Available online at www.sciencedirect.com

ScienceDirect

Journal of Power Sources 177 (2008) 412–418

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

# Reliability and availability analysis of low power portable direct methanol fuel cells

N.S. Sisworahardjo[a,b,*], M.S. Alam[b], G. Aydinli[b]

[a] School of Electrical Engineering and Informatics, Bandung Institute of Technology, Bandung, 40132, Indonesia
[b] Department of Electrical and Computer Engineering, University of South Alabama, Mobile, AL 36688, USA

Received 8 November 2007; accepted 9 November 2007
Available online 22 November 2007

## Abstract

This paper presents a methodology for modeling and calculating the reliability and availability of low power portable direct methanol fuel cells (DMFCs). System reliability and availability are critical factors for improving market acceptance and for determining the competitiveness of the low power DMFC. Two techniques have been used for analyzing the system reliability and availability requirements for various system components. Reliability block diagram (RBD) is formed based on the failure rates of irreparable system components. A state-space method is developed to calculate system availability using the Markov model (MM). The state-space method incorporates three different states—operational, derated, and fully faulted states. Since most system components spend their lifetime in performing normal functional task, this research is focused mainly on this operational period. The failure and repair rates for repairable DMFC systems are estimated on the basis of a homogeneous Poisson process (HPP) and exponential distribution. Extensive analytical modeling and simulation study has been performed to verify the effectiveness of the proposed technique.

*Keywords:* Reliability; Availability; Reliability block diagram; Markov model; Low power DMFC

## 1. Introduction

Portable electronic devices such as, cellular phone, laptop, palm pilot, play an important role in daily activities. Power requirement for these portable devices have been steadily increasing coupled with high degree of availability and reliability. Under such conditions, research indicates that direct methanol fuel cell (DMFC) is the most appropriate power source for portable applications. Studies indicate that the DMFC system provides higher energy density and longer operational life compared to rechargeable Li-ion battery. Therefore, it is vital to analyze and improve the reliability and availability of low power portable DMFC systems.

Several studies related to reliability evaluation of fuel cell systems have been investigated [1,2]. Reliability modeling and analysis of stand alone proton exchange membrane (PEM) fuel cell power plants is presented in [1]. Another study [2], considered fuel cells for distributed generation to achieve high reliability, durability, and environmental benefits. In the area of portable DMFC, several studies [3,4], related to its design and model development have been proposed. Studies on the design of a 1 W direct methanol fuel cell system is presented in [3]. In [4], the development of a 2 W direct methanol fuel cell power source is investigated. To the best of the authors' knowledge, the reliability evaluation of a low power portable DMFC has not been reported in the literature. This may be due to the early developmental stage of low power DMFCs. During product development and design, system reliability assessment is critical because it affects topology and design related decisions. Accordingly, in this paper, we present a step-by-step approach for reliability modeling and analysis of low power portable DMFCs.

In this study, both repairable and irreparable systems are evaluated. For irreparable systems, the reliability block diagram (RBD) is used, where failures may be considered as statistically independent. The RBD is a graphical and mathematical representation of the relationship between subsystems or various system components and their impact on the system reliability

---

* Corresponding author. Tel.: +1 251 460 6117; fax: +1 251 460 6028.
*E-mail address:* nurh@ieee.org (N.S. Sisworahardjo).

0378-7753/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2007.11.048

[5]. A state-space method using Markov model (MM) is used to evaluate the repairable DMFC system model. The state-space method is used due to its flexibility and it can also provide a realistic model of system reliability over the operational period.

The rest of this paper is organized as follows. Section 2 presents DMFC system configuration and the underlying assumptions used for system reliability model development. In Section 3, a RBD for low power portable DMFC is introduced. Section 4 presents the state-space method using MM for repairable DMFC systems. Section 5 discusses the simulation results followed by concluding remarks in Section 6.

## 2. System configuration and model development

A low power portable DMFC system schematic is shown in Fig. 1 [4]. A typical DMFC system consists of three major subsystems: (1) fuel cell stack, which converts chemical energy into electrical energy, (2) fuel tank, which provides pure methanol as fuel for the fuel cell stack, and (3) the balance of plant (BOP). The BOP includes all auxiliaries such as, mixing chamber, pumps and methanol sensor and electronics such as drivers and converters. A detailed description of each component/subsystem is presented as follows.

