient	Duration:	0.008 seconds (0.48 cycles)
Nominal RMS Voltage:	480.0	Frequency:	60.0 Hz

RMS Data:

Channel	Min	Max	Worst Case RMS as % of Nominal
1	473.5	478.8	98.7%
2	477.5	479.5	99.5%
3	475.9	481.4	99.1%

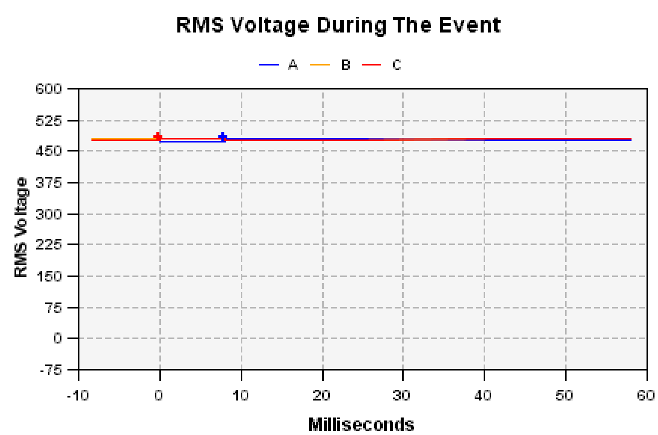

Fig. 3.29. Voltage transient data from i-grid for the third of three transients.

ORNL had two questions pertaining to this event: (1) why were the I52 disconnect and I26 idle messages within 1 sec of the first transient, and (2) why did the fuel cell not reconnect to the grid following the third transient when the grid returned to normal? Discussions with IFC provided plausible answers. In regard to the first question, the event log times are not entirely accurate, and the sequence of events may be shuffled somewhat. In reality, the I52 disconnect into an I26 idle state likely followed all three transients.

The second question is based on the fact that if the transients were over and the grid returned to a normal state within 10 sec[11] of the initial interrupt, the settings in the fuel cell would have provided for an automatic reconnection to the grid. According to IFC, although it appears that the transients were over in 5 or 6 sec, it is IFC's belief that with the inverter flags and flag resets that were occurring, the repercussions of the transients lasted the full 10 sec, precluding a return to grid-connect operation.

Thus it appears that this event was an example of an entirely normal function of the fuel cell's protective relaying in which a transient-initiated interrupt was extended by a series of transients until the preset time limit was reached, causing a transfer from the grid-connect operating mode into idle.

3.3.6 Event of December 14

On Sunday, December 14, at approximately 3:36 p.m., the fuel cell operating mode switched from grid-connect to idle. The fuel cell had been producing 110 kW since the first of the month. The event log shown in Table 3.15 indicates that a grid voltage unbalance condition lasting >0.5 sec caused an interrupt and then a disconnect to an I26 idle condition (a correct logical sequence of events is assumed).

Table 3.15. Event log for event of December 14, 2003

Date	Time	Message
12/14/03	1536:38	Entered I52 disconnect
12/14/03	1536:38	Entered I55 interrupt
12/14/03	1536:38	Utility grid voltage unbalanced
12/14/03	1536:39	Interrupt duration > 0.5 seconds
12/14/03	1536:40	Entered I26 idle

Grid voltage unbalance transients almost always last only a fraction of a second. Figure 3.30 shows a portion of the voltage transient as recorded by the event recorder installed in the fuel cell. (The times shown are not corrected for the change from EDST to EST.) Although the data provided in the figure indicate that phase C experienced an ~11.5 V sag for approximately four cycles, it is based on the recorder's threshold setting. The accompanying plot indicates that some level of unbalance occurred for at least nine cycles. The event recorder reported on a similar but separate unbalance 1 sec later. However, by the third second, the event recorder shows that the fuel cell had begun its inverter interruption process.

Because of the short duration of the unbalance transient, ORNL and IFC analysts immediately recognized that it was highly probable that this mode change occurred because IFC had temporarily disabled the automatic reconnect feature in the fuel cell's protective relaying earlier in the month (as discussed in Sect. 3.3.3) because of a software problem related to the UPS. Had this change not been made, unnecessary full shutdowns of the fuel cell could result during certain grid-disconnect events. This preventative measure is in response to recent experience that IFC has had with grid-connect fuel cell installations at other locations that rely on external permissive signals from RPR protection systems.

[11] This was adjusted up from a 5-sec setting in the preceding month. See Sect. 3.3.3.

