Microelectronics Reliability 88–90 (2018) 1177–1182

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Reliability assessment of power conditioner considering maintenance in a PEM fuel cell system

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ARTICLE INFO

Keywords:
Reliability assessment
Fault-tree analysis
Weibull distribution
Maintenance

ABSTRACT

Proton exchange membrane fuel cell recently emerges in the telecom backup power, where its reliability and availability issues are with high priority. In this paper, as one of the fragile sub-systems, the reliable performance of the power conditioner, including the power stage, the controller, the gate driver, the auxiliary the power supply and the printed circuit board, is the key focus. According to the configuration and main functions of the aforementioned key components, the fault tree structure of power conditioner can be established. With the help of the Weibull distribution, the random failure mode and wear-out failure mode impacts on the reliability can be estimated. Moreover, the reliability and availability curves can be studied by considering the maintenance scheme. In this case study, it can be seen that the wear-out issue is more worthy to be taken care compared to the random failure. Moreover, the regular maintenance with the key components significantly increases the reliability and availability performance of the power conditioner.

1. Introduction

Recently, renewable energy generation is rapidly growing in the power sector. One of them is the fuel cells, which are becoming more promising for various kinds of applications [1]. The first fuel cell was prototyped by a British scientist in 1839 [2]; in the 1990s, proof-of-concept fuel cells followed, and sub-scale and full-scale prototype systems were developed to demonstrate the technology [3]. Proton Exchange Membrane Fuel Cells (PEMFCs) are one of the promising types, as they can be used in multiple applications. The PEMFCs transform the chemical energy into electrical power via the electrochemical reaction [4]. From the sustainable development perspective, the PEMFCs are more suitable and competitive in comparison with other renewable energy systems, as the fuel cell contributes on high energy conversion efficiency, a more compact design and environmentally friendly [5]. In addition, as budgets in any project are limited in both the design and operational stages, it is reasonable to invest in critical components in order to increase the reliability of the system. Since fuel cell systems are used for reliability or safety critical occasions such as backup power for the emergency, their reliable operation is vital. For the aforementioned reason, it is required to pay more attention to their reliability and availability.

Reliability assessment is frequently a crucial and mandatory step in designing and analyzing systems [6]. An important characteristic of engineering systems is that they behave dynamically, i.e., their response to an initial perturbation evolves as system components interact with one another as well as with the environment [7]. In addition, different maintenance strategies could have different impacts on reliability and availability; while maximal reliability and availability or minimal costs in a system could be achieved when these strategies are optimized [8].

In this paper, the Fault Tree Analysis (FTA), as a conventional method for reliability assessment [9, 10] is designed to illustrate the relations between basic event logical variables and significant components. One of the principal aspects that could affect system reliability is aging. Considering aging effects in the calculations by choosing an appropriate reliability distribution is an important issue. At last, by applying Monte Carlo simulation and considering maintenance and inspection policy, the availability is calculated for five years of the system operation.

2. System configuration and reliability assessment method

2.1. Critical components of power conditioner

The power conditioner is one of the main sub-systems in the PEMFC system, which consists of five components: the power stage, the auxiliary power supply, the gate driver, the controller and the Printed

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https://doi.org/10.1016/j.microrel.2018.07.085
Received 9 June 2018; Received in revised form 28 June 2018; Accepted 8 July 2018
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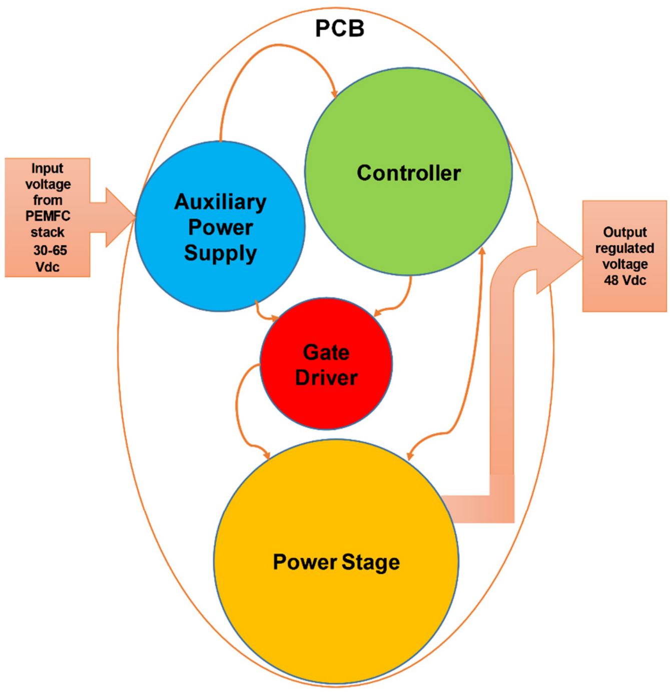

Fig. 1. The configuration of the power conditioner.

Circuit Board (PCB) [11]. Fig. 1 illustrates the configuration of the power conditioner.

