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Fuel Cells As Power Quality Solutions

TR-113469

Final Report, October 1999

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REPORT SUMMARY

Fuel cell systems are advancing beyond conventional bulk power applications. Now, technological approaches are allowing dynamic responses that can solve short-term power quality problems, specifically voltage sags and momentary interruptions. In addition to solving short-term problems, fuel cells also can provide long-term back-up and stepped-load changes using traditional, clean, natural gas fuel. This report describes the need for and applications of advanced fuel cell systems for end-use customers.

Background

Traditional solutions to power quality disturbances have been UPS systems based either on battery banks or engine generators. Neither is ideally suited for short ride-through because of high maintenance and slow response time. Advanced fuel cell systems offer performance advantages over traditional approaches. In addition, they offer long-term back-up not economically possible with other stored energy solutions.

Objectives

- To provide fuel cell power system and application information to utility personnel responsible for end-use power quality mitigation.
- To show how fuel cells can be used in power quality solutions and the status of product development for this product.

Approach

This report describes the need and applications for advanced fuel cell systems for end-user customers. It emphasizes the fundamental difference between standard or conventional fuel cells and advanced fuel cells capable of handling dynamic loads and power quality situations. Further, it compares both types of fuel cell systems to other energy storage systems.

Results

The fundamental principles of fuel cells are described, along with applications, especially for power quality. Products of various types and sizes are described, as well as their commercial status. Finally, fuel cell systems are compared with other power quality technologies and a means to distinguish and select fuel cell systems is suggested.

EPRI Perspective

Development and maturation in the fuel cell arena has been phenomenal in the past few years. Not only in the United States, but worldwide, fuel cells are improving, costs are dropping, manufacturing is maturing, and the number of installed systems is growing rapidly. Because of the tremendous advantages of efficiency and cleanliness over other technologies (no emissions), utilities should expect to be incorporating fuel cells in their own systems or their customers'.

TR-113469

Keywords

Fuel cell
Energy storage
Power quality
Power conditioning

ABSTRACT

Fuel cell systems are advancing beyond conventional bulk power applications. New technological approaches are allowing dynamic response that can solve short-term power quality problems, specifically voltage sags and momentary interruptions. In addition to solving short-term problems, fuel cells can also provide long term back-up power, using conventional, clean natural gas fuel. This report describes the need and applications for advanced fuel cell systems in customer end-use situations. It also presents the fundamentals of fuel cell technology and how it works in power quality applications. Different configurations of fuel cell systems are discussed, along with a comparison with other technologies.

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1 INTRODUCTION

Fuel cells are energy conversion devices that have been in use in various forms for a long time, but are only in recent years becoming commercially mature for power-related applications. Based on an electrochemical reaction, they have similarities to a battery. Unlike a battery, however, they can generate power continuously using an external fuel supply.

Fuel cells have several attractive features when used as a power supply, which will be discussed in this report. These include:

- high efficiency
- clean energy conversion, i.e. no environmental pollution
- quiet operation
- modularity
- fuel flexibility

The fundamental principles are described, along with applications, especially for power quality. Products of various types and sizes are described, as well as their commercial status. Finally, fuel cell systems are compared with other power quality technologies and a means to distinguish and select fuel cell systems is suggested.

2
FUEL CELL APPLICATIONS

Fuel cell systems provide power by consuming a fuel and oxidizer. Because there is no thermal conversion process involved, fuel cells are more efficient than most other forms of power generation. Thus, one of the earliest uses of fuel cells was to power spacecraft subsystems where a compact, efficient power generation technology was needed. In these applications, the fuel and oxidizer have typically been hydrogen and oxygen, respectively. Other hydrogen-containing fuels and other oxidizers (e.g. air) can be used in applications where compactness is not a major concern.

Fuel cells have been developed and are already in use in several markets: transportation, distributed generation, and central generation. In the transportation field, fuel cells are being used in buses for vehicle propulsion and have been demonstrated in cars, especially for air pollution control. For central generation facilities, fuel cells as large 20 MW have been installed. For remote power, isolated systems in sizes as small as 1 kW have been installed.

New applications of fuel cells are for premium power, power quality, portable power, and telecommunications. These new applications are highlighted in this report.

3
FUNDAMENTALS OF FUEL CELL TECHNOLOGY

3.1 General Principles

In a fuel cell, an electrochemical reaction between the fuel and oxidizer generates electricity. As shown in Figure 1, the fuel cell consists of an anode, cathode, and electrolyte. Fuel is supplied to the anode, where it is oxidized, freeing electrons and hydrogen ions. The electrons flow in an external circuit and the hydrogen ions pass through the electrolyte to the cathode, where they combine with oxygen and electrons to form water. (The reverse process, in which current passes through water to form hydrogen and oxygen, is called electrolysis.) The electrodes are usually catalyzed carbon, although many forms of electrodes are now in production. The electrolyte can be either acid or alkaline; the reaction mechanisms at the electrodes will differ, but the overall reaction is the same:

$$H_2 + 1/2\ O_2 \rightarrow H_2O$$

The generic arrangement is shown in Figure 3-1.

