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Short communication

Reliability of Plug Power GenSys^{TM} fuel cell systems

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Abstract

The pace at which fuel cell systems are widely adopted by the marketplace will be determined primarily by two factors: (1) the rate at which system cost decreases and (2) the rate at which system reliability increases. This paper describes the field reliability and its improvement through a combination of software and hardware changes of Plug Power's GenSys^{TM} fleet of 5 kWe (plus up to 9 kW of thermal energy) proton exchange membrane (PEM) fuel cell systems. Plug Power has shipped more than 300 of these systems to more than 50 customer locations in more than 10 countries. This fleet is of sufficient size, and has been operating for a sufficient length of time, to develop statistically significant observations of system reliability. Nondimensionalized probability plots of PEM stack lifetime in field units are presented, and a series of system-level changes are described that have increased PEM stack life by about a factor of 4. Nondimensionalized, system-level reliability statistics are also presented for the installed fleet. Pareto charts describing the top causes for system failures in the field are shown, and the general methodologies for improving system-level reliability are discussed.

Keywords: Reliability; Reliability growth; PEM fuel cell system; PEM stack life; Plug Power; GenSys^{TM}

1. Introduction

For several years, Plug Power Inc. has been developing, manufacturing, and selling proton exchange membrane (PEM) fuel cell systems intended for stationary power generation in residential and commercial applications. The GenSys^{TM} family of products is one of Plug Power's current offerings in this market. GenSys^{TM} fuel cell systems can be fuelled by either natural gas or liquefied petroleum gas (LPG), and can provide both heat and electric power to the end user. Depending upon the specific model and installation configuration, GenSys^{TM} systems are capable of producing up to 5 kW of ac electric power, 5 kWe (at either 50 or 60 Hz) and up to 9 kW of thermal energy. Plug Power has shipped more than 300 5 kWe fuel cell systems to more than 50 customer locations around the world.

Barbir [1] discusses the overall design of fuel cell systems for stationary power generation applications. A picture of the GenSys^{TM} fuel cell system is shown in Fig. 1. This fuel cell system contains five major modules, numbered 1–5 in this figure: (1) a fuel processing module, which converts a hydrocarbon fuel into a high H_2, low CO content reformate stream; (2) a power generation module, which electrochemically converts hydrogen and oxygen into water inside a PEM fuel cell stack, producing both electric power and heat; (3) a power electronics module, which converts the dc power produced by the stack into ac power; (4) an electrical energy storage module, which ensures continuity of electric power during transients; and (5) a thermal management module, which transfers usable heat to the customer.

Inadequate reliability is one of the primary factors that impede the large-scale commercialization of proton exchange membrane fuel cell systems. The reliability of the entire fuel cell system depends upon the reliability of the fuel cell stack and the reliability of all the other components within the system. Every component within a fuel cell stack may affect the

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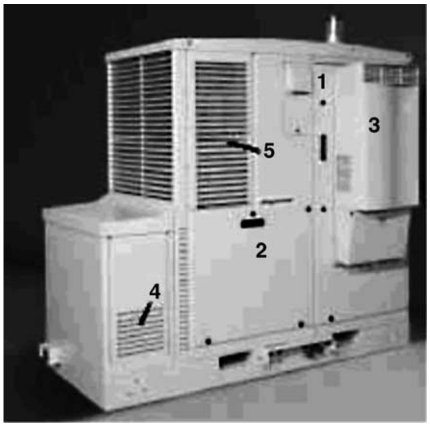

Fig. 1. A GenSys™ fuel cell system. Numbers refer to modules which are described in Section 1.

reliability of the stack. A PEM stack is normally composed of tens to hundreds of unit cells, and these unit cells are stacked in series to generate the power and voltage required by the end user. A failure within a single cell may require the entire fuel cell system to be shut down. In addition, failures of upstream components within the fuel cell system can lead to premature stack damage and failure.