Transient (OSC) **Transient (NTRC) 12-14-2003 16:40:51**
12-14-2003 16:40:51
Trigger at 0.0833333 on Vc Inst

Channel	Negative Peak	Positive Peak	Duration	Rise Time	Principle Freq
Va Inst	-171.81	172.44	3.99 Cyc	6.2500	180.0
Vb Inst	-173.83	174.67	3.99 Cyc	3.5156	300.0
Vc Inst	-161.46	161.88	3.99 Cyc	1.5625	180.0

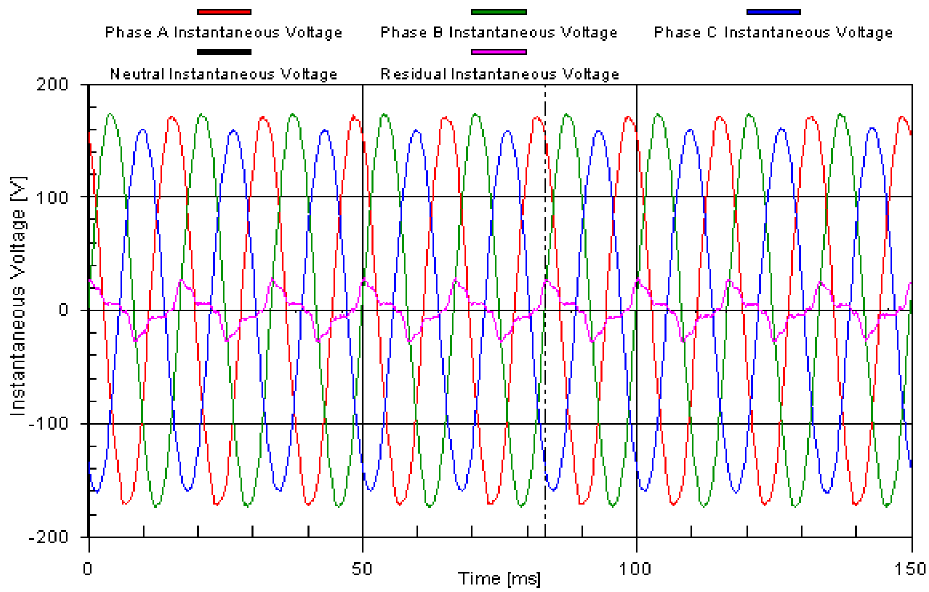

Fig. 3.30. Partial example of a December 14 voltage unbalance transient.

4. SUMMARY AND RECOMMENDATIONS

This section will summarize the results of this study and, based on those results, present a comprehensive list of recommendations that will be helpful in planning and operating other DER grid-connected installations.

4.1 FUEL-CELL-TO-GRID COMPATIBILITY SUMMARY

ORNL and EPRI-PEAC conducted this study of the IFC PC25C fuel cell from July 1, 2003, until December 31, 2003[12]. The results of the test were satisfactory and can be readily summarized. Table 4.1 lists the 12 events involving a reverse power lockout relay trip. The table lists the event date, the grid anomaly (if any), the specific cause of the event, and the potential applicability that the event is deemed to have to other fuel cell or DER grid-connected sites (referred to as "global applicability"). None of the events in the table caused a full shutdown of the fuel cell.

One of the events during the first half of the test period, on August 13, was complex and difficult to explain. The explanation that an SEL relay error was responsible for the August 13 event is somewhat difficult to justify for an instrument that has proven high reliability and high respect in the power industry; however, three very significant conditions were coincident: (1) the error was small, (2) the error was known to last over only a 5-sec interval, and (3) very high levels of harmonic distortion were present.

The global applicability of the events in Table 4.1 is, of course, based on the existence of a reverse power protection system similar[13] to the one used in this study. The global applicability of the reverse-power-in-absence-of-load-tracking (RPALT) events is considered to be low because the barriers ORNL encountered in establishing load tracking were rather exceptional both in number and in type, as discussed in Sect. 2.5. If the recommendations of Sect. 4.3 are heeded, it is unlikely that another DER grid-connected installation would find load tracking to be comparably elusive.

The global applicability of the September 3 event is very low since it entails very low levels of reverse real power (~5 kW) and would not have resulted in a Device 32 trip assuming the setting would have been ≥10 kW. Device 32 is very commonly used in an installation such as this one. In the August 13 event, where dynamometer operation caused high levels of harmonic distortion and very poor PF, the potential global applicability is also considered to be very low.