All components of the power conditioner and their key sub-components are shown in Fig. 2. Concisely, the main functions of components in the power conditioner are listed as follows [12]:

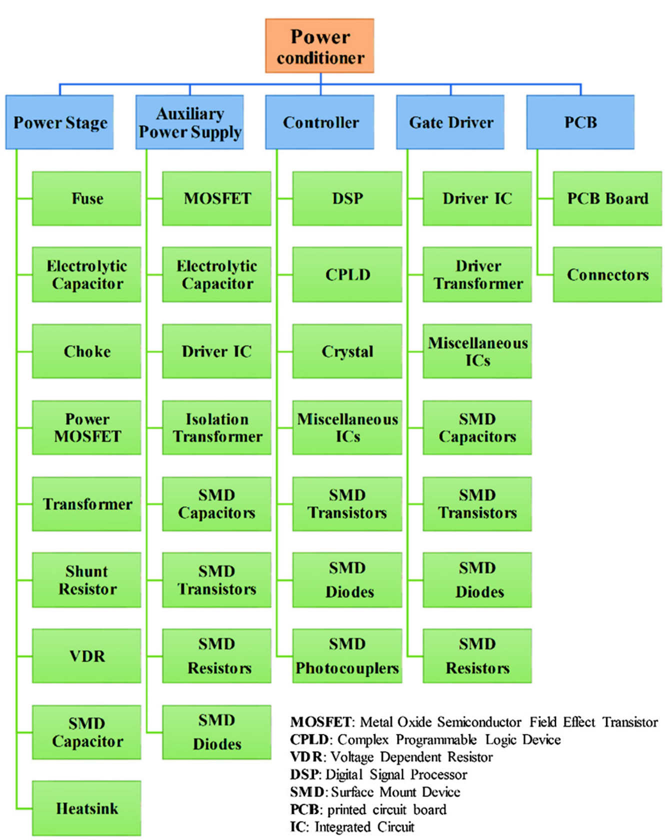

Fig. 2. All components and sub-components of the power conditioner.

1. The power stage mainly consists of the isolated DC/DC converter, which performs the basic power conversion from wide range of the input voltage (+30–65 V_{dc}) to fixed output voltage (+48 V_{dc}).
2. The controller makes it possible to operate the converter in either boost mode or buck mode, depending on the fuel cell output voltage. In addition, the output of the controller is the drive signal of the power devices, which is further sent to the gate driver.
3. The gate driver aims to amplify the drive signals from the microprocessor in order to actively control the power switches on and off.
4. The function of the auxiliary power supply is to power on all of the Integrated Circuits (ICs) used in the controller and gate driver.
5. As shown in Fig. 1, all of the key sub-components are accommodated in the PCB. In addition, the connectors are used to link the input power and output load.

2.2. Fault tree analysis

The fault tree approach is a deductive process by means of which an undesirable event (top event) is postulated, and the possible ways for this event to occur are systematically deduced [6]. The deduction process is performed so that the fault tree embodies all component failures (i.e., failure modes) that contribute to the occurrence of the top event. The fault tree itself is a graphical representation of the various combinations of failures that lead to the occurrence of the top event [13].

The postulated fault events that appear on the fault tree may not be exhaustive. Only those events considered important can be included. However, it should be noted that the decision for inclusion in failure events is not arbitrary. Besides, it is affected by the fault tree construction procedure, system design and operation, operating history, available failure data, and experience of the analyst. At each intermediate point, the postulated events represent the immediate, necessary, and sufficient causes for the occurrence of the intermediate (or top) events [6]. Based on the key sub-components as shown in Fig. 2 and the operation principle of the power conditioner, the fault tree structure of this case study can be developed and established. As shown in Fig. 3, the relationship between the sub-system of the power conditioner and the five components, as well as the corresponding component and its sub-components are described in detail.

3. Random and wear-out failure modes

3.1. Basic concepts

The bathtub curve describes a general form of the failure rate through the life cycle of the product, which basically includes three regions as shown in Fig. 4 [14, 15]:

1. Decreasing failure rate, known as early failures.
2. Constant failure rate, known as random failures.
3. Increasing failure rate, known as wear-out failures.

In region one, the initial failure rate is high but decreases rapidly as defective components are identified and discarded. In region two, the failure rate is generally low and constant, which can be expressed by the exponential distribution. The exponential distribution is the probability distribution referring to a process, in which events occur continuously and independently at a constant mean rate. In region three, the failure rate increases due to [the] aging and wear out effects, which can be analyzed in reliability engineering by using the Weibull distribution.