A recent review of membrane electrode assembly (MEA) and short stack reliability is available [2], and a general discussion on reliability of fuel cell stacks can be found in Fowler et al. [3]. However, there is much less information in the literature on the reliability of PEM fuel cell systems. This paper is intended to help fill this gap.

Several major design iterations have been deployed in order to improve fuel cell system reliability and/or performance since the first GenSys™ units (referred to here as the "B1" units) were placed in the field in August 2001. Subsequent major product revisions are referred to as the "B2"–"B6" units in this paper, with the numbering scheme reflecting the chronological order in which revisions were released. Table 1 summarizes the approximate date each GenSys™ version entered production and the number of units manufactured. The most recent version, B6, is still in production (as of December 2004) and continues to be deployed to customer sites.

The installed fleet of GenSys™ units is of sufficient size, and has been operating for a sufficient length of time, to enable us to develop statistically significant observations of system reliability. These observations help identify the root causes for system failures in the field, and can be used to prioritize future technology development needs. The rate at which system reliability is improving is an important metric that can be used for program planning purposes. The remainder of this paper will focus on these topics.

Table 1
Summary of GenSys™ build version dates and production volumes

GenSys™ build version	Production launch date	Number of units produced
B1	August 2001	33
B2	August 2001	33
B3	October 2001	40
B4	March 2002	54
B5	September 2002	45
B6	January 2003	108

2. Definitions

Any discussion of reliability requires a common understanding of terms and nomenclature. In this section, we define some of the terms that will be used in the subsequent discussion of system and component reliability. A *failure* is defined as an end-user detectable and verifiable loss of product functionality, resulting in an unscheduled repair and/or replacement to restore the lost functionality. For example, a failure is regarded as occurring when the stack voltage becomes lower than a predetermined value at a certain power output, even if the fuel cell system is still operable. Product *reliability* is the conditional probability, at a given confidence level, that the system will perform its intended function(s) without failure for a specified time period when operated under proscribed usage and environmental conditions. *Development time* is the total accumulated time between the launch of the first product version (or B1) and any subsequent product revision (e.g., the B4 version). *Cell ratio* is defined as the ratio of the lowest cell voltage to the mean cell voltage within a stack.

3. Results and discussion

3.1. Overall system reliability

The evolving reliability of the GenSys™ fleet is shown in Fig. 2, which plots the cumulative average number of failures per system as a function of development time for units that have been in the field for 3 months (▲) and 12 months (■). The data in this figure have been normalized by taking the cumulative average number of failures per system for the B1 units after 12 months as 1.0. Cumulative average failures per system were determined by fitting a Crow power law reliability growth model [4] to the raw data on failures for the systems considered. The units within each product revision had acquired an average of 5900–7900 h of field run time before being fit to the Crow power law model. The B2 unit reliability is not shown in this figure because the B2 units were released the same month as the B1 units and had the same reliability.

The reliability data from only about 40% of the units listed in Table 1 were included in Fig. 2 for a variety of reasons. For example, most units were installed at distant locations and required remote communication capability to acquire reliability data. Some of these units experienced data corruption or transmission errors. In other cases, customers simply declined to provide the necessary reliability data.

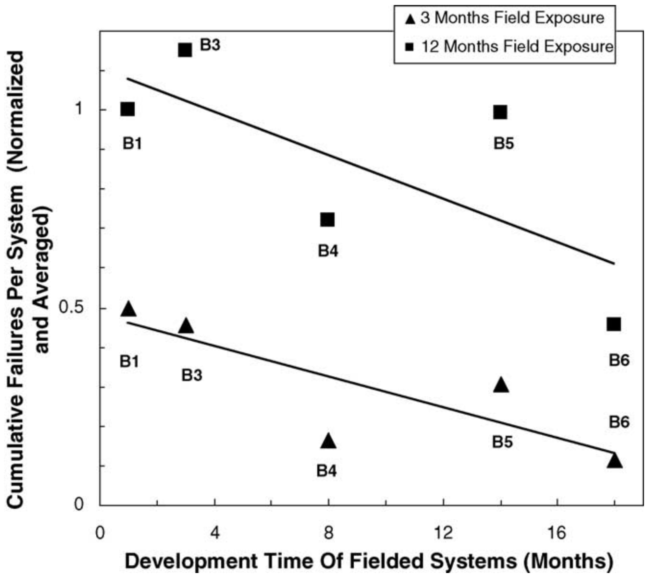

Fig. 2. Cumulative failures of the GenSys^{TM} fuel cell system fleet. The build version from Table 1 is shown next to each point for clarity.