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[12] This entire summary section also applies if 7th and 8th months (Jan-Feb 2004) are included since the fuel cell remained grid-connected both months without interruption at a 110-kW generation level.

[13] There is some question regarding what "similar" might mean. IFC claims that at ~25 other sites, where reverse power protection schemes based on standard reverse load (Type 32 protection) are employed, the protection system worked quite well. The analysts for this study believe that had load tracking been operable and the SEL relay been initially set up to recognize only i-lag angles from 110º–270º as "reverse," comparably good results would have resulted.

Table 4.1. Summary of fuel cell reverse power lockout trip events

Date	Local grid anomaly	Cause of event	Global applicability
7/15	None	RPALT[1]	Low
7/28	Unbalanced, undervoltage	RPALT	Low
8/13	Dynamometer operation	Unknown. Suspect SEL relay phase error of ~4º in high harmonic environment with very poor PF	Very low
8/28	None	RPALT	Low
9/3	Minor storm transients	RPALT (Note: a Device 32 protection scheme would not have tripped.)	Very Low
9/10	None	RPALT	Low
9/18	None	RPALT	Low
9/24	None	RPALT	Low
11/1	None	RPALT	Low
11/4	None	RPALT	Low
11/14	None	RPALT	Low

[1] RPALT = Reverse power in absence of load tracking

As discussed in Sect. 2.3.4, LCUB expressed concern over fault currents from the fuel cell compromising their substation safety systems. The events with the 2 highest levels of reverse current occurred on August 13th and September 18th as indicated in Table 4.2. It is interesting to see from the table that, based on the stated conclusions and justifications, both of the events have little or no significance in regard to fault current in general DER applications. The other lower-current, reverse power events pose little danger in fault situations and can be addressed with effective load tracking systems.

Table 4.2. Summary of the highest two reverse current events

Date	Average I	Conclusion	Justification
8/13	1300 A	Not believed to be an actual reverse power event	Suspect SEL relay phase error of ~4º in high harmonic environment with very poor PF caused by dynamometer operation
9/18	300 A	Event believed to have low global applicability to other DG sites	Building load was 150 kW; the only reason that reverse current was high was because PF was very low (likely due to dynamometer operation)

This study initially anticipated only the non-RPR events, and the analysts still view non-RPR events as the ones of greatest interest relative to DER-grid compatibility. Table 4.3 lists the six events that were not related to reverse power protection. The table lists the dates, local grid anomalies or conditions, whether a full shutdown of the fuel cell occurred, the cause, and an assessment of the global applicability. The events dated August 31 and November 28 are the only two that represent a normal and desired response of the fuel cell's protective circuitry to a grid disturbance. Of the four remaining events, the UPS either failed or took inappropriate action in two cases, and the other two relate to a timer setting error and an equipment-related problem (i.e., UPS software flaw).

Table 4.3. Summary of fuel cell trip events not related to reverse power

Date	Local grid anomaly	Full shut-down	Cause of event	Global applicability
8/31	Three storm-related unbalanced grid voltage for >0.5 sec	No	Fuel cell protective relay system registered an "excessive disconnect count"	High
9/28	Fuel cell log data for this event lost because of a "controller reboot."	Yes	UPS inverter failure in fuel cell (UPS replaced)	Medium to low
10/14	Grid undervoltage and voltage unbalance conditions (possibly weather related)	No	Internal timer setting error prevented automatic reconnect when grid was restored.	High
11/4	Fuel cell log data for this event lost because of a "controller reboot."	Yes	The UPS inverter interpreted an overcurrent condition and caused a shutdown. Root cause unknown.	High
11/28	Interrupt >0.5 sec followed by unbalanced grid voltage transients	No	The inverter reported several flags being set and then cleared apparently exceeding set time limit for automatic reconnect.	High
12/14	Grid voltage unbalance >0.5 sec	No	IFC disabled auto reconnect until resolution of a UPS software flaw.	High

The global applicability of these events is high except in one case, because normal responses of protective relaying, timer errors, software flaws, etc. can be expected in any sophisticated and complex DER grid-connected installation. The UPS inverter failure applicability is listed as medium-to-low, because IFC stated that this UPS has an excellent reliability record based on its other installations and because there is some suspicion that the extremely poor power quality resulting from dynamometer operation may have been a root cause of the failure.