### 2.1. The fuel cell stack

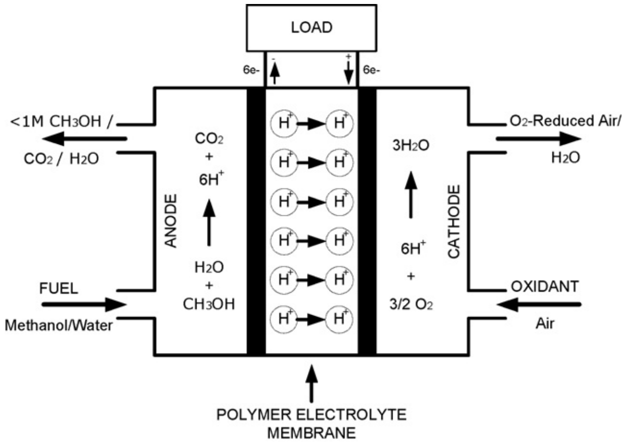

Fig. 2. The schematic diagram of a DMFC stack.

The fuel cell stack is the heart of a fuel cell power source, which converts chemical energy into electrical energy as shown in Fig. 2. The liquid fed DMFC is based on the electro-oxidation of an aqueous solution of methanol in a polymer electrolyte membrane fuel cell without the use of a fuel processor [5]. The present technology for the membrane electrode assembly (MEA) incorporates a commercially available polymer membrane (Nafion 117) coated with a electro-catalyst material. The electro-oxidation of methanol to carbon dioxide occurs in the presence of platinum/ruthenium (Pt/Ru) catalyst at the anode, and the conversion of oxygen to water occurs in the presence of the platinum catalyst at the cathode. During these reactions, methanol easily diffuses across the Nafion membrane from the anode to the cathode. This phenomenon is called methanol crossover, which may lead to performance deterioration of the stack.

The methanol permeation equivalent ranges from 100 mA cm$^{-2}$ to several hundred mA cm$^{-2}$, while the total cell current densities may range from 100 to 500 mA cm$^{-2}$ [6]. The most important factor is to keep the stack performance high when these reactions occur. Stack performance is affected by air flow rate, methanol–water flow rate, methanol concentration, and operating temperature.

Pure methanol is an excellent choice for small fuel cell systems due to its high energy density. Theoretically, the energy content of methanol is approximately 6000 Wh kg$^{-1}$. The DMFC reaction requires one molecule of water for every molecule of methanol. Dilute methanol is fed at the anode side of

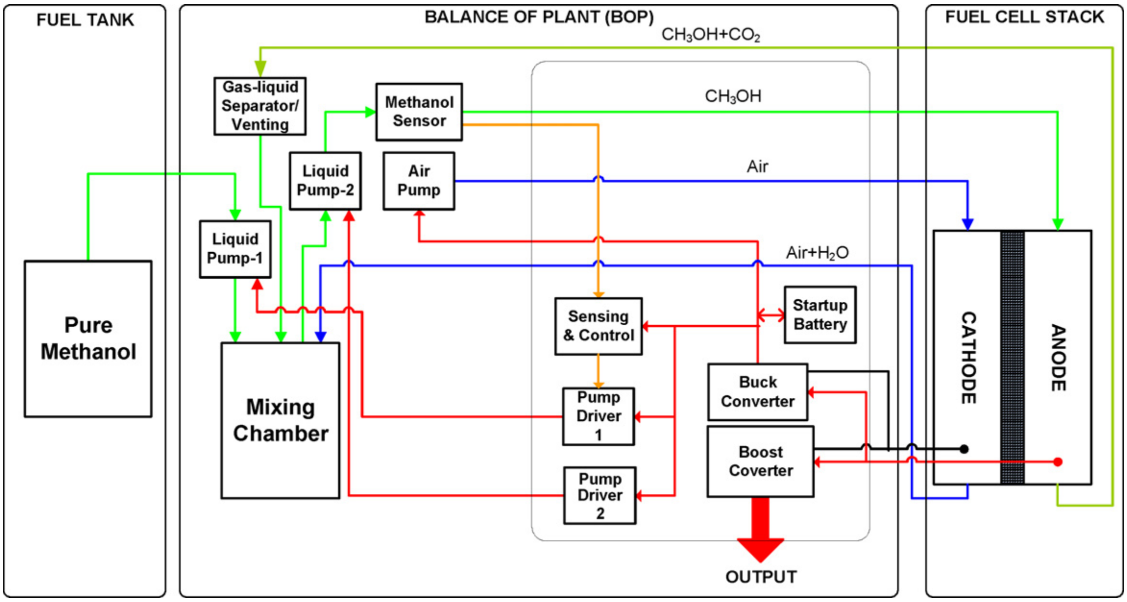

Fig. 1. The schematic diagram of a low power direct methanol fuel cell (DMFC) system.

the DMFC stack. Methanol is directly oxidized when it comes in contact with the catalyst Pt/Ru (1:1 atomic ratio). The simplified reaction in the anode side may be expressed as

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \quad (1)$$

From Eq. (1), it is evident that six moles of electrons and protons are produced per-mole of methanol consumed. During this reaction, protons are transported through the Nafion membrane to the cathode, while electrons move from anode to cathode via the outer circuit producing electricity.

