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Impact of load management on reliability assessment of grid independent PEM Fuel Cell Power Plants

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Abstract

In this paper, operating benefits from demand-side load management are evaluated for a Proton Exchange Membrane (PEM) Fuel Cell Power Plant (FCPP). For reliability modeling and evaluation of the PEM FCPP, a state-space generation model for a stand-alone PEM fuel cell that calculates the system availability and the expected energy not supplied (EENS) index has been developed. A systematic technique and detailed computer simulation software for a stand-alone PEM fuel cell station reliability assessment have been built. The suggested technique can be used for practical engineering applications to provide information for stand-alone FC generating station planning, design, and operation. The simulation results are obtained using the MATLAB software for a 5 kW stand-alone PEM fuel cell that supplies a typical residential house.

Keywords: PEM fuel cell; Reliability; State-space modeling; Load management

1. Introduction

Considerable attention has been devoted to distributed sources of energy for meeting the power demand instead of constructing new conventional power plants due to better power quality, reliability, portability and ecological constraints. Among the various types of distributed generation, fuel cells (FCs), particularly PEM FCPPs generated tremendous interest for electricity and heat generation due to their low operating temperature, fast start up characteristics, and ecological constraints [1]. The use of Fuel Cell Power Plants (FCPPs) is expected to become more widespread in the near future, in spite of their high current capital cost. During normal operation, FCPPs are subjected to a number of possible outage and derated modes due to partial or full failure of system components as well as degradation of the fuel cell stack and battery. Some FC failure modes include membranes drying out (insufficient humidification), overheating, passages clogging up with water and freezing of water in humidification channels. For these reasons, fuel cells, particularly grid-independent FCPPs may encounter lack of generation in meeting the peak demand. One way to overcome this problem is to use load management system in stand-alone FCPPs. Load management in this study refers to any load curtailment activity that shaves the peak so that the power demand stays in the range of FCPP supply limits. This action is also needed to increase competitiveness and market value of the FCPP. To show the impact of load management on FC operation, it is important to analyze FCPP system reliability for likely operational and loading conditions. However, very little information is available on the reliability of FCPPs possibly due to the early stage of FCPP technology dependent, insufficient data and uncertainties. Consequently, the results presented in this paper provide key information for individual FCPP planning, design and operation. The reliability studies related to FCPPs are generally investigated from the viewpoint of improving the continuity of electricity supply rather than the reliability level of FCPP itself. Smith and Giancaterino [2] utilized the PEM FCPP in a telecommunication back-up power system to maintain high system reliability. Another study by [3] considers the fuel cells as a distributed power generation with high reliability, durability and environmental benefits. In this study [3], a component-based state-space representation technique is considered as a basic model in the stand-alone PEM FCPP reliability evaluation. The

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state-space method includes different states such as operation, derated, fully faulted or maintenance, since FCPPs are subject to a number of possible outage and derated states. The aging failures in the state-space generation model of the PEM FCPP are estimated based on the assumption that the failure and repair rates of the components change with the operation age of FCPPs. The functional relationship between the age of FCPP and transition rates, namely failure and repair rates is estimated based on the fuzzy set theory and expert knowledge.

2. Background and notations

In a fuel cell, hydrogen is fed at the anode, oxygen is fed at the cathode, and an electrolyte is sandwiched between the two electrodes for conveying ion e^- from the anode to the cathode. Electrons are carried to the cathode through both anode and a conducting wire, and a load is placed in between. There are many auxiliary devices needed to operate the FCPP, which take part in the gas and electricity management and are used for regulating the parameters such as reactant flow rate, total pressure, reactant partial pressure, temperature and membrane humidity at a desired value to ensure that FCPPs can run smoothly without getting the stack either flooded or drying out [4]. Accordingly, any malfunctioning, performance loss, and/or failure in these auxiliaries can reduce the overall performance of the FCPP. This section introduces an overview and the terminology used throughout this paper.

2.1. PEM fuel cell model

Fuel cells basically convert chemical energy of hydrocarbon fuels directly into dc form of electrical energy. A FCPP mainly consists of a fuel-processing unit (reformer), FC stack and power-conditioning unit. The FC uses hydrogen as input and produces dc power at the output of the stack. A simple representation of a FC system is shown in Fig. 1.

The performance of a FC is generally characterized by using the polarization curve, which is a plot of the FC output voltage as a function of load current. The polarization curve is computed by using the Tafel equation [5], which subtracts the various voltage losses from the open circuit dc voltage, and is expressed as

$$V_{\text{stack}} = V_{\text{open}} - V_{\text{ohmic}} - V_{\text{activation}} - V_{\text{concentration}} \quad (1)$$

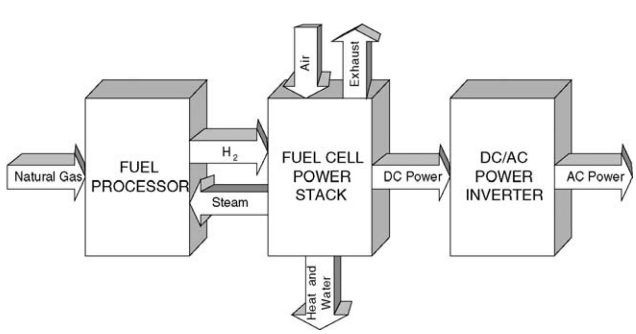

Fig. 1. Basic fuel cell components.