Two observations are immediately apparent from Fig. 2. First, units that have been in the field for 12 months have more cumulative failures than units that have been in the field for only 3 months, as expected. Second, after 18 months of continuous development, the B6 systems are significantly more reliable than the B1 systems. Early life failures (failures within the first 3 months of field exposure) were reduced by 77% from the B1 to B6 versions. After 12 months of field use, the projected failures from the B6 units were 54% lower than the B1 units.

The GenSys^{TM} fuel cell system is a repairable system. In other words, when a component fails, a repair is made and the system is restored to operation. For repairable systems, the time between successive failures is particularly interesting because the reliability can be modeled using a nonhomogeneous Poisson process [5]. The rate of improvement in system reliability, referred to as a "learning curve", can be modeled by this process, and design decisions can be made which affect the overall system reliability [6]. By monitoring learning curves over several development programs, the similarities across programs can be used to guide program plans and evaluate development efforts. For these reasons, we believe Fig. 2 conveys a significant amount of valuable technical information.

The overall system reliability improvements shown in Fig. 2 were achieved through a combination of hardware and software changes to the original B1 product. These changes not only improved reliability, but also decreased system cost by ∼50% and added two new product features. The two new product features were: grid standby capability, which allows the unit to continue to power critical loads, even if the local electrical grid goes down; and LPG fuel capability. Major hardware changes implemented in this time period include: a new inverter design; changes to the stack coolant circulation scheme; changes to the PEM stack membrane electrode assembly (MEA); and the elimination of selected sensors.

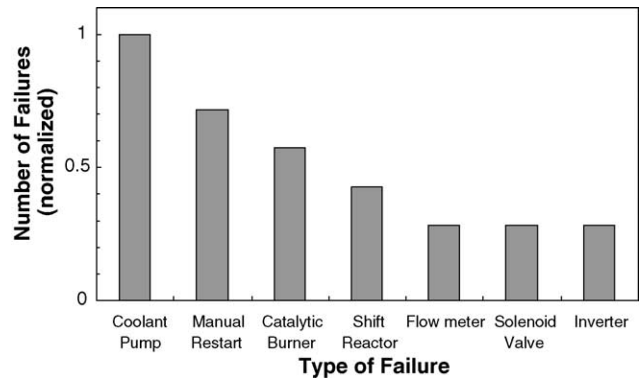

Fig. 3. Most frequent component failures in the installed fleet during October 2002.

3.2. Component reliability

One aspect of the overall system reliability improvement shown in Fig. 2 is a series of component-level changes designed to eliminate failures. Tracking and understanding the failure modes and failure frequencies of system components are important elements in improving overall system reliability. Figs. 3 and 4 are "snapshots" in time from October 2002 and from June 2004, respectively, illustrating the seven most frequent component failures in the GenSys^{TM} fleet during each of the two months indicated. The data from October 2002 come from a sample of 75 field units, while the June 2004 data come from a different sample of 45 field units. Since the sample sizes are not identical (and the samples contain different build versions), the component failure data in each figure have been normalized by the number of failures of the component that failed most frequently during the month indicated. The run time for the units in each sample ranged from about 4000 to 12,000 h. Stack failures exceeded the failures of any other individual component, and have been excluded from the component failure data shown