The final summary table, Table 4.4, lists all events with a global applicability of either medium or high. The table provides the date, whether the grid acted as an initiator, whether the 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 six events would have been the full outcome of this study. Of the six events, two were desirable (i.e., normal responses of the fuel cell's internal protective relaying) and four were undesirable. The grid played a medium-to-high role in the event in less than half of the cases. Of the four undesirable interruptions, the fuel cell hardware, settings, and/or software are causes in each case. 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.

Table 4.4. Summary of all high/medium global applicability fuel cell events

Date	Grid initiator	Overall grid contribution	Full shutdown	Desirable interruption? (with justification)		Global applicability
8/31	Yes	High	No	Yes	Normal protection	High
9/28	Possible	Low	Yes	No	Hardware failure (UPS)	Medium to low
10/14	Yes	Low	No	No	Timer setting error	High
11/4	Possible	Low	Yes	No	Spurious trip (UPS-related)	High
11/28	Yes	High	No	Yes	Normal protection	High
12/14	Yes	Medium	No	No	Software flaw	High

The state of fuel-cell-to-grid compatibility based on the results of this six-month study is considered to be good. There are valuable lessons learned, discussed in Sect. 4.3, that should be helpful to any organization that is contemplating the operation of grid-connected DER. 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.

4.2 ADEQUACY OF PROTECTIVE RELAYING RELATIVE TO IEEE 1547 [10]

IEEE 1547, approved in June 2003 and published a month later, is the IEEE standard for interconnecting DR with EPS. The standard is divided into three main parts. IEEE 1547.1 is a guide for monitoring, information exchange and control of DR interconnected with EPS. IEEE 1547.2 is the application guide for the standard. IEEE 1547.3 provides conformance test procedures for the equipment that interconnects DR with the EPS.

IEEE 1547 does not provide all the details for DR interconnection; addition barriers will remain to the orderly transition to an integrated system encompassing all EPS-connected DG systems. Although the standard is designed to help in reducing the costs and other barriers to grid interconnection through application guidance, tips, techniques, etc., other legislative actions must come first. Since IEEE 1547 is a national standard, it has a high potential for being used in federal rule-making, state public utility commission deliberations, and the formulation of technical requirements for interconnection agreements by utilities across the nation. Barriers are beginning to come down not only because of the standard, but also because of the improved communications resulting from the dialog.

The effectiveness of the Model PC25C fuel cell's synthesized relay protection scheme relative to the new standard is not an issue considering the sophistication and versatility of the system (see Sect. 2.2.3). The system is designed to continuously look for symptoms of an abnormal EPS (e.g., undervoltage, overvoltage, voltage imbalance, abnormal frequency, excessive interrupts) and, if found, execute a rapid change into an interrupt state and/or a mode transfer into idle. Thus, the design approach has been for the fuel cell to be transparent to the EPS during EPS anomalies. As the new IEEE standard leads to interconnection innovation in the electric power industry, protective relaying schemes such as this one may become lacking only because they do not take advantage of new opportunities such as supplying voltage support and other ancillary services.

4.3 RECOMMENDATIONS FOR IMPROVED DER SYSTEMS

The recommendations produced by this study for improving the performance of grid-connected DER 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 in this section are not all based on experience gained in this specific study; some are recommendations relating to anticipated or potential problems based on general knowledge of the fuel cell and other DER systems. For instance, although ORNL enjoyed a high level of cooperation from both LCUB and IFC, some recommendations allow for the fact that this is not always the case.

The following are the primary recommendations of this study.

1. If possible, choose a DER 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 DER 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 reverse power lockout relay manual resets to assess the level of cooperativeness and ensure that 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 of reverse power should be permitted since reverse power up to that level should not significantly jeopardize the safety of power grid protective relaying systems. Higher levels of reverse power must be tolerated for at least 5 sec.
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 DER operators have ownership and management of the entire load tracking system including the source of the control signal. (Review Sect 2.5 for potential applicability of other related barriers.)
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 DER system control software and all the features and functions that it may control.
9. In installations where the PF is poor, avoid selecting a DER generator with a real power output that will routinely come close to matching the real power load. 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 DER system during interrupt events. If the DER system has an event log, arrange for access to those data also. Review data soon after events to minimize the learning curve.

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APPENDIX A: OPERATION SUMMARY

This appendix summarizes the electrical operation data for the fuel cell generation output during the six-month study period. The data were obtained from a monitor placed in the fuel cell cabinet and connected to the output from the main inverter.