Since on the cathode side, there is no advantage in using the expensive Pt/Ru catalyst, only Pt is used for this purpose. On the cathode, the reaction between protons and the oxygen in the air produces water, which flows through the cathode compartment. The reaction at the Pt catalytic layer is shown in Eq. (2). Since pure methanol is used as fuel, water created during the reaction must be recovered and reused.

$$(3/2)O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \quad (2)$$

During system operation, a fraction of the methanol diffuses through Nafion and comes in contact with the cathode. It reduces the voltage of the cathode and reacts directly with oxygen at the cathode to produce heat. This phenomenon is known as methanol crossover, which occurs according to Eq. (3). Methanol crossover is the most severe problem in limiting the performance and life expectancy of DMFC systems. It lowers the fuel utilization and fuel efficiency. Furthermore, methanol brings electrons directly from the anode to the cathode causing an internal short circuit, and therefore, loss of current [7].

$$CH_3OH + (3/2)O_2 \rightarrow CO_2 + 2H_2O \quad (3)$$

In order to maintain high fuel efficiency and achieve better performance of the stack, methanol crossover rate must be minimized. This can be achieved by controlling the methanol fed on the anode side to keep methanol concentration low. Alternatively, it can also be achieved by increasing the cathode pressure or by using more diffusion resistive MEA.

### 2.2. *The balance of plant*

The balance of plant is a subsystem that supports the power generation process. It consists of a mixing chamber, a methanol control sensor, pumps, gas–liquid separator, control electronics and converters. Due to the high crossover rates of methanol through the membrane (Nafion 117), pure methanol cannot be used in the stack. Pure methanol must be diluted to approximately 4% of volume in water prior to reacting at the MEA [4]. The dilution occurs in the mixing chamber. The fuel from the gas–liquid separator and the water-mix from the cathode are fed into the mixing chamber. Also, it takes pure methanol from the fuel tank when necessary. Once they are mixed, this mixture is then fed to the fuel cell stack.

A control system is used to monitor and maintain the methanol concentration level. When the concentration of methanol is too high or too low, it may result in unstable operation or may cause failure due to insufficient stack voltage to support the power conditioning circuit [4]. The sensor and control loop are required to monitor the level of methanol and to generate a signal when additional methanol is needed in the system. The methanol concentration is expected in the range of 0.5–2 mol $L^{-1}$ in the output of the mixing chamber. The sensor triggers the first liquid pump (liquid pump-1 in Fig. 1) when methanol level falls below a preset value. The first liquid pump located between the fuel tank and the mixing chamber then adds more methanol to the mixing chamber. The second liquid pump (liquid pump-2 in Fig. 1) located between the mixing chamber and the fuel cell stack continuously feeds fuel to the fuel cell stack in a recirculation loop.

In the anode side of the stack, carbon dioxide is produced which mixes with liquid methanol and water. The separation of these mixed liquids and gases occur in the gas–liquid separator. The $CO_2$ produced is vented from the system and the liquid is sent back to the mixing chamber.

Air as a source of $O_2$, is introduced in the stack with an appropriate device such as a fan or a compressor. Airflow rate is one of the most critical parameters in the system design and the main operating parameter besides methanol concentration and stack temperature for ensuring the performance of the DMFC [8]. Therefore the air pump is considered as one of the most significant auxiliary parts in the DMFC system.

All pumps and the sensor require power at specific voltages. Buck and boost converters supply the required voltages to various system components. However, during start-up, the buck converter does not supply the required power to the auxiliary components. The power required is provided by a rechargeable battery until the reactants are made available to the stack. During normal operation of the DMFC, the rechargeable battery is kept charged at all times by using a small fraction of the produced power.

## 3. Reliability block diagram for low power DMFC

The RBD is a graphical and mathematical representation of the relationships between system components or subsystems and their impact on the resulting system reliability [5]. It is a simple model that can be used at all stages of development of a product, and provide a pictorial representation of the reliability structure [9]. As mentioned earlier, the low power portable DMFC system consists of three main subsystems: fuel cell stack, fuel tank, and the BOP. In the RBD representation, these major subsystems are assumed to be independently connected to each other in series as shown in Fig. 3. For a serial system, all failures are independent, i.e., the system fails when one of the component fails.