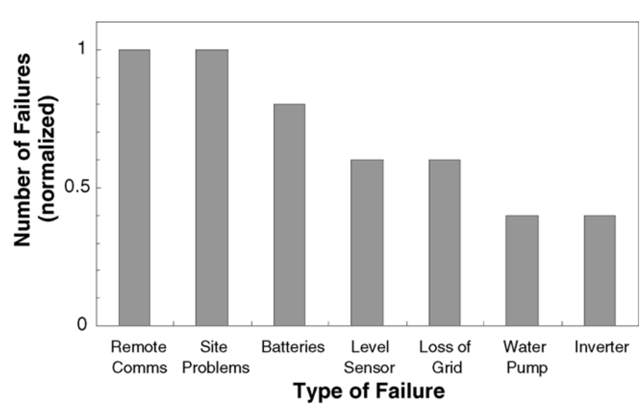

Fig. 4. Most frequent component failures in the installed fleet during June 2004.

in Figs. 3 and 4 to highlight the reliability of other parts of the system. Stack reliability will be discussed in Section 3.3.

Component reliability changed significantly from the B1 to B6 systems. A comparison of Figs. 3 and 4 shows that six of the seven most frequent component failures in October 2002 no longer made the top seven list in June 2004. As the most frequent component failures were retired through hardware and/or software changes, other problems percolated to the top of the list. Enterprise-wide software tools were used to systematically report failures and track problems to resolution. We believe that tools of this type are essential to achieving the high reliability required for stationary power generation equipment.

When comparing Figs. 3 and 4, note that some components may experience more than one failure mode, and design changes that reduce or eliminate one failure mode may not eliminate all failure modes caused or experienced by that component (and may actually create new, unanticipated failure modes). The failures shown in Figs. 3 and 4 are failure categories which group together all failures of a particular component, regardless of the failure mode. In other words, the reliability of a component can be improved without necessarily eliminating all failures associated with that component, or improving the overall reliability of the system. Aging of the fleet and component wear can, over time, cause new problems to appear with higher failure rates than previous problems.

3.3. PEM stack reliability

No discussion of PEM fuel cell system reliability is complete without mentioning the reliability of the fuel cell stack. We have found that a Weibull distribution [7] provides a reasonably good fit to failure time data of stacks deployed in the field.

Fig. 5 shows Weibull fits to field stack reliability data from the B3–B6 systems. System run time in Fig. 5 has been normalized by the time required for the reliability of B3 stacks to reach zero. Fig. 5 shows that the time required for 50% of the stacks to fail (i.e., the median stack life) has increased by more than a factor of 4 from the B3 to B6 builds.

The large increase in median stack life was achieved through a combination of software and hardware changes. The dramatic improvement from the B3 to B4 builds was mainly due to a software upgrade and control algorithm changes. The new software and control algorithms provided better control of stack coolant inlet temperature by using a cascaded proportional–integral–derivative (PID) control scheme. The coolant temperature change across the stack was put under closed loop control, using the coolant pump speed as the adjustable parameter. Closed loop control of cathode humidification was also implemented. These software changes enabled more precise control of the stack coolant and reactant inlet temperatures. In addition, the new software and control algorithms periodically cycled certain movable components to prevent them from sticking.

The improvement in stack life in the B5 and B6 builds was primarily the result of hardware changes. One change reduced cell-to-cell temperature variations by improving the coolant distribution between cells within the stack. A hardware change in the fuel processing module resulted in a reduction in the reformate CO concentration. Other major changes included using more reliable components and reducing unit-to-unit variation.

For each GenSys™ fuel cell system deployed in the field, more than 200 parameters are periodically recorded. Several stack parameters are used, in conjunction with other indicators, as monitors of stack "health". Fig. 6 shows two of these indicators, stack voltage (normalized by the maximum recorded stack voltage) and cell ratio, in the time period between January and December 2004. The data in Fig. 6 are from a single fielded system that was commissioned in May 2003 and had been running for over 13,000 h at the time this paper was written. From a linear regression of the stack