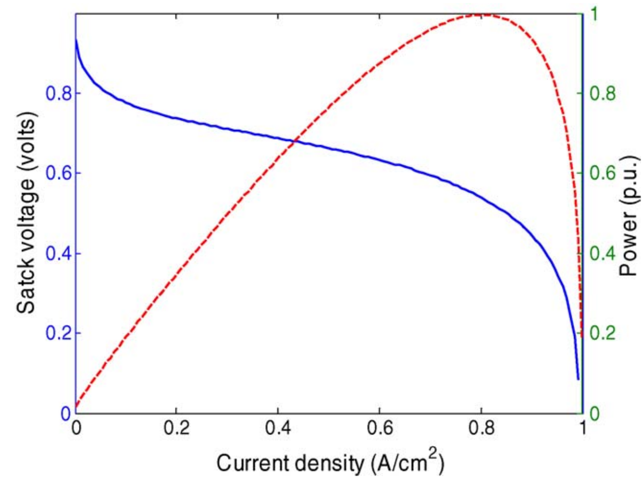

Fig. 2. Plot of stack voltage and power vs. current density.

where,

$$V_{\text{open}} = N_0 \cdot (E^0 + E^1) = N_0 \cdot \left[-\frac{\Delta \bar{g}_f^0}{2F} + \frac{RT}{2F} \ln\left(\frac{p_{H_2} \cdot \sqrt{p_{O_2}}}{p_{H_2O}} \right) \right] \quad (2)$$

$$V_{\text{ohmic}} = (i + i_n) \cdot R_{FC} = I_{dc} \cdot R_{FC} \quad (3)$$

$$V_{\text{activation}} = N_0 \cdot \frac{RT}{2\alpha F} \ln\left(\frac{I_{dc}}{I_0}\right) \quad (4)$$

$$V_{\text{concentration}} = -c \ln\left(1 - \frac{I_{dc}}{I_{\text{Lim}}}\right) \quad (5)$$

In the above equations, N_0 is the cell number, V_0 the open cell voltage, R the universal gas constant, T the temperature of the fuel cell stack, F the Faraday's constant, P_{H_2} the hydrogen partial pressure, P_{H_2O} the water partial pressure, P_{O_2} the oxygen partial pressure, P_O the standard pressure, α represents the charge transfer coefficient of the electrodes, I_{dc} the current of the FC stack, I_{Lim} the limiting current of FC stack, I_0 the exchange current of FC stack and c is the empirical coefficient for concentration voltage. The steady state voltage for one cell ($N_0 = 1$) and power versus cell current density is obtained based on Eq. (1) and as shown in Fig. 2.

Various auxiliary components such as air compressors, pumps, humidification equipment, blower and coolers are used in the FCPP that are related to thermodynamics and flow control. Besides the power-conditioning unit (dc/dc converter plus dc/ac inverter), control electronics, energy storage and transformers are used in power conversion and overall system control. Fig. 3 shows a PEM FCPP block diagram that shows the auxiliary components along with input and output signals.

2.2. State-space based generation unit reliability

Most generation units require auxiliary equipment and therefore they are subjected to different possible derated capacity states based on factors such as outage of auxiliaries, fuel quality and environmental conditions [6]. Hence, the state-space model

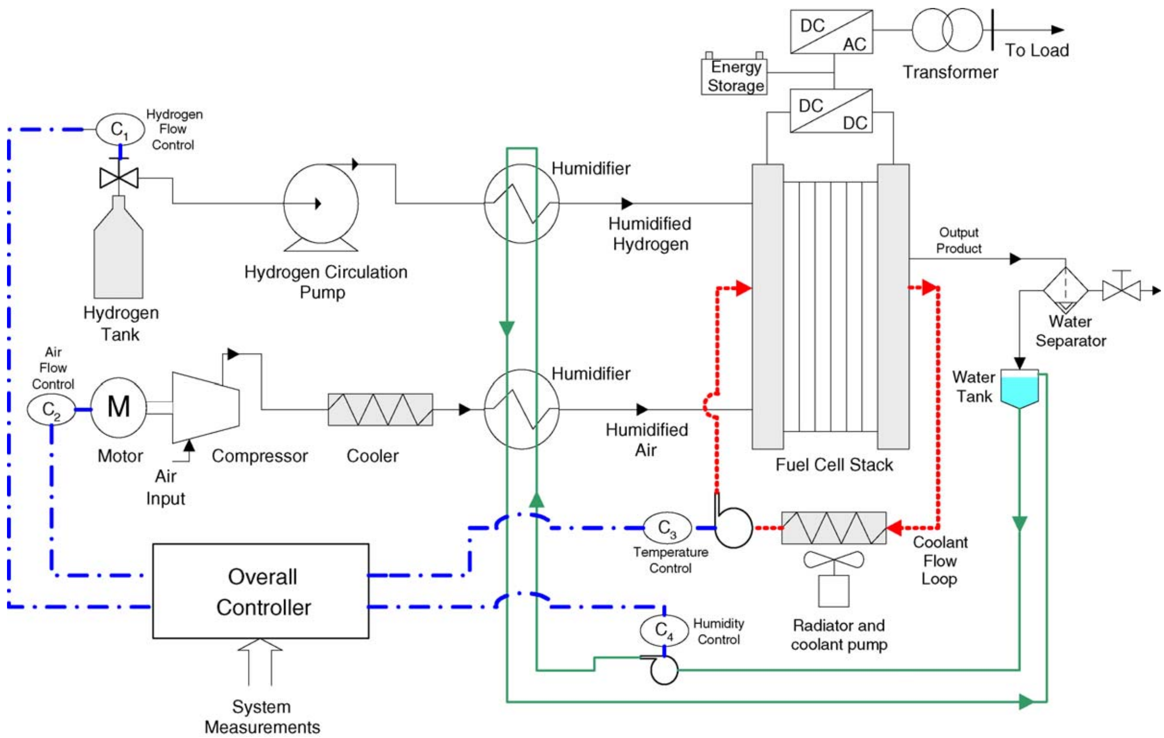

Fig. 3. PEM fuel cell system block diagram.

of the generating unit may include different states such as up, derated and completely down. The general state-space model of a generating unit for the aforementioned case is given in Fig. 4, where λ is the failure rate and μ is the repair rate.