DC electricity at low voltage (approximately 1.23 V) is the output from the external circuit. As long as there is a continuous flow of hydrogen and oxygen, the output of the cell will be low voltage DC. To achieve higher voltage, cells are stacked, similar to battery or capacitor configurations.

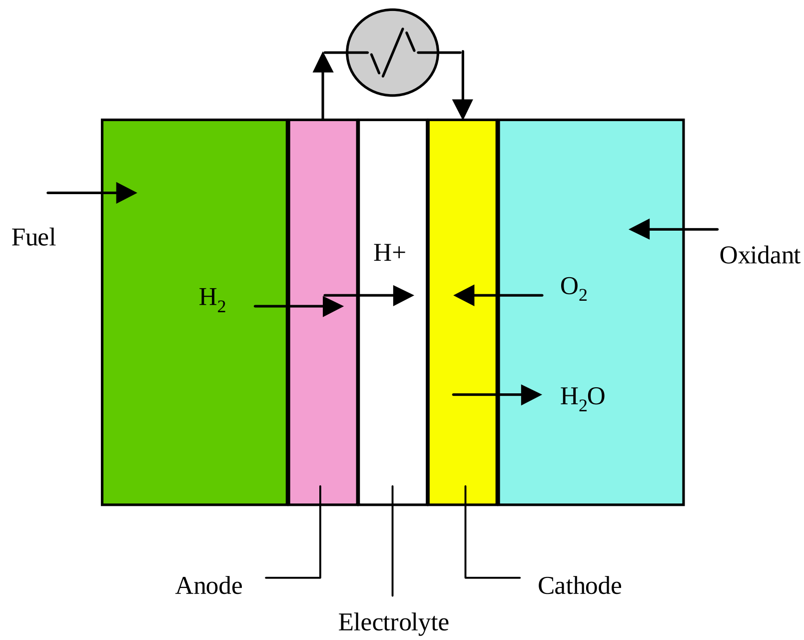

Figure 3-1
Basic Components of a Fuel Cell

3.2 Types of Fuel Cells

Fuel cells may be broadly classified by operating temperature, type of electrolyte, and type of fuel. In general, lower temperature fuel cells need high purity, expensive catalysts, such as platinum, and relatively simple fuel, such as hydrogen. Higher-temperature systems have the advantages of using hydrocarbon fuels and lower-cost catalysts, but require more sophisticated thermal management.

In practice there are four types of fuel cells currently available, as listed in Table 3-1. Their operational characteristics and primary application areas are also indicated. The operating temperature is an important practical feature. In large stationary systems, such as power plants, high temperature can be used to advantage for process or space heating to co-generation. In small portable systems, ambient operation is preferred.

Table 3-1
Characteristics of Fuel Cell Types

Type	Temperature	Fuel/Oxidizer	Typical Applications
Phosphoric Acid (PAFC)	Low (≤ 200°C)	Natural gas or hydrogen/ air or oxygen	Spacecraft, on-site power generation, building heat
Molten Carbonate (MCFC)	High (> 650°C)	Hydrocarbon/ air	Power generation, co-generation
Solid oxide (SOFC)	High (> 1000°C)	Hydrocarbon/ air	Power generation, co-generation
Proton exchange membrane (PEM)	Low (≤ 80°C)	Hydrogen or hydride/air or oxygen	Passenger vehicles, portable devices, on-site power generation

These same fuel cell types can also be compared on the basis of system features. In Table 3-2 are listed the typical power rating, efficiency, and footprint.

Table 3-2
Fuel Cell Performance Characteristics

Type	Maximum Power Rating, kW	Efficiency % (kW_{out}/kW_{in})	Footprint, ft^2/kW
Phosphoric Acid (PAFC)	1000	43-50	1.1
Molten Carbonate (MCFC)	2000-3000	54-70	.9-1.0
Solid Oxide (SOFC)	2000-3000	60% w/ co-gen	.25-3.0
Proton Exchange Membrane (PEM)	250	40-60	~.5

3.3 Fuel Cell Power Plants

The traditional utility application for fuel cells is for central power generation. The components of an integrated fuel cell power plant will include:

- Fuel processing system
- Fuel cell power section
- Power conditioner

These components are shown in Figure 3-2. Typically, methanol or natural gas is the fuel and air the oxidizer. The purpose of the fuel processor (typically a reformer) is to convert the hydrocarbon fuel to hydrogen and carbon monoxide. The fuel cell uses only the hydrogen.