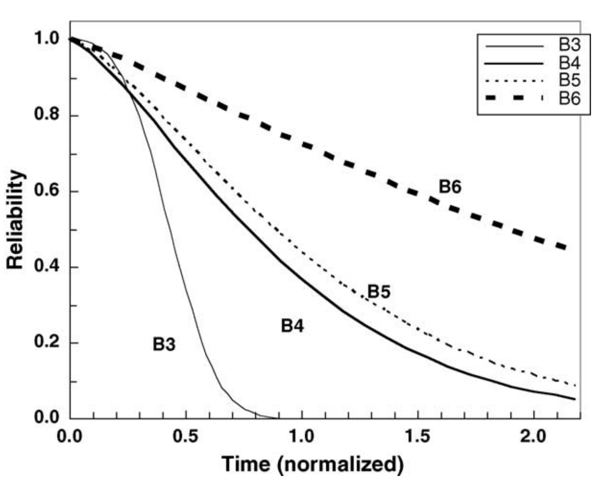

Fig. 5. Weibull distributions of GenSys™ fuel cell system stack reliability.

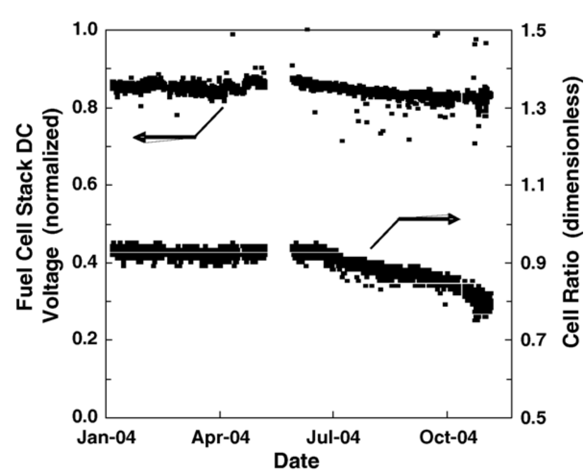

Fig. 6. Performance of a fuel cell stack in a GenSys™ fuel cell system. As of December 2004, this system has been running in the field for over 13,000 h.

voltage, an average stack degradation rate was found to be 3.5 $\mu V\,cell^{-1}\,h^{-1}$.

Fig. 6 also shows that the cell ratio, which is defined as the ratio of the lowest cell voltage to the mean cell voltage, was nearly constant before July 2004. This observation indicates that the performance of all the cells was about the same during the first 9500 operating hours. However, starting in July 2004, the cell ratio decreased, indicating that the voltage of one or more cells decreased much faster than the majority of other cells. The loss of an adequate voltage in one or more cells in a GenSys™ stack will cause a stack failure, even if the stack voltage as a whole is still acceptable.

We find that individual cells within a GenSys™ stack often exhibit similar patterns while failing. Failing cells often experience a slow voltage decay over a long time period, much like other cells. Cells that will eventually fail then experience a somewhat faster voltage decrease over a shorter time period, followed by a very rapid loss of voltage during a short time period (a phenomenon sometimes referred to as "sudden death"). We note that once the voltage loss within a cell starts to accelerate, sudden death of that cell is normally not far away.

The acceleration of voltage loss is consistent with the formation of small holes in the MEA. We believe that the onset of accelerating voltage decrease corresponds to the formation of pinholes in the MEA. Sudden death occurs when the MEA holes reach a critical size.

4. Conclusions

Improving the reliability of complex fuel cell systems requires problem identification, tracking, and resolution at the system level. High stack reliability is necessary but not sufficient to guarantee high system reliability, as the failure of other components within the fuel cell system can cause a loss of product functionality. Over an 18 month period, Plug Power has demonstrated a factor of 2 improvement in the overall reliability of GenSys™ fuel cell systems while simultaneously increasing the median stack life by a factor of 4, decreasing product cost by about 50%, and adding new features through a combination of software and hardware changes. The rate at which system reliability was improved in this fleet of fuel cell systems can be used to develop program plans and schedules. The Weibull distribution was found to provide a reasonably good fit to failure time data of stacks deployed in the field. Data presented here on component reliability can be used to prioritize future research and development needs.

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