The BOP includes all auxiliary and electronic components as depicted in Fig. 1. These components are necessary to keep the system operational. Therefore, these components are serially connected in the RBD except the start-up battery and buck

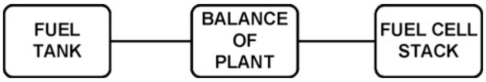

Fig. 3. A serial DMFC system.

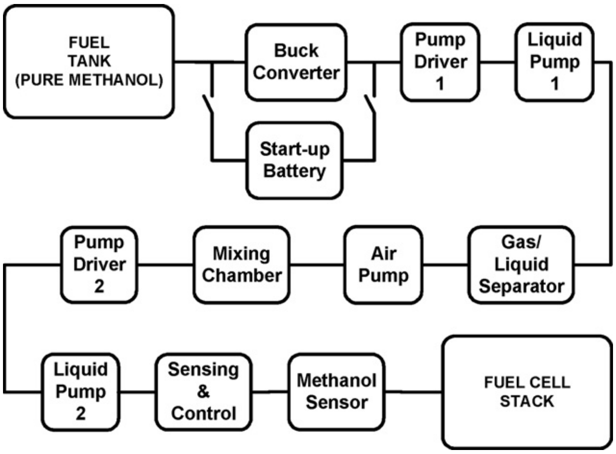

Fig. 4. The RBD of a low power portable DMFC.

converter. The start-up battery can be considered as a passive or standby backup to the buck converter. The corresponding RBD of the DMFC system is illustrated in Fig. 4. When the passive or standby assumption is applied to redundant systems, the supporting units are assumed to remain idle and begin to operate only when the preceding component fails. Therefore, when a buck converter operates, the start-up battery remains on stand by to take over the operation when the first component fails. The RBD representation corresponding to the start-up period is illustrated in Fig. 5.

After starting the system, it is assumed that the battery switch is off and the buck converter supplies the required power to the auxiliary components. The corresponding RBD representation is depicted in Fig. 6.

Assuming that the system reliability during operational condition does not depend on the rechargeable battery, the system RBD represented in Fig. 6 can be used.

### 3.1. Reliability calculation

Since most of the system components spend their lifetime in performing normal functional task, this study is assumed to be valid for this operational period. Since the failure rate remains almost constant during this period, an exponential distribution can be used to model the failure rate. An advantage of the exponential function is that it is independent of the age of a component or a system as long as the constant failure rate condition persists [10]. The probability distribution function (PDF), $f(t)$ and the cumulative distribution function (CDF), $F(t)$ for the exponential distribution are given by

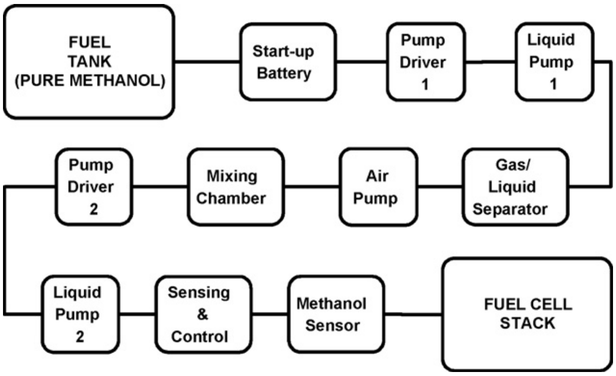

Fig. 5. The RBD of the low power portable DMFC during start-up.

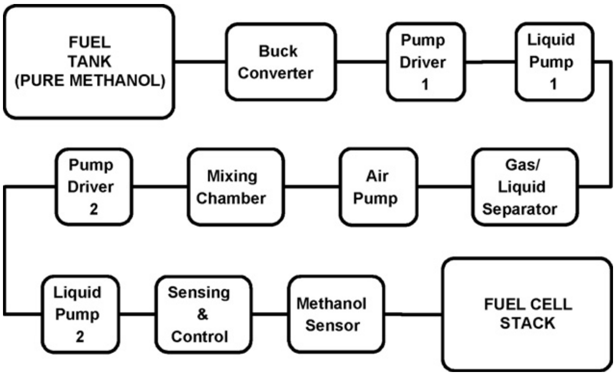

Fig. 6. The RBD of low power portable DMFC when running.

$$f(t) = \lambda\, e^{-\lambda t} \tag{4}$$

and

$$F(t) = 1 - e^{-\lambda t} \tag{5}$$

Thus the reliability, $R(t)$ may be calculated as

$$R(t) = 1 - F(t) = e^{-\lambda t} \tag{6}$$

The failure rate function, $h(t)$ for the exponential distribution is given by

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda\, e^{-\lambda t}}{e^{-\lambda t}} = \lambda \tag{7}$$

This result shows that the failure rate $\lambda$ is a constant in the exponential distribution.