In Fig. 4, the indices $i=1, 2, \ldots, k$ represent the number of components that cause unit failure; the indices $j=1, 2, \ldots, m$ represent the number of components that affect derating level of the unit. The state-space based reliability calculation is performed using Markov models. The state-space equation of Fig. 4 can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t} P(t) = A \cdot P(t) \tag{6}$$

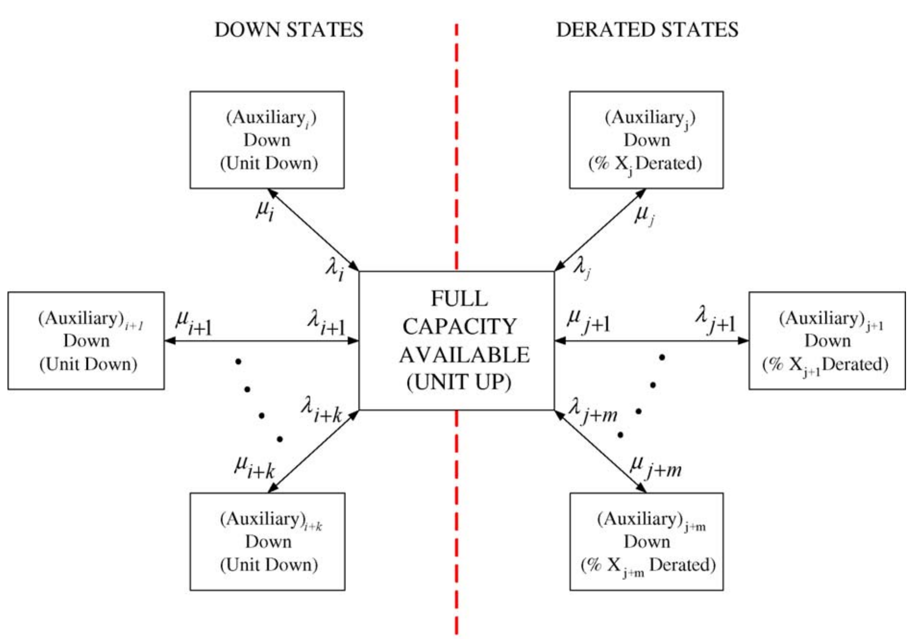

Fig. 4. The state-space model of the generating unit.

where A is the transition matrix defined as

$$A=\begin{bmatrix} -\sum_{i=2}^{n}\lambda_{1i} & \lambda_{21} & \cdots & \lambda_{n1} \\ \lambda_{12} & -\sum_{i=1,i\neq 2}^{n}\lambda_{2i} & \cdots & \lambda_{n2} \\ \cdots & \cdots & \cdots & \cdots \\ \lambda_{1n} & \lambda_{2n} & \cdots & -\sum_{i=1}^{n-1}\lambda_{ni} \end{bmatrix}, \quad (7)$$

and

$$P(t)=[P_1(t)\ P_2(t)\ P_3(t)\ P_4(t)]^{\mathrm{T}}. \quad (8)$$

In Eqs. (7) and (8), λ_{ij} represents the transition rate between the ith state and the jth state, and $P_i(t)$ represents the probability of the ith state.

2.3. Load management system

The primary goal of the load management system is to reduce the overall power consumption while leveling the load by smoothing the peaks and valleys in the power demand profile of the system. The load management and control system includes data acquisition system, user interface, and smart energy management control (SEMaC) software. The SEMaC software makes decisions regarding the control actions needed to keep the maximum load below the FCPP rated capacity at any given instant as shown in Fig. 5.

Power management decisions must be made in the context of minimizing user inconvenience and maximizing user comfort while reducing the overall power consumption. An effective system is virtually unnoticeable to the user, but results in substantial savings in the annual power bill by shaving peak demands in the system load profile. Peak loads are managed based on the load rescheduling algorithms. The load management system scans the data acquisition system and calculates the power usage of all loads. If the power is over a predefined level, the peak load is managed by sending an appropriate signal to the SeMAC system to reduce or turn off the load.

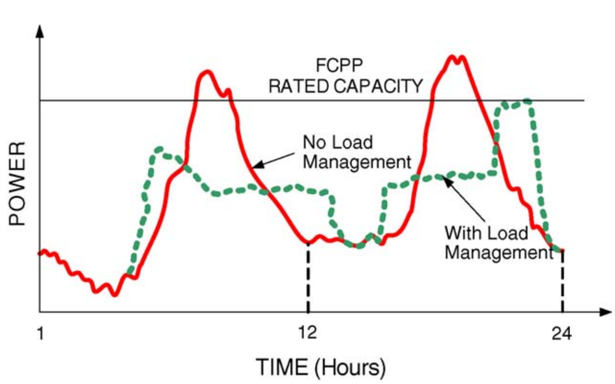

Fig. 5. Load profile comparison with and without load management system.

3. PEM FCPP reliability model

The FCPP includes fuel cell stack and auxiliary equipments such as air compressors, pumps, humidifiers, coolers and control electronics, as shown in Fig. 3. During normal operation, some FCPP components such as compressor, fans, pumps, motors, temperature and humidity sensors, relays and other control electronics may contribute to system failure or derated mode for different reasons such as ignition of any leaking hydrogen, material fatigue, wear outs, break-downs, membrane drying out, overheating and freezing of water in channels [7]. If any of these components go beyond the operating limits, the output of that component will be reduced by a factor. For instance, insufficient circulating coolant flow due to the coolant water pump failure may cause a reduction in the nominal output. Other failures may cause either a reduction in nominal output power or total system outage. The results of the aforementioned auxiliary failures are considered herein rather than the failure modes themselves to calculate the effects of sub-system performance reduction on overall FCPP performance.

3.1. Cooling system

If the cooling is insufficient due to loss of performance in the coolant system, the operating temperature of the FCPP will increase to $\dot{T}=T+\Delta T$, where $\dot{T}$ denotes the new operating temperature. An increase in temperature leads to reduction in FCPP output voltage due to the fact that Gibbs free energy changes inversely with temperature as shown in the following equation.

$$\dot{V}_{\text{stack}}=V_{\text{stack}}-\Delta V$$

The other effects of temperature change include

- Resistive voltage loss, V_{ohmic} tends to increase at higher temperature due to dry out mode of the FC stack.
- Activation voltage loss, $V_{\text{activation}}$ increases due to the constant of $\frac{RT}{2\alpha F}$ in the equation.
- The only reduction takes place at concentration voltage loss due to the negative coefficient $\frac{RT}{2F}$ in $V_{\text{concentration}}$ expression. However, percentage voltage loss reduction in $V_{\text{concentration}}$ will be smaller than a percent voltage loss increase in $V_{\text{activation}}$ due to coefficient α that takes a value between 0 and 1 (generally, $\alpha=0.5$). Hence, a decrease in the maximum power level ($\dot{P}=P-\Delta P$) will be observed for higher temperature, where the power change ΔP is expressed as $\Delta P=\Delta P\ I_{\text{dc}}$.