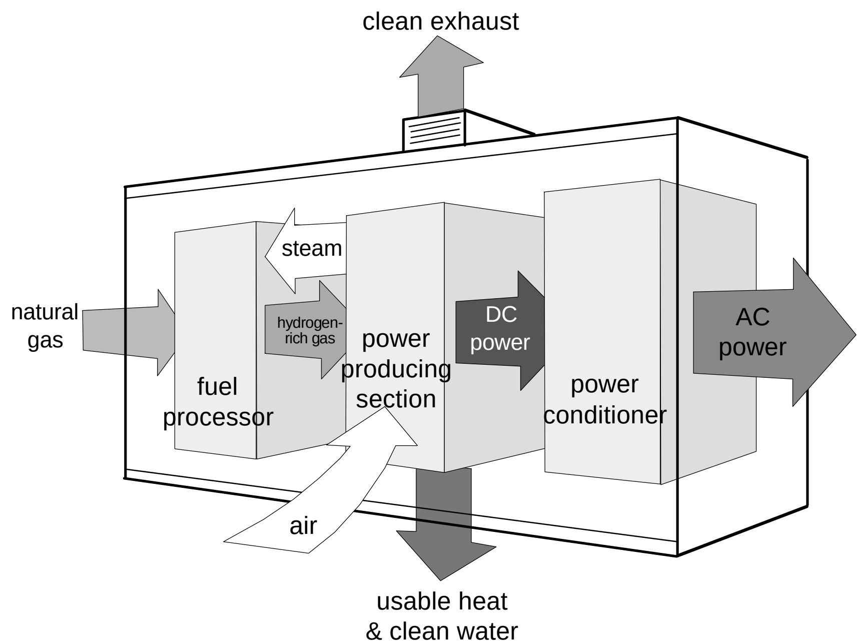

Figure 3-2
Components of a Fuel Cell Power Plant

In other power applications, pure hydrogen and oxygen may be used. In these cases, storage reservoirs of these gases (in pressurized containers or chemical compounds) replace the fuel processing system. In vehicle applications, the power conditioning system will be part of the drive train/propulsion unit; typically, hydrogen fuel is carried on-board in pressurized containers or chemical compounds.

4
NEW APPLICATIONS OF FUEL CELLS

In this section, new applications of fuel cells are described. These include premium power, power quality, and portable power. These differ from standard, steady power applications in that quick response is required. Figure 4-1 indicates this distinction. Also shown is a further categorization into systems that combine technologies to make hybrid configurations, and those that don't.

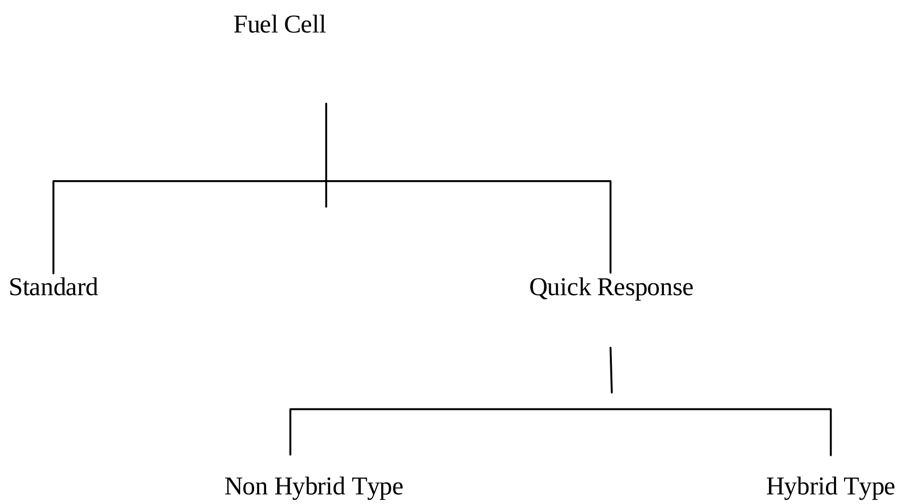

Figure 4-1
Hierarchy of Fuel Cell Applications Categorized by Time Response and Technology Types

4.1 Premium Power

In general, a fuel cell system is an excellent technology to provide highly reliable, glitch-free, premium power on-site for a customer or group of customers. In this application, it either augments or replaces entirely power from the grid. Critical loads are powered exclusively from the fuel cell. Such systems have been installed in industrial facilities, computer centers, and even hotels where owners preferred guaranteed power over possible interruption from the local utility. In principle, any type of fuel cell could be used in this application. To date, only phosphoric acid fuel cells have been installed because their commercial maturity and power rating are suitable for this application. In some cases, integrating the fuel cell thermal management system with the heating/cooling system of the building has also provided benefits. A premium power configuration is shown in Figure 4-2.

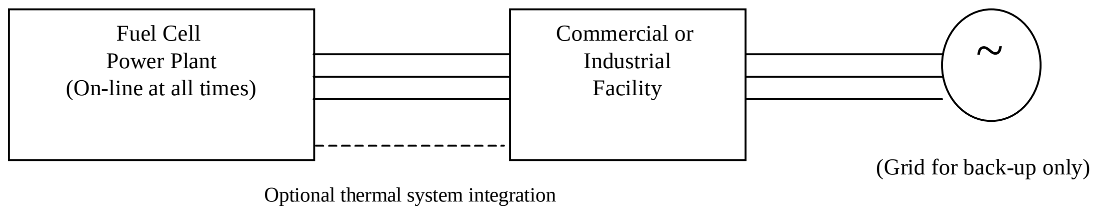

Figure 4-2
Fuel Cell in Premium Power Configuration.