The RBD series model is used to transition from individual components to the entire system, assuming the system fails when the first component fails and all components fail or survive independent of one another. The system reliability function $R_s(t)$ corresponds to the probability that all components simultaneously survives or remains operational with respect to time $t$ is given by

$$R_s(t) = \prod_{i=1}^{n} R_i(t) = R_1(t) \times R_2(t) \times \ldots\ldots \times R_n(t) \tag{8}$$

Therefore, the system reliability of the low power DMFC can be expressed as

$$\begin{aligned} R_s(t) &= R_1(t) \times R_2(t) \times \ldots\ldots. \times R_{11}(t) \times R_{12}(t) \\ &= \exp\left(\sum_{i=1}^{12} \lambda_i t\right) \end{aligned} \tag{9}$$

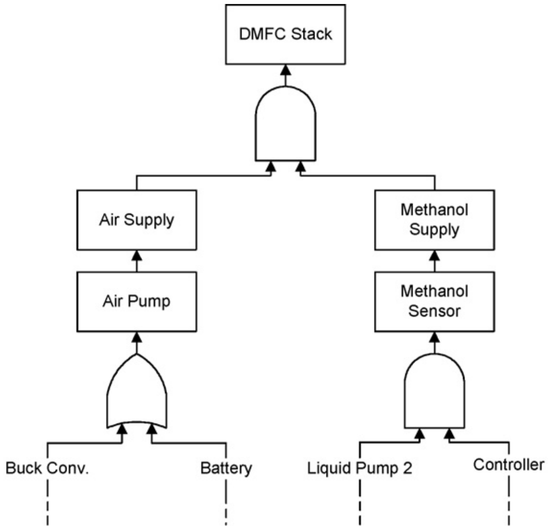

Fig. 7. The bottom-up model of the DMFC system.

## 4. State-space model For DMFC

Failure and repair frequently occur in real life, and the RBD cannot handle the dependencies such as event-dependent failure and shared repair [11]. For this reason, a state-space method using Markov model (MM) is used for DMFC reliability analysis. This method is flexible and gives a realistic and dynamic model reliability. The method can include common cause failures, multiple failures, different repair times and variable failure rates. The state-space method is not limited to two states only, such as ‘up’ and ‘down’. Furthermore, components can have different states such as operational, derated, down, and/or under maintenance.

### 4.1. State-space Markov model development

The fuel cell stack is the heart of a DMFC system, its operation depends on two sources—air supply feed to the cathode and methanol supply feed to the anode. Other components in the system support the air and methanol supplies. For instance, adequate supply of $O_2$ comes from the air supplied by the air pump. The power required by the air pump during the start-up and regular operation is supplied by the battery and buck converter, respectively. Similarly, the continuation of methanol supply with proper concentration based on preset levels depends on the functionality of the methanol sensor. The DMFC stack performance is dependent on the air and methanol supplies as depicted in the reliability model shown in Fig. 7.

If the failure ($\lambda$) and repair ($\mu$) rates are assumed to remain constant, these parameters can be estimated by homogeneous Poisson process (HPP). The state transition diagram for the DMFC system for five possible states is shown in Fig. 8 corresponding to three cases—unit is up (U), unit is derated (D), and unit is down (W).

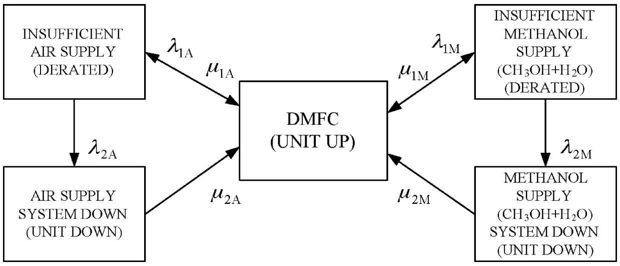

Fig. 8. The state-space diagram of a low power DMFC system.