Consequently, if the temperature increases due to insufficient cooling, the power supplying capacity of the FCPP also reduces as shown by the following expression

$$\mathrm{RP_C}[\%]=\frac{P-\Delta P}{P}\times 100=\frac{\dot{P}}{P}\times 100 \quad (7)$$

where $\mathrm{RP_C}$ is the percent reduction in power supplying capacity of FCPP due to insufficient cooling. If the FCPP cooling system completely fails or if such failure leads to instability in FCPP operation, then an emergency stop function is activated to shut off the system, and the system will go to off state.

3.2. Humidification system

PEM fuel cells are quite sensitive to the humidity of reactant gases. Any excess liquid water from the humidification process that flows into the FCPP can reduce the output power capacity and may cause stack damage. The system performance loss is mainly caused by the internal ohmic resistance increase resulted from drying-out of the membrane (insufficient humidification). After the membrane dry-out mode, the magnitude of the FCPP stack impedance increases. This change can be expressed by $\dot{R}_{FC} = R_{FC} + \Delta R$. However, the reduction in FCPP output power depends on the severity of insufficient humidification. The resistive voltage loss, V_{ohmic} increases in proportion to FCPP stack resistance, which leads to output voltage reduction and consequent power reduction.

Since humid reactants are a mixture of dry gasses and vapor, dry partial pressure is the difference between total pressure and the vapor pressure, which can be expressed as $\dot{p}_T = p_T - p_v$. Since humidity ratio (ϕ) is expressed as the ratio of partial pressure of water vapor (p_v) to saturation pressure (p_s), then the vapor pressure (p_v) can be written as $p_v = \phi \cdot p_s$. If Nernst voltage (V_{open}) is rewritten in terms of the total system pressure (p_T), we get

$$V_{open} = E^0 + \frac{RT}{2F} \ln\left(\frac{w \cdot \sqrt{x}}{y}\right) + \frac{RT}{4F} \ln(p_T) \tag{8}$$

where w, x, and y are the constants related to molar masses and concentrations of H_2, O_2 and partial pressures, denoted as $p_{H_2} = w \cdot p_T$, $p_{O_2} = x \cdot p_T$, $p_{H_2O} = y \cdot p_T$. From Eq. (8), it is evident that if the total system pressure, p_T, reduces to $\dot{p}_T$, then the open circuit voltage and the corresponding output voltage will be reduced by $\frac{RT}{4F} \ln(p_T - \dot{p}_T)$.

3.3. Fuel supply system

For the PEM FCPP, the cell must be supplied by a continuous flow of hydrogen to provide continuous energy output. Besides mechanical wear outs and control malfunction, degeneration of pure hydrogen may lead to possible reduction in hydrogen supply to lead to derated states of FCPP unit. Since $Q = 2F \times w_{H_2}$, where Q is the charge and w_{H_2} is the amount of hydrogen in mol; $Q = I_{dc} \times t$, then $I_{dc} = 2F \times \frac{w_{H_2}}{t}$. Because $q_{H_2} = \frac{w_{H_2}}{t}$, then $I_{dc} = 2F \times q_{H_2}$, where I_{dc} is the total stack current and q_{H_2} is the molar hydrogen usage per second. If the stack current is written in terms of total stack power, then $I_{dc} = P/V_{stack}$, which can be rewritten as

$$P = 2F \cdot q_{H_2} \cdot V_{stack} \tag{9}$$

From Eq. (9), it is evident that if the maximum designed level of power reduces by Δq_{H_2}, the FCPP output power will decrease by $\Delta P = 2F \cdot \Delta q_{H_2} \cdot V_{stack}$. As a result, percent reduction in power supply capacity of FCPP due to insufficient hydrogen usage can be calculated as follows:

$$RP_q[\%] = \frac{q_{H_2} - \Delta q_{H_2}}{q_{H_2}} \times 100 = \frac{\dot{q}_{H_2}}{q_{H_2}} \times 100 \tag{10}$$

3.4. Air supply system

In a FCPP, oxygen derived from air is used to complete the chemical reaction. The molar oxygen usage per second, q_{O_2} of the FCPP for a given output power can be computed as

$$q_{O_2} = \frac{P}{4FV_{stack}} \tag{11}$$

Eq. (11) can be adopted easily for air usage by multiplying q_{O_2} with 0.21 since 21% oxygen is available in the air mixture. However, it is not practical to consume all oxygen entering the FC stack. Hence, in real applications, the FCPPs are typically supplied with twice the amount of air needed [8]. For this reason, the blower and the compressor are sized so that the excess oxygen ratio γ is equal to 2, where γ = (supplied rate O_2)/(reacted rate of O_2). Since more than enough oxygen is supplied, FCPP output will not be affected unless partial pressure of oxygen drops below a certain threshold value. If oxygen partial pressure falls below the critical level, FCPP will experience oxygen starvation, which may lead to catastrophic membrane failure. Before the system reaches this stage, an emergency stop function will either isolate the system from load or shut down the system. Hence, none of the failure mode in airflow circulation leads to any derated state but may result in FCPP failure.

3.5. Energy storage system

The flow rate of hydrogen is controlled continuously in order to follow the electrical load variations. However depending upon FCPP type, flow rate adjustment can be achieved with a time delay, ranging from a few microseconds to 30 s. For this reason, some type of energy storage is needed for fast transient response and meeting the peak load requirement. Among the various types of energy storage devices, batteries are the common choice, but they have relatively shorter lifetime and need maintenance. Assume that the FCPP designed power is P and system peak load is P_{peak}. Thus, based on the 80% battery usage, the energy storage power is $P_{storage} = 1.25 \times (P_{peak} - P)$. The energy storage capacity is measured in watt-hours, expressed as $W = P_{storage} \times t$, where t represents the number of hours used for power, $P_{storage}$.