4.2 Power Quality

When used for power quality, a fuel cell would be installed for ride-through or back-up power supply. It operates only in the event of an outage or disturbance (e.g., voltage sag) on the main power source. In conventional power quality systems, power-line conditioners or energy storage systems serve the short-term mitigation need, and back-up generators serve the long-term need.

Recent studies have shown that the biggest power quality problem faced by utility customers is voltage sag, as shown in Figure 4-3.

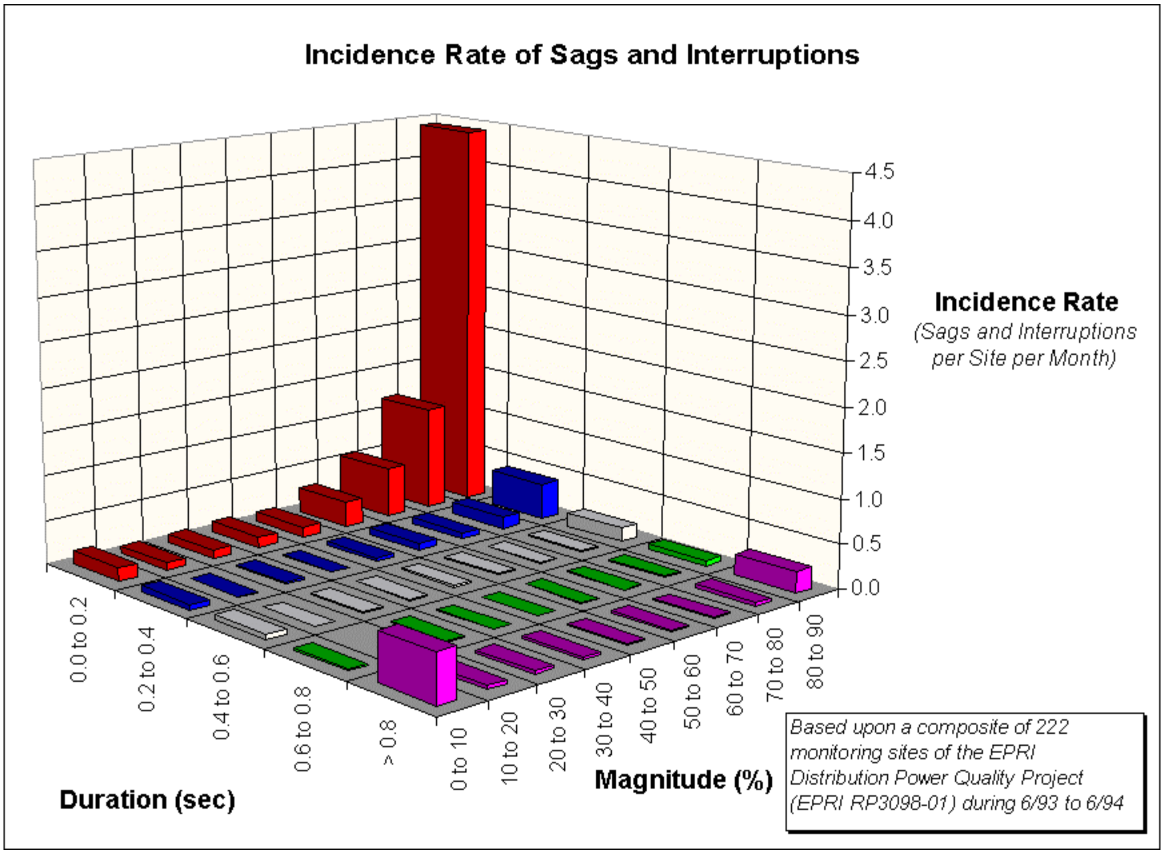

Figure 4-3
Frequency and Duration of PQ Events

Conventional fuel cell technologies have been designed only for relatively steady-state operation. These products will not operate properly under dynamic load conditions, such as sudden step changes in load. However, new developments show that fuel cells can also operate in a power quality mode, either for short- or long-term carry-over. If only short events are anticipated or served, stored fuel (and oxidizer, if necessary) may be the most cost-effective approach. If a long-term back-up need is to be served, connection to a natural gas fuel supply may be suitable. Figure 4-4 shows a possible configuration.