### 4.2. System mathematical modeling

Based on Fig. 8, the system rate transition matrix $M$ may be expressed as

$$M=\begin{bmatrix} -\lambda_{1M}-\lambda_{1A} & \mu_{1M} & \mu_{2M} & \mu_{1A} & \mu_{2A} \\ \lambda_{1M} & -\lambda_{2M}-\mu_{1M} & 0 & 0 & 0 \\ 0 & \lambda_{2M} & -\mu_{2M} & 0 & 0 \\ \lambda_{1A} & 0 & 0 & -\lambda_{2A}-\mu_{1A} & 0 \\ 0 & 0 & 0 & \lambda_{2A} & -\mu_{2A} \end{bmatrix} \tag{10}$$

Suppose $X_i(t)$ is the probability that the system is in state $i$ at time $t$, $i=1, 2, 3, 4$, and 5. In order to obtain the availability of the system, it is necessary to solve the following differential equation:

$$\dot{X}=MX \tag{11}$$

Applying Laplace transform to solve Eq. (11), we get

$$X(s)=(sI-M)^{-1}X(0) \tag{12}$$

where $X(0)$ are the initial states. Assuming the initial states $X(0)$ correspond to the following values: $P_U(0)=1$, $P_{D1}(0)=0$, $P_{W1}(0)=0$, $P_{D2}(0)=0$, and $P_{W2}(0)=0$, then $X(0)$ may be expressed as

$$X(0)=\begin{bmatrix} P_U(0) \\ P_{D1}(0) \\ P_{W1}(0) \\ P_{D2}(0) \\ P_{W2}(0) \end{bmatrix}=\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Then the system probability can be calculated by using Eq. (12) as

$$X(s)=\left\{ s\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} -\lambda_{1M}-\lambda_{1A} & \mu_{1M} & \mu_{2M} & \mu_{1A} & \mu_{2A} \\ \lambda_{1M} & -\lambda_{2M}-\mu_{1M} & 0 & 0 & 0 \\ 0 & \lambda_{2M} & -\mu_{2M} & 0 & 0 \\ \lambda_{1A} & 0 & 0 & -\lambda_{2A}-\mu_{1A} & 0 \\ 0 & 0 & 0 & \lambda_{2A} & -\mu_{2A} \end{bmatrix} \right\}^{-1} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{13}$$

By solving Eq. (13) the state probabilities can be obtained. The time-dependent availability of the system can be calculated by adding the three probabilities, the probability when the system is up, the derated probability related to air supply, and the derated probability related to methanol supply, i.e.,

$$A = P_{\mathrm{U}}(t) + P_{\mathrm{D1}}(t) + P_{\mathrm{D2}}(t) \tag{14}$$

The long term or the steady state availability is obtained when $t$ approaches infinity, i.e., when the negative exponential approaches zero.

## 5. Simulation results

### 5.1. Reliability evaluation based on RBD

Low power portable DMFC system is still an immature technology and there is no publicly available failure rate data for DMFC components. An estimate of the failure rate of each component of the DMFC system with lifetime analysis simulation using the exponential distribution was studied. The estimated failure rates, shown in Table 1 are used to calculate the reliability of the components of low power portable DMFC systems.

Low power portable DMFC stack lifetime is assumed to be 5000 h. This assumption is used to calculate the reliability of each component using Eq. (6). Fig. 9 illustrates the reliability of each component of the DMFC system. In Fig. 9, $R_1(t)$, $R_2(t)$, $R_3(t)$, $R_4(t)$, $R_5(t)$, $R_6(t)$, $R_7(t)$, $R_8(t)$, $R_9(t)$, $R_{10}(t)$, $R_{11}(t)$, $R_{12}(t)$ correspond to the reliability factor relating to fuel tank, buck converter, pump driver-1, liquid pump-1, gas/liquid separator, air pump, mixing chamber, pump driver-2, liquid pump-2, sensing control, methanol sensor, and fuel cell stack, respectively. The reliability of the low power portable DMFC system during stack lifetime is then calculated with Eq. (9) and the corresponding result is depicted in Fig. 10. From Fig. 10, it is evident that the system reliability during stack lifetime is 90.51%.

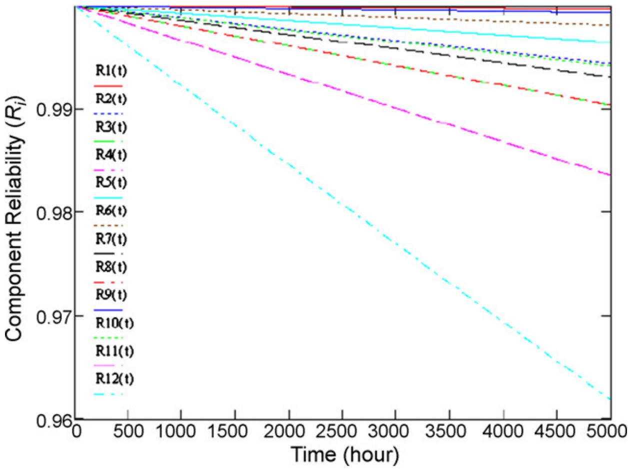

Fig. 9. The reliability of each component of a DMFC system.