Figure A-1 shows the RMS output voltage and current plots during the test. There are a few minor data omissions, and the most significant omission is indicated. The voltage plot tends to become “noisy” during idle periods; however, the current plot clearly shows the idle periods when current output falls to ~0 amps. September had the most outages and the poorest percentage of operating time.

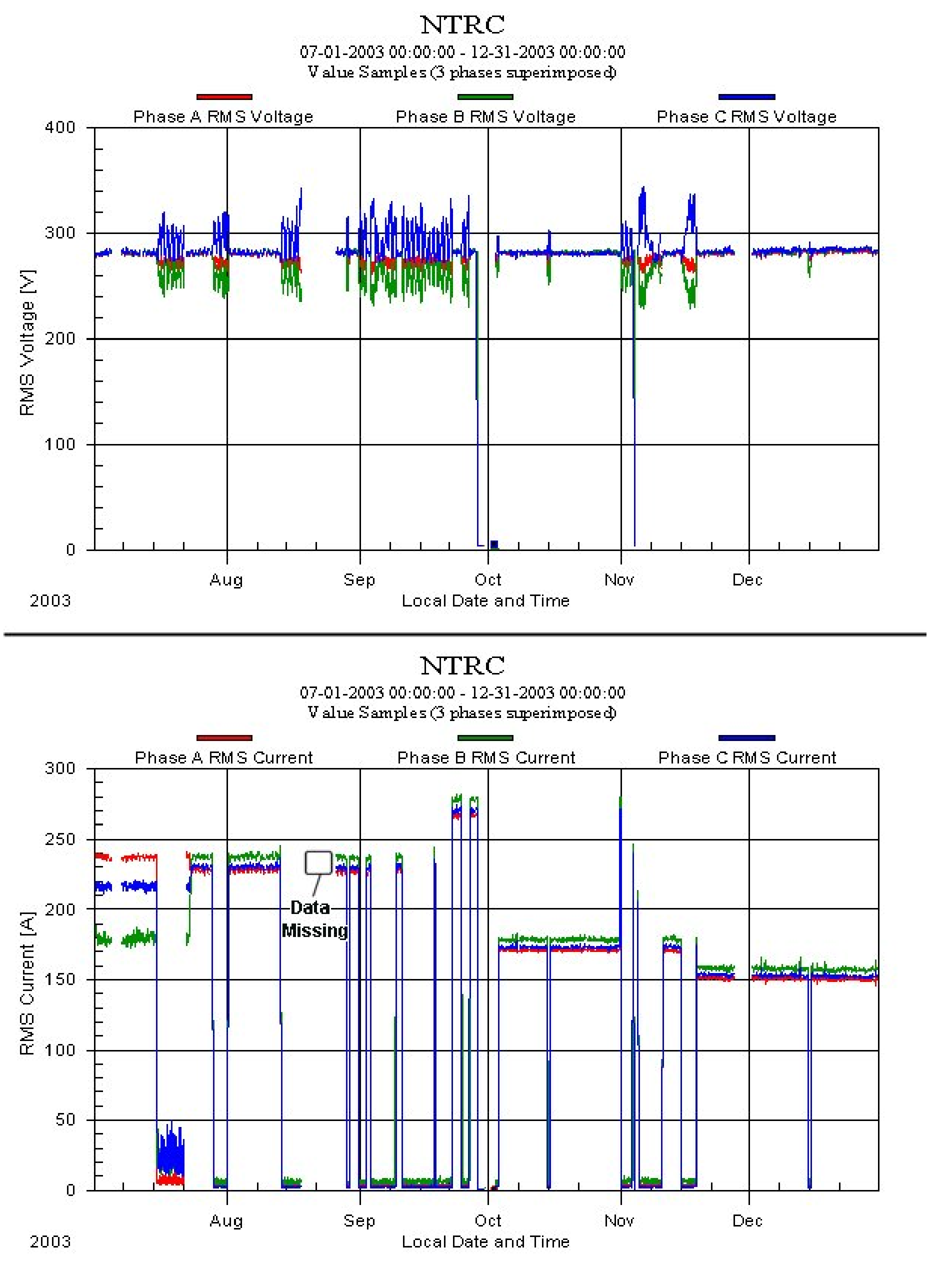

Fig. A-1. RMS V and I fuel cell generation plots for the six-month test period.