If the total power supply capacity of the system falls below the load demand due to energy storage degradation and/or failures, it is assumed that the excess load can no longer be supplied and ought to be disconnected from the system by the SeMAC system. Hence, the percent reduction in the power supply capacity of the system due to energy storage failure may be calculated as

$$RP_{ES}[\%] = \frac{|(P + \dot{P}_{storage}) - P_{demand}|}{P + \dot{P}_{storage}} \times 100, \quad \text{if}(P + \dot{P}_{storage}) < P_{demand} \tag{12}$$

Table 1
Summary of state-space model of FCPP associated with each system auxiliaries

FC sub-systems	Failure severity	FC system	State-space representation	Possible inadequacy effects on system output
Cooling system	Inadequacy down	Derated Down	Cooling Down (UNIT Down) ↔ PEMFC (UNIT UP) ↔ Inadequate Cooling (UNIT Derated)	Output power will be derated by RP_C% due to increase in temperature and internal resistance
Humidification system	Inadequacy sown	Derated derated	Humidification Down (UNIT Derated) ↔ PEMFC (UNIT UP) ↔ Inadequate Humidification (UNIT Derated)	Output power will be derated by $\mathrm{RP_H}$% due to increase in internal resistance and decrease in partial pressure of the reactants
Fueling system	Inadequacy down	Derated down	Fueling Down (UNIT Down) ↔ PEMFC (UNIT UP) ↔ Inadequate Fueling (UNIT Derated)	Output power will be derated by RP_q% due to decrease in hydrogen supply and/or degeneration of pure hydrogen
Air supply system	Inadequacy down	Down down	Air Supply Down (UNIT Down) ↔ PEMFC (UNIT UP) ↔ Inadequate Oxygen (UNIT Down)	Relative inadequacy of air supply will not lead reduction in output power, but may result in complete system failure
Energy storage system	Inadequacy down	Derated derated	Energy Storage Down (UNIT Derated) ↔ PEMFC (UNIT UP) ↔ Inadequate Energy Storage (UNIT Derated)	Output power will be derated by $\mathrm{RP_{ES}}$% due to FC stack and battery degradation

where, $\dot{P}_{\text{storage}}$ denotes the new battery power due to loss of energy storage performance. As a consequence, any possible energy storage failure results in only derated state. Other system components such as stack, reformer, power conditioner, and transformer can be considered as essential components for the FCPP power supply and any of these component failures may bring the system down. However, the stack has gradual performance deterioration rather than catastrophic failures. As the electrodes and electrolyte become older, FCPP output power drops steadily with time. This is more important generally for stand-alone FCPPs. Table 1 summarizes the effects of inadequacies/failures of FC sub-systems on the system output power with their state-space models.

3.6. Estimation of transition probabilities and aging effects

Assume that system auxiliary component failure or performance loss takes place after operating the FCPP for a while, typically for 5000 h. Failure rate of the components increase with time until maintenance and drops to its original value after maintenance. It is assumed that maintenance is performed at regular intervals, and the repair time and duration of maintenance increase when the components become older. In addition, the state of health of the auxiliary components becomes worse in proportion to component aging. The relationship described above is estimated by a Weibull model, which is a practical tool for modeling component aging [9]. The Weibull distribution and its failure rate are defined as

$$f(T) = \frac{\beta T^{\beta-1}}{\alpha^{\beta}} \cdot \mathrm{e}^{-(T/\alpha)^{\beta}} \tag{13}$$

$$\lambda(T) = \frac{\beta T^{\beta-1}}{\alpha^{\beta}} \tag{14}$$

where T is the component age (or the time from last overhaul), β the shape factor which determines how the failure rate changes with equipment age and α is the characteristic time interval. If $\beta < 1$ the failure rates decreases with age, if $\beta = 1$ the failure rate is independent of age, and if $\beta > 1$ the failure rate increases with age. Since FCPP technology is new and there is no publicly available data associated with the failures of FCPP system, a fuzzy logic rule based system is used based on the expert knowledge to determine the performance loss of system auxiliary components. The rule format for non-healthy state level is shown as below:

If input is < component age and maintenance cycle and ... >

then, output is < degree of failure severity >

3.7. Reliability and EENS calculation

In the Markov model, the reliability of a system corresponds to the summation of operating state probabilities, expressed as

$$R = \sum_{i=1}^{n} \mathrm{P}_i \tag{15}$$

where P_i is a row vector and represents the operating state probabilities. If the state probabilities corresponding to up and derated states are grouped in a vector, then P_i can be expressed as

$$\mathrm{P}_i = [\mathrm{P}_1^u\, \mathrm{P}_2^u \cdots \mathrm{P}_m^u | \mathrm{P}_{m+1}^d\, \mathrm{P}_{m+2}^d \cdots \mathrm{P}_n^d]_{1\times n} \tag{16}$$

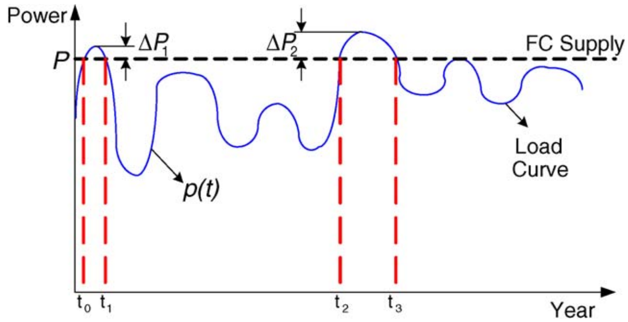

Fig. 6. System behavior during inadequate power supply.

where "*u*" represents the up states and "*d*" represents the derated states. Derated state implies that the unit may not operate at full rated capacity. Thus derated state probabilities must be reduced by a factor i.e., correction vector, C_i, appropriate to the derated state, given by

$$C_i = [1\ 1\ \cdots\ 1|c_1\ c_2\ \cdots\ c_n]^T_{1\times n} \tag{17}$$

where, $C_i = 1 - \mathrm{RP}_i\%$ and $\mathrm{RP}_i\%$ represents the percentage power reduction corresponding to each derated state. Hence, reliability of the system can be calculated as

$$R = [\mathrm{P}_i]_{1\times n} \cdot [\mathrm{C}_i]_{n\times 1} \tag{18}$$

As stated earlier, FCPPs are subject to a number of possible outage and derated states due to partial or full failure of auxiliary components. Hence, it is essential to obtain an estimate of the expected energy not supplied (EENS) index, which corresponds to the expected number of watt-hours curtailed per year due to inadequate generation, given by

$$\mathrm{EENS} = \mathrm{EPNS} \times 8760 \tag{19}$$

where EPNS represents the expected power not supplied per hour at the bus of interest, which is expressed as

$$\mathrm{EPNS} = \frac{\sum_{i=1}^{n}(\mathrm{PNS})_i}{n} \tag{20}$$

where $(\mathrm{PNS})_i$ is the amount of un-served power demand at the FCPP load point associated with the system state "*i*", and *n* is the total number of system states. Fig. 6 shows the FCPP behavior during inadequate power supply. From Fig. 6, it is evident that the probability of EENS, P(EENS), at the FCPP load bus for state *i* can be calculated as