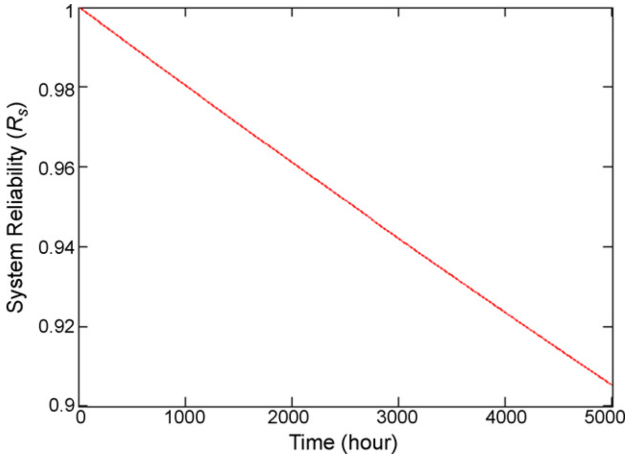

Fig. 10. The reliability of a low power portable DMFC system.

### 5.2. Availability assessment with state-space MM

To the best of the authors' knowledge, no failure and repair rate data for repairable DMFC system or components are available in the literature. Thus, the failure and repair times for repairable DMFC systems were estimated by using the HPP. The model parameters were estimated using the maximum likelihood estimation (MLE) [12]. The failure and repair rates were estimated using the state-space diagram of the DMFC system depicted in Fig. 8, where $\lambda_{\mathrm{M}} = 1.7476 \times 10^{-5}$, $\lambda_{\mathrm{2M}} = 1.8471 \times 10^{-5}$, $\lambda_{\mathrm{A}} = 1.1112 \times 10^{-6}$, $\lambda_{\mathrm{2A}} = 1.4742 \times 10^{-6}$ (failure h$^{-1}$) and $\mu_{\mathrm{1M}} = 8.132 \times 10^{-4}$,

Table 1
Components failure rate of a low power portable DMFC system

| Component | Failure rate |
|---|---|
| Fuel tank | 5.42E−08 |
| Buck converter | 1.11E−06 |
| Pump driver-1 | 1.93E−06 |
| Liquid pump-1 | 1.22E−07 |
| Gas/liquid separator | 6.96E−07 |
| Air pump | 3.63E−07 |
| Mixing chamber | 1.38E−06 |
| Pump driver-2 | 1.93E−06 |
| Liquid pump-2 | 1.22E−07 |
| Sensing control | 1.16E−06 |
| Methanol sensor | 3.31E−06 |
| Fuel cell stack | 7.78E−06 |

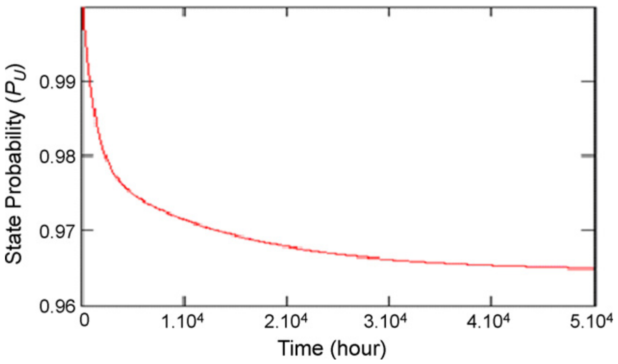

Fig. 11. State probabilities of DMFC system up $P_{\mathrm{U}}$.

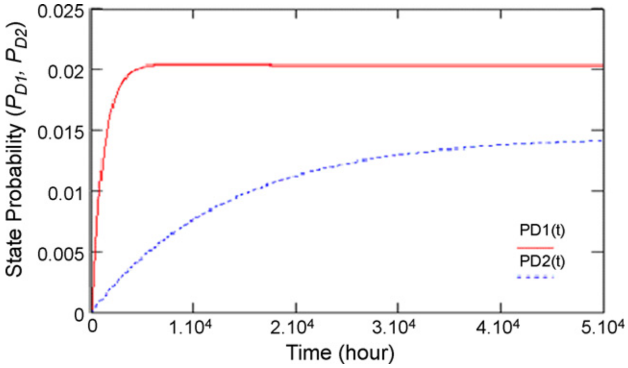

Fig. 12. State probabilities of DMFC system derated $P_{D1}$ and $P_{D2}$.