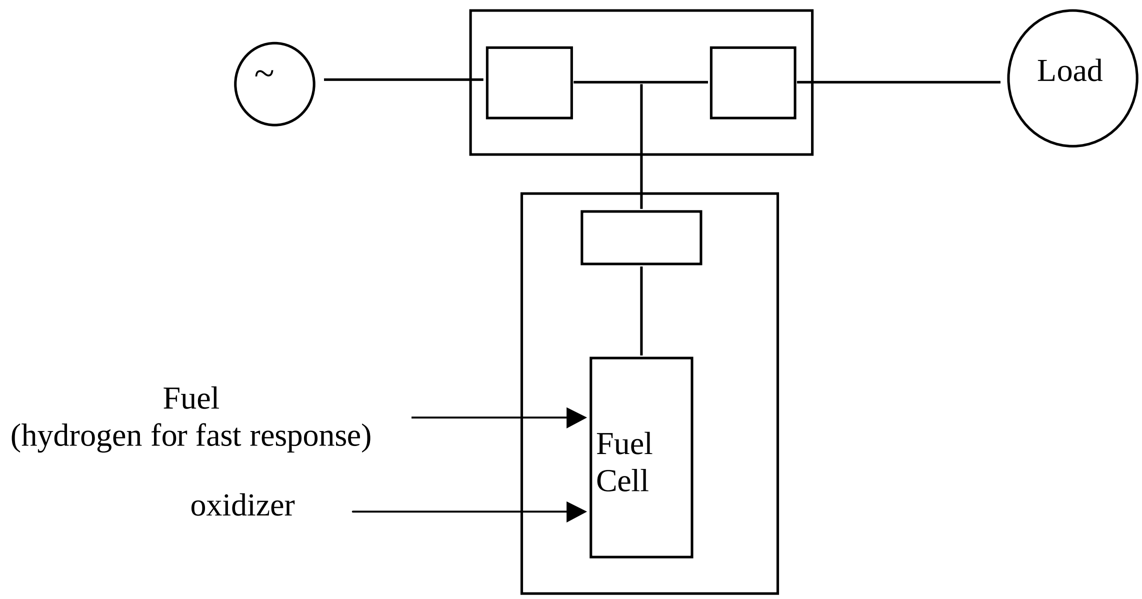

Figure 4-4
Fuel Cell System in a Power Quality Configuration

In power quality applications, however, the biggest challenge is quick response. Typical electronic or advanced storage solutions (e.g., supercapacitors, flywheels, SMES, batteries) can supply power within a single cycle (< 1 millisecond) because solid state power electronics are used to control the response. A fuel cell can operate the same way, if the cell is directly fueled using hydrogen or easily oxidized fuel such as hydrazine or ammonia. In other types of fuel cells, the response of the fuel processor (which generates hydrogen from a hydrocarbon fuel) will be too slow, unless the system is constantly on-line. In practical terms, this restricts a fast-response, fuel cell power quality system to PEM or PAFC, with PEM the most suitable technology. For guaranteed fast response, oxygen oxidizer may also be needed.

Dynamic response from a fuel cell system requires a special design of the fuel cell stack. The most challenging aspect is to keep hydrogen and oxygen flowing rapidly through the system. Los Alamos National Laboratory (LANL) has been in the forefront of developments for this type of application. Recently, a LANL innovation has been licensed to DCH Technology, Inc. of Valencia, California for commercialization. The diagram in Figure 4-5 indicates how flow-field design details can control the time response of the system.

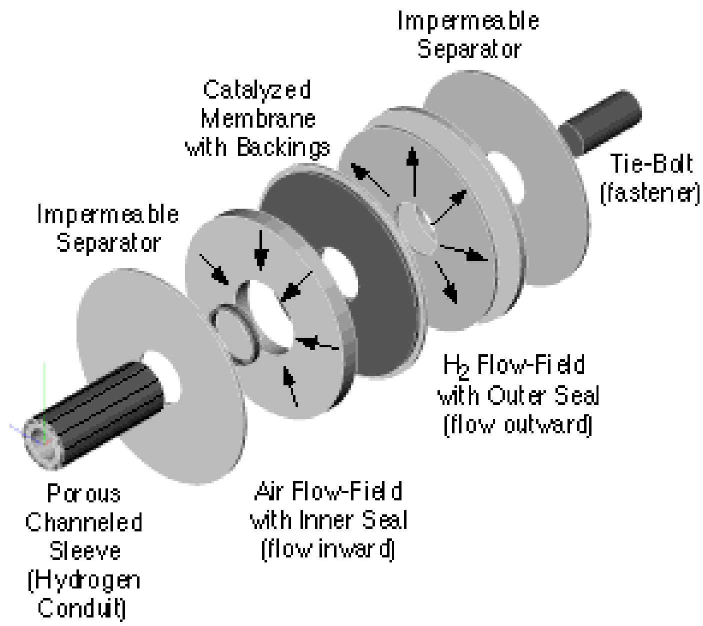

Figure 4-5
Radial Flow Fuel Cell for Fast Response

Another type of energy supply can be provided by having portable fuel cells units available for customers with temporary problems. Some examples may be :

- during transition to a new or remodeled facility or upgraded power configuration,
- during testing of new equipment,
- during seasonal variations, such as seasonal peaking, or seasonal problems on the grid.