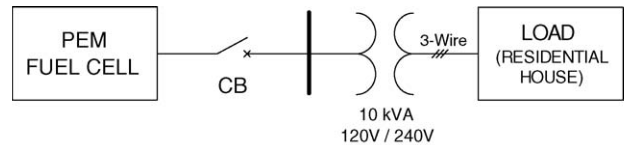

Fig. 7. Considered PEM fuel cell system used for reliability evaluation.

$$P(\mathrm{EENS})_i = \frac{\int_{t_0}^{t_1}(p(t)-P)\,\mathrm{d}t + \int_{t_2}^{t_3}(p(t)-P)\,\mathrm{d}t}{\int_0^{8760} p(t)\,\mathrm{d}t} \cong \frac{\Delta P_1 \cdot (t_1 - t_0) + \Delta P_2 \cdot (t_3 - t_2)}{\int_0^{8760} p(t)\,\mathrm{d}t} \tag{21}$$

If Eq. (21) is generalized, $\mathrm{P(EENS)}_i$ can be rewritten as

$$P(\mathrm{EENS})_i = \frac{\sum_{j=1}^{N}\int_{t_j}^{t_{j+1}}(p(t)-P)\,\mathrm{d}t}{\int_0^{8760} p(t)\,\mathrm{d}t} \tag{22}$$

where, $j = 1, 2, \ldots, N$ is the number of time span $(t_{j+1} - t_j)$ per year that the system must curtail load due to inadequate FCPP generation. From the Markov model, the total duration of derated state that the FCPP may experience may be obtained (in hours) as $t_i = (1 - A_i) \times 8760$, where A_i is the availability of derated FCPP states that result in lack of power supply.

4. Example

A methodology for reliability analysis of stand-alone PEM FCPPs is proposed and the structure of the new algorithm has been described in earlier sections. In this section, the proposed approach is applied for a 5 kW PEM FCPP that supplies a typical residential house as shown in Fig. 7.

The parameters of the 5 kW PEM fuel cell are shown in Table 2, where a 0.0001% value is assumed for the percent stack power deterioration per hour.

The residential power demand was recorded over a 800-min period at a sampling rate of 15 s. Since the capacity of the considered PEM fuel cell is 5 kW, the balance must be supplied by using a standby energy storage system. The power demand and the power supplied to a typical home through the FCPP and a standby battery are shown in Fig. 8(a–c), respectively, for a stand-alone PEM FCPP.

From Fig. 8(c), it is evident that the battery energy is about 3 kWh. The battery is recharged by the fuel cell when the power demand falls below the 5 kW level. It is assumed that the battery

Table 2
Five kilowatt PEM fuel cell parameters

Parameter	Value	Parameter	Value
Cell number (N_0)	100	Oxygen partial pressure (p_{O_2})	2.17 atm
Active area of a cell	100 cm^2	Charge transfer coefficient of the electrodes (α)	0.5
Universal gas constant (R)	8.1345 J mol^{-1} K^{-1}	Current of the FC stack (I_{dc})	94.69 A
Temperature of the fuel cell stack (T)	353 K	Limiting current of FC stack (I_{Lim})	105 A
Faraday's constant (F)	96485 C mol^{-1}	Exchange current density (I_O)	$10^{-6.912}$ A cm^{-2}
Hydrogen partial pressure (p_{H_2})	1.087 atm	Empirical coefficient for concentration voltage (c)	0.0147
Water partial pressure (p_{H_2O})	0.464 atm	Stack internal resistance (R_{FC})	0.00303 Ω

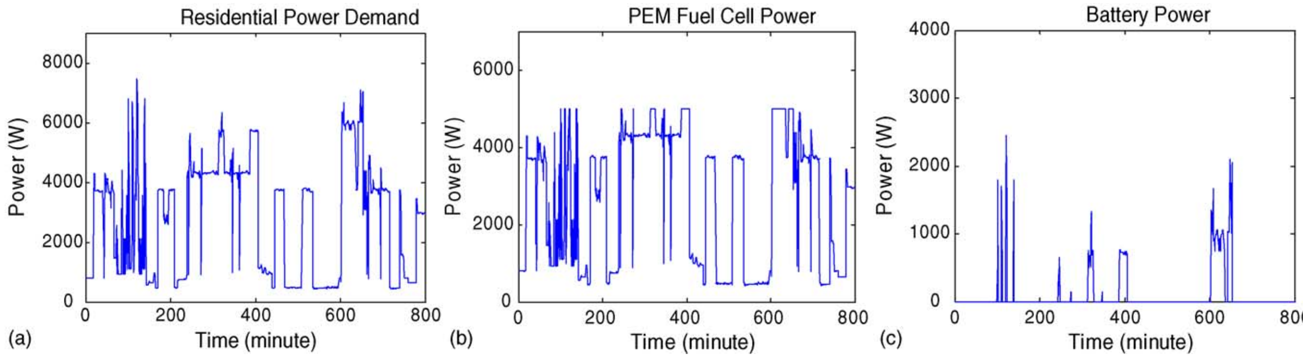

Fig. 8. (a) Typical residential power demand, (b) fuel cell power and (c) battery power to the load vs. time.

is replaced periodically (5 years interval), which is defined as the point where the capacity has declined to 80% of the nominal value.

The proposed FCPP modeling incorporates the component age and maintenance cycle (input values) and determines the degree of failure and failure rates via membership functions and Weibull distribution function. It is assumed that the possible wear out period starts after 5000 h of operation and continues to maintenance time, typically 1 year. This process is repeated at regular maintenance intervals and the repair times and the duration of maintenance increase at each cycle as the state of health of the auxiliary components decreases. The states of health of subsystems are represented individually by the triangular membership functions as shown in Fig. 9, which are developed by using expert knowledge. In Fig. 9, since maintenance is supposed to be done at regular intervals, component age gives direct information about the number of maintenance that has been done so far. Therefore, input membership function is chosen for only component aging.