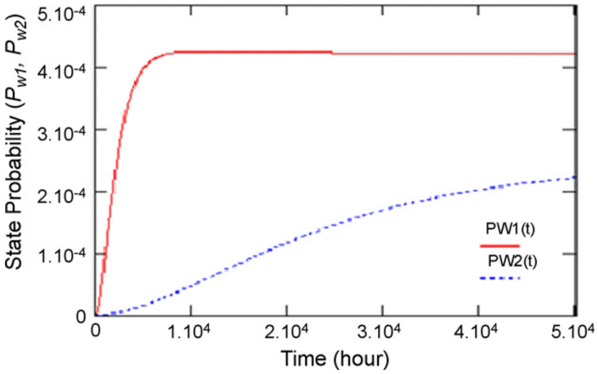

Fig. 13. State probabilities of DMFC system down $P_{W1}$ and $P_{W2}$.

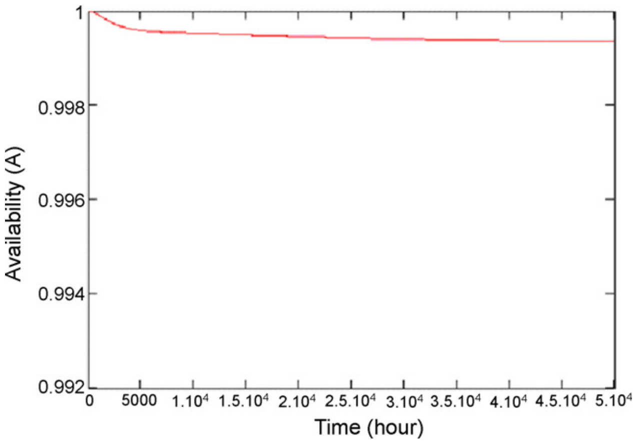

Fig. 14. Availability of low power portable DMFC system.

$\mu_{2M} = 8.878 \times 10^{-4}$, $\mu_{1A} = 7.246 \times 10^{-5}$, and $\mu_{2A} = 8.787 \times 10^{-5}$ (repair $h^{-1}$).

The failure and repair rate estimates were used in the system transition rate matrix to obtain the availability of the system. The results obtained after solving Eq. (13) are illustrated in Figs. 11–13. In the long term, i.e., when $t$ approaches infinity, the steady state availability of DMFC for system up ($P_U$) condition is 0.965 (Fig. 11). The steady state availabilities for the derated system ($P_D$) and system down ($P_W$) conditions are shown in Figs. 12 and 13, respectively. Fig. 14 shows the system availability as a function of time $t$. As depicted in Fig. 14, the steady-state system availability is calculated as $A = 0.99936$.

## 6. Conclusions

In this paper, reliability and availability evaluation of low power portable DMFC system for irreparable and repairable scenarios are presented. The RBD system model is developed to evaluate irreparable system reliability. Based on the component failure rates estimated from the exponential distribution function, the components and system reliabilities are calculated. The availability evaluation of repairable low power portable DMFC system is performed based on the state-space method using MM. The component failure and repair rates are considered to remain constant during the operational period of the system. System model evaluation for 5000 h of operational period indicates that the system reliability and availability are 90.51% and 99.94%, respectively.

## References

[1] M. Tanrioven, M.S. Alam, Renew. Energy 31 (7) (2006) 915–933.
[2] S. Rahman, IEEE Power Engineering Society Summer Meeting, 2001, pp. 551–552.
[3] J. Bostaph, C.G. Xie, J. Pavio, A.M. Fisher, B. Mylan, J. Hallmark, DMFC Proceedings of the 40th Power Sources Conference, 2002, pp. 211–214.
[4] J. Bostaph, C.G. Xie, J. Pavio, J. Power Sources 136 (1) (2004) 55–65.
[5] W. Vielstich, A. Lamm, H.A. Gasteiger, Handbook of Fuel Cells, vols. 3 and 4: Fundamentals Technology and Applications, Part 2: Fuel Cell Technology and Applications, Willey, England, 2003.
[6] T. Schultz, Experimental and Model-based Analysis of the Steady-state and Dynamic Operating Behavior of the DMFC, Ph.D. Thesis, Max Planck Institute, Germany, May 2004.
[7] A. Hacquard, Improving Understanding DMFC Performance, M.S. Thesis, Chemical Engineering Department, Worcester Polytechnic Institute, May 2005.
[8] A. Oedegaard, C. Hentschel, J. Power Sources 158 (1) (2006) 177–187.
[9] R.D. Leitch, Reliability Analysis for Engineers, Oxford Science Publications, New York, 1995.
[10] I. Bazovsky, Reliability Theory and Practice, Prentice Hall, New Jersey, 1961.
[11] R. Billinton, R.N. Allan, Reliability Evaluation of Engineering System, Plenum Press, London, 1983 (concepts and techniques).
[12] P.A. Tobias, D.C. Trindade, Applied Reliability, Chapman & Hall/CRC, New York, 1995.