In these cases, customers may benefit from having portable generating units sited at their facilities. Fuel cells are currently being applied to portable applications. In principle, they could replace batteries or combustion generators. Although presently only available in very small units (several Watts), mainly for computer equipment and mobile telecommunications, these systems will have advantages of no emissions, high efficiency ($\geq$ 60%), no noise, no toxic components, modularity, and fuel flexibility (unless rapid response is required).

5
APPLICATION DISCUSSIONS

5.1 Comparison of Fuel Cells with Other Ride-Through Technologies

Fuel cells can be used for premium power and power quality applications. It is important to compare this technology with other approaches to solving the same problems. In general, a fuel cell system will be able to perform the same functions as energy storage technologies and thus could be used wherever energy insertion (i.e., real power) is required. Ride-through of short or long outages or voltage sags are good examples. Table 5-1 shows a comparison of some important features of fuel cells and other ride-through technologies.

Table 5-1
Comparison of Ride-Through Technologies

Technology	Discharge Rating, kW	Ride-through Time, sec	Footprint, ft^2/kW	Environmental Factors	Commercial Status	Approx. Cost ($/kW)[3]
Fuel Cell - Standard	200-1000	Not applicable	.25 - .3	Minimal emissions, no safety issues	*1*	1500
Fuel Cell - Quick response	1-50	Depends on H_2 supply	.6 - .8		*2*	TBD
Supercapacitors	10-100	5-10	.05 - .2	No emissions or safety issues	*2*	300
Flywheels-low speed	100-1000	10-15	.03 - .05	No emissions, no safety issues	*1*	200
Flywheels-high speed	1-350	5-10	.02 - .05	Some safety issues	*2*	~500
Battery energy storage	10-2000	10-15	.3 - .5	No emissions, some with toxic materials	*1*	500
Micro-SMES	.5-4000	1-5	.4 - .5	No emissions, some magnetic field issues	*1*	300
MG set / Written Pole	5-300	15-45	1 – 1.5	No emissions or safety issues	*1*	1000

1: Mature commercial products, in demonstration
2: Early commercial stages; need application demonstration
3: For short duration ride-through

5.2 Hybrid Ride-Through Applications

As indicated previously, rapid response can be achieved with a fuel-cell based system if the system arrangement makes hydrogen instantly available to the fuel cell stack. This can be accomplished either by using hydrogen (or other non-hydrocarbon, easily oxidized) fuel or operating the fuel processor in “hot” stand-by mode. If neither of these approaches is desirable, a fuel cell can be used in a hybrid configuration in which short-term ride-through using a supercapacitor, flywheel, or other system responds first, providing power for up to perhaps 10 seconds while the fuel cell system prepares to operate. This approach makes sense when a ride-through period of more than about 30 seconds is anticipated. Otherwise, the rapid response storage unit should simply be sized for the entire ride-through period. A hybrid configuration is shown in Figure 5-1.

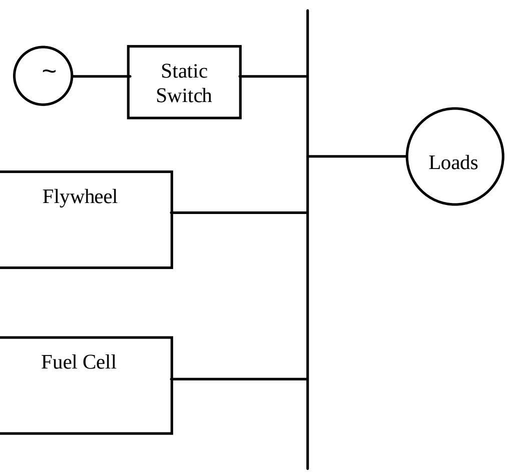

Figure 5-1
Hybrid Technologies Ride-Through Configuration

Configuration

Another variation would be to consider “hybrid” fuels, but not hybrid technologies. When hydrogen (and oxygen) are needed for fast response, a small store of these gases can be provided for the initial carry-over period while the fuel processor ramps up to full capacity. Switchover to converted fuel could take place in 10 to 30 seconds, allowing the normal system to run thereafter. Only ambient temperature fuel cells would be practical for these applications because full warm-up time for a high-temperature fuel cell is on the order of many minutes and keeping these systems in “hot” standby would be inefficient and expensive. A hybrid fuel configuration is shown in Figure 5-2. A benefit of this system is that natural gas can be used for the long-term outage fuel. This eliminates the need for diesel fuel storage.