Figure A-2 presents the real power and reactive power plots corresponding with the plots in Fig. A-1. The real power plot shows how lower generation production levels were used beginning in October in order to avoid RPALT events. This measure was used most consistently in October and December and, as a result, relatively high fuel cell availability is evident in those 2 months. Reactive power production was activated in the fuel cell to the full amount possible beginning in late September. As the fuel cell power production was scaled back, the kVAR production also fell proportionately. The amount of correction that was possible was modest compared with the effect on PF when dynamometers were in operation.

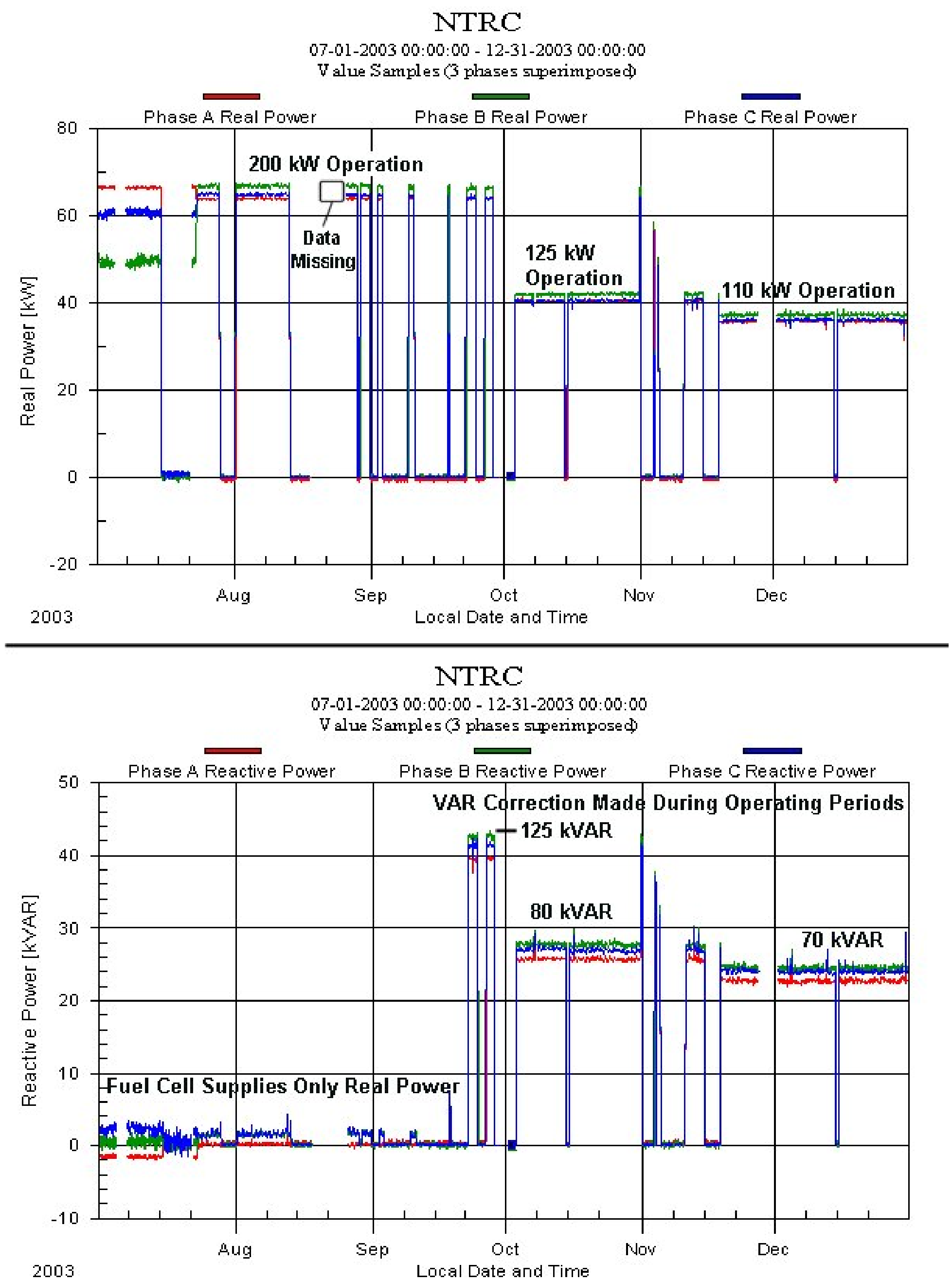

Fig. A-2. Real and reactive fuel cell power plots for the six-month test period.

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