Rules used in the fuzzy inference system are listed below:

- If age is <A_1 (very young)>, then reduction is <B_1 (very healthy)>
- If age is <A_2 (young)>, then reduction is <B_2 (healthy)>
- If age is <A_3 (medium)>, then Reduction is <B_3 (medium)>
- If age is <A_4 (old)>, then reduction is <B_4 (worn)>
- If age is <A_5 (very old)>, then reduction is <B_5 (very worn)>

These rules show the functional relationship between component age and reductions in auxiliary performance. Fig. 10 depicts the state-space modeling of a 5 kW PEM FCPP generation for a 5-year operational period. It is assumed that the stack and battery performance degrades gradually with time. Hence, the stack and battery energy generation sets are merged. The transition probabilities in the model are estimated for each subsystem based on the Weibull distribution.

5. Simulation results

The simulation of FCPP reliability variations using the proposed approach is carried out for different operational lifetimes as shown in Fig. 11. The instantaneous FCPP reliability variations for operational period of 1–5, and 6–10 years are shown in Fig. 11(a) and (b), respectively. Fig. 11 shows the FCPP reliability as a function of stack and battery degradation indicating that the reliability decreases with time.

Fig. 12 shows the steady-state reliability as well as cumulative EENS variation of FCPP as a function of time. In Fig. 12, the solid line represents the reliability of FCPP, while the dashed line represents the cumulative EENS values, which are given for the first and second 5-year period of operation. The results of Fig. 12(b) is obtained assuming that the battery is replaced at the end of 5-year operational period.

It is evident from Fig. 12 that the reliability level drops faster with time. The reliability increased considerably in Fig. 12(b)

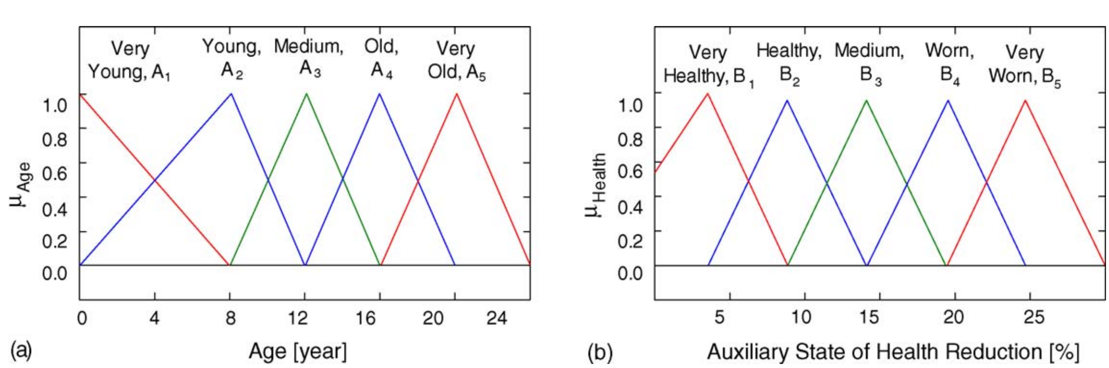

Fig. 9. An example of input (a) and output membership (b) functions for state of health of fuel cell auxiliaries.

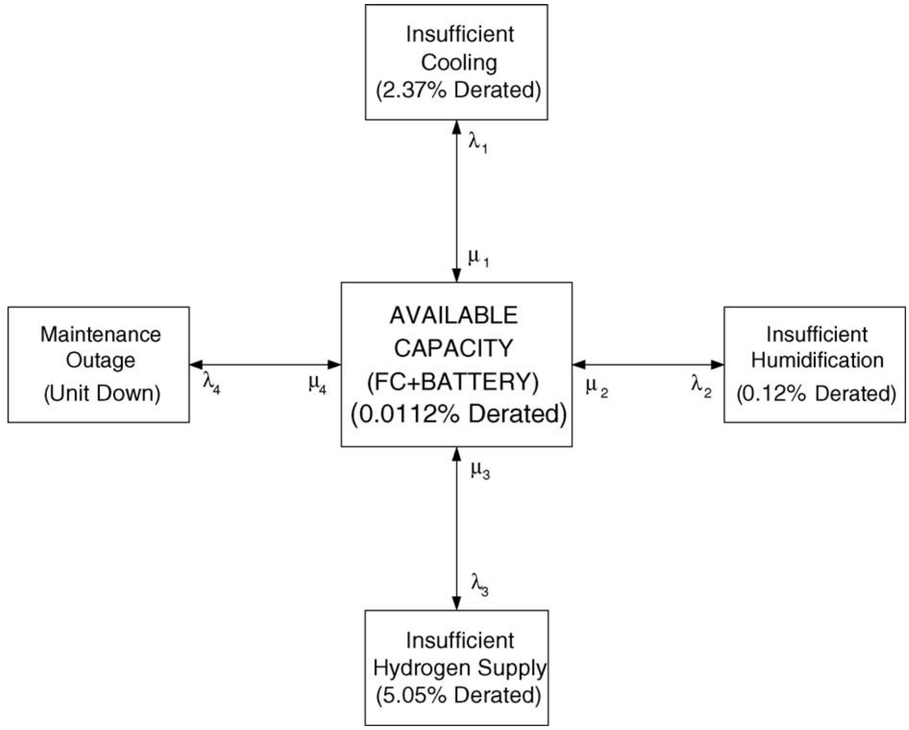

Fig. 10. The state-space model of a 5 kW PEM FCPP generating unit for the fifth year operation, where $\lambda_1 = 1.1423 \times 10^{-4}$, $\lambda_2 = 1.1422 \times 10^{-4}$, $\lambda_3 = 1.1421 \times 10^{-4}$, $\lambda_4 = 1.1419 \times 10^{-4}$ [failure/hour] and $\mu_1 = 0.3088$, $\mu_2 = 0.3388$, $\mu_3 = 0.3758$, $\mu_4 = 0.2857$ [repair/hour].