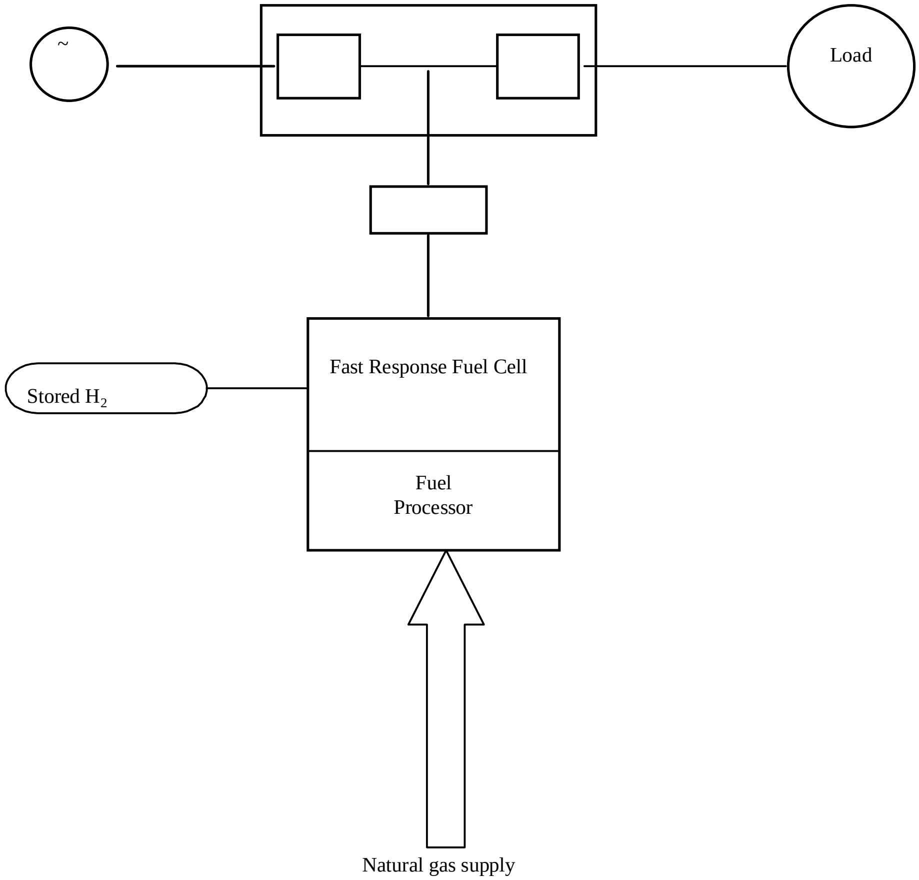

Figure 5-2
Hybrid Fuel Ride-Through Application

Yet another version of this system is a completely closed cycle in which the hydrogen storage is recharged from the fuel processor in a separate flow stream. This is shown in Figure 5-3.

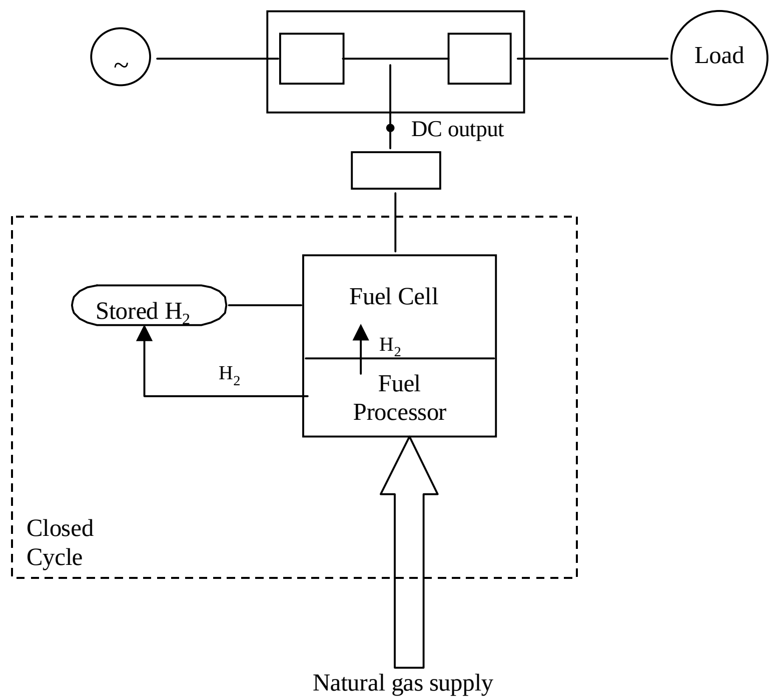

Figure 5-3
Fuel Cell Power Quality System Showing Closed Hydrogen Cycle

5.3 Short- and Long-Term Applications

Since a fuel cell will operate continuously as long as fuel is supplied, it makes an ideal technology for long-term back-up power. In this case it replaces a diesel or gasoline-powered generator. The advantages of this application are many:

- A single fuel can be used for both short and long-term back-up. When this is natural gas, it will likely already be available on-site.
- A fuel cell is more energy efficient (60% vs. 30% for a diesel engine) and requires little maintenance.
- There are no regulated emissions, little noise, and no toxic materials.
- Once installed, a fuel cell may be used for peaking power to avoid demand charges, if they apply.
- The expected life of a fuel cell system is 20 years.

5.4 How to Select and Apply

Fuel cells are rated by power output, kW. Therefore sizing for the load to be carried is straightforward. For continuous power generation, any type of fuel cell can be chosen. PAFC are the most mature (see next section). If thermal uses are envisioned, high temperature systems should be considered. Power quality applications, with rapid response requirements will be best suited to PEM systems.

Fuel cells produce dc power. The required power and voltage are generated by appropriate cell stacking, similar to battery and capacitor systems. If ac power is desired, appropriate power conditioning is required.

Fuel cells can operate using a wide variety of fuels including natural gas, methanol, or hydrogen. Natural gas is the simplest to use since it is available at most developed sites. Methanol would be delivered in tanks. Hydrogen can be supplied by pipeline, in tanks, or in chemical compounds such as nickel-metal-hydrides, ammonia, or hydrazine.

6
TECHNOLOGY STATUS

6.1 Product Status / Manufacturers and Developers

Fuel cells of the various types are in different stages of product maturity. Solid polymer electrolyte and phosphoric acid fuel cells consuming pure hydrogen and oxygen have been used in spacecraft since 1960. On-site power generation systems based on phosphoric acid cells fueled by natural gas and air have been operating in numerous installations since 1992. A 2 MW molten carbonate fuel cell (MCFC) power station has been operating in Santa Clara, California since 1994. Japanese firms are also installing MCFC units for power system testing beginning in 1999. PEM-based fuel cell vehicles are operating in a number of North American cities and the first PEM-based power plants (250 kW) are expected to be delivered in 1999. Portable fuel cell systems have been demonstrated for consumer applications and products are expected for commercial sale in 1999 or 2000. Further information can be found in the proceedings of recent seminars or on a number of Internet web sites (See Bibliography).

Fuel cell systems are under study and development at many companies and U.S. national laboratories. The technology for power quality systems is available for field testing at the present time, although mature products have not been established. Table 6-1 indicates the product status of several types of fuel cells. Table 6-2 lists some prominent manufacturers and developers.

Table 6-1
Product Features

Application	Type	Maximum Rating, kW	Commercial Status
Vehicle propulsion	PAFC	~1	Available
	PEM	20	Custom Order
On-site power generation	PAFC	675	Available
	PEM	250	In development
Power plant	MCFC	2000	In operation
	SOFC	1000	In demonstration
Portable power	PEM	1	Custom order
Power quality	PEM	TBD	Needs demonstration

Table 6-2
Manufacturers/Developers

Company or Lab	Product or System	Location
ONSI	PAFC on-site systems	So. Windsor, CT
Fuji Electric Company	PAFC power plant	Chiba, Japan
Energy Research Corporation	MCFC power plants	Danbury, CT
M-C Power	MCFC power plant	Burr Ridge, IL
Ballard Automotive	PEM vehicle fuel cells	Vancouver, B.C.
Ballard Generation	PEM power plant	Princeton, NJ
Avista Labs	PEM fuel cells	Spokane, WA
H-Power Corporation	PEM fuel cells	Belleville, NJ
Hydrogenics Corporation	Hybrid PEM systems	Toronto, CANADA
DLR	Portable PEM systems	Freiburg, Germany
Los Alamos National Laboratories	Fast response PEM cells, also direct methanol-fueled cells	Los Alamos. NM
DCH Inc.	Fast response PEM cells	Valencia, CA
Analytic Power	Residential PEM systems	Boston, MA
Plug Power	Residential PEM systems	Detroit, MI
Seimens/Westinghouse	SOFC power plant	Pittsburgh, PA
Mitsubishi	SOFC development	Nagasaki, Japan
Ztek	SOFC development	Waltham, Massachusetts
EPYX	Premium Power	Cambridge, CA

6.2 Cost Discussion

Fuel cell systems range in cost depending on type, application and some special features. The Department of Energy fuel cell development program has established a cost target of $1000/kW for stationary fuel cell systems. This includes fuel processing for natural gas or methanol and assumes 3-phase grid-quality output power. Systems fueled by hydrogen will cost less because the fuel processing subsystem is not required. Systems using more complex hydrocarbons will cost more.

Fuel cells for applications not requiring 3-phase ac power (e.g. vehicles) do not need solid-state power electronics and thus cost less. In fact, fuel cell propulsion units mass produced for the passenger vehicle market are expected to cost as little as $25/kW someday.

For the present, customers can expect to pay at least $1500/kW for a complete power plant as shown previously in Figure 4-2. A power quality unit using only a small store of hydrogen for fast response, short ride-through may ultimately cost in the range of $500/kW. This is comparable to other uninterruptible power technologies.

6.3 Future Expectations

Development and maturation in the fuel cell arena has been phenomenal in the past few years. Not only in the U.S., but worldwide, fuel cells are improving, costs are dropping, manufacturing is maturing, and the number of installed systems is growing rapidly. Because of the tremendous advantages of efficiency (60% vs. 30%) and cleanliness over other technologies (no emissions), utilities should expect to be incorporating fuel cells in their own systems or their customers'. Premium power applications are already available. Portable systems are becoming available. Power quality ride-through is an applications area needing demonstration and assessment.

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