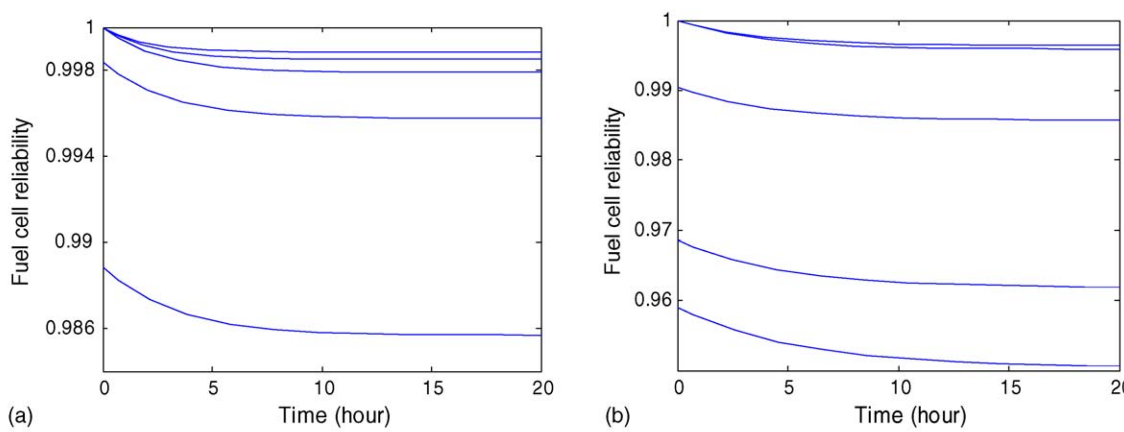

Fig. 11. Instantaneous FC system reliability (a) from 1 to 5 years, and (b) from 6 to 10 years, respectively, from upper to lower lines.

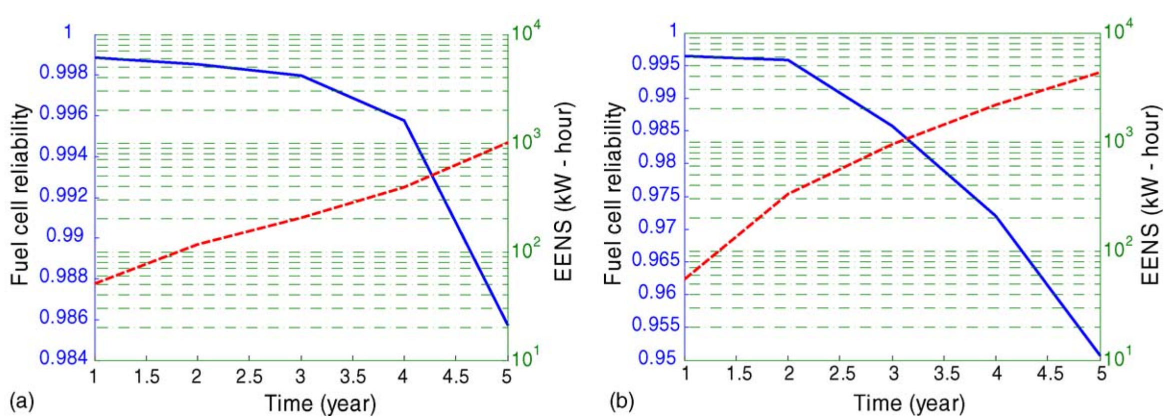

Fig. 12. Steady-state reliability and cumulative EENS variation of FCPP as a function of time for the: (a) first 5-year lifetime, and (b) second 5-year lifetime with battery replacement (solid line: reliability variation, dashed line: EENS variation).

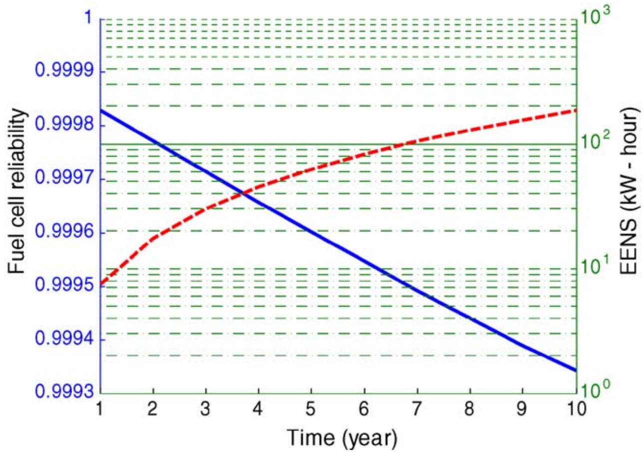

Fig. 13. Steady-state reliability and cumulative EENS variation of FC with load management system for 10-year operational period (solid line: reliability variation, dashed line: EENS variation).

due to battery replacement. However, 2 years after battery renewal, a noticeable reliability decrease started due to stack degradation from the first 5-year operation period.

In general, a FCPP may be unavailable for a significant duration due to lack of generation capacity resulting from stack and battery degradation. However, this negative impact can be minimized by utiliziing a smart energy management control (SEMaC) system in stand-alone FCPPs. A SEMaC system can intelligently schedule the power demand based on the user load profile and priority of needs, especially to tackle excess energy requirements. The steady-state reliability and cumulative EENS variation of the FCPP as a function of operational age is depicted in Fig. 13. It is evident from Figs. 12 and 13 that the FCPP availability can be increased significantly by implementing the SEMaC system. For example, using SEMaC based load management system, a customer may experience as low as 90 min unavailability (instead of 10 h) during the first year and 4 h unavailability (instead of 5 days) in the 5th year of FCPP operation.

6. Conclusions

In this paper, the operational benefits from load management are evaluated for a stand-alone PEM FCPP by implementing a novel FCPP reliability assessment technique. The proposed technique has been found to be an effective tool for modeling the reliability of FCPP and associated systems. The results obtained using the proposed technique confirms that the reliability of FCPPs drops steadily with time as the components become older. However, FCPP reliability can be considerably improved by utilizing the SEMaC based load management and control system, which also increases the competitiveness and market value of the stand-alone FCPPs. The proposed FCPP reliability evaluation method can be used as a tool to facilitate maintenance scheduling of FCPPs such as battery replacement. Apart from these, bipolar plates and membrane electrode assemblies can be renewed in order to lengthen the lifetime of FCPPs. The schedule for this replacement can be effectively decided by utilizing the proposed approach.

Acknowledgement

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