The Weibull distribution is a probability distribution, which can generally be determined by the shape parameter β and the scale parameter η. The shape parameter is also known as the Weibull slope [6]. If β is equal or less than one, it approximately becomes exponential distribution, and η expresses the mean value [6]. If β is more than one, the

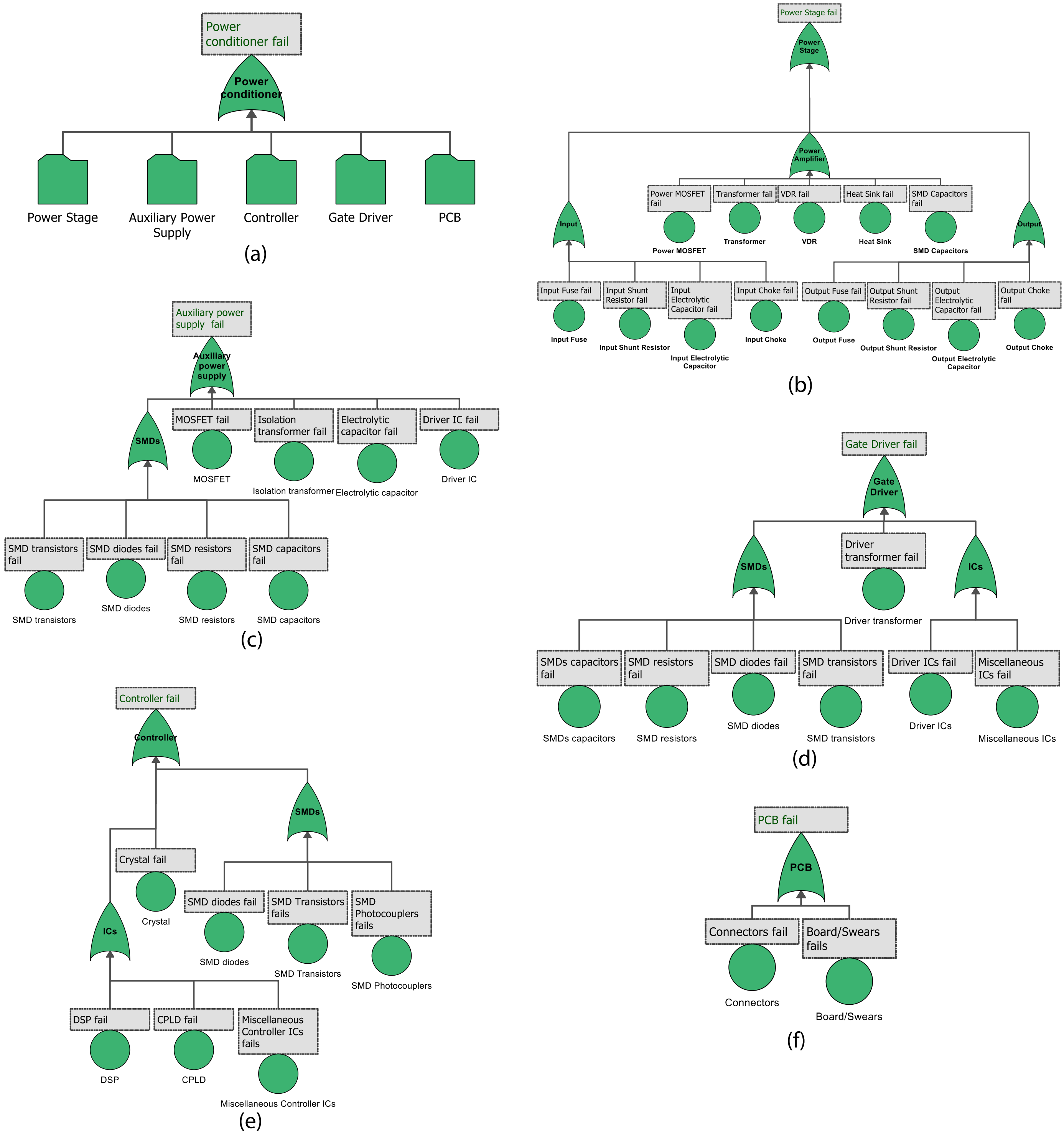

Fig. 3. Fault tree simulations of the power conditioner. (a) Sub-system of the power conditioner. (b) Components of the power stage. (c) Components of the auxiliary power supply. (d) Components of the gate driver. (e) Components of the controller. (f) Components of the printed circuit board.

probability density function generally has a maximum value. This shape factor is used to represent the aging effect on components by increasing failure rates. Table 1 summarizes the relationship between the shape parameter and the corresponding failure rate [16]. It is worth mentioning that the exponential distribution is a particular case of the Weibull distribution.

Due to the lack of a reliability model at the stage of the early failures, only the constant failure and wear-out failure stages are considered in the following. With respect to the random failure stage, the failure rate can be obtained from MIL-HDBK-217F. In addition, if $\beta = 1$, the relationship between the scale parameter and failure rate λ can be found,

$$\lambda = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \Rightarrow \eta = \frac{1}{\lambda} \tag{1}$$

with respect to the wear-out failure stage, assuming that the shape parameter equals two, the scale factor can be calculated by using the goodness of fit testing method. With the information of the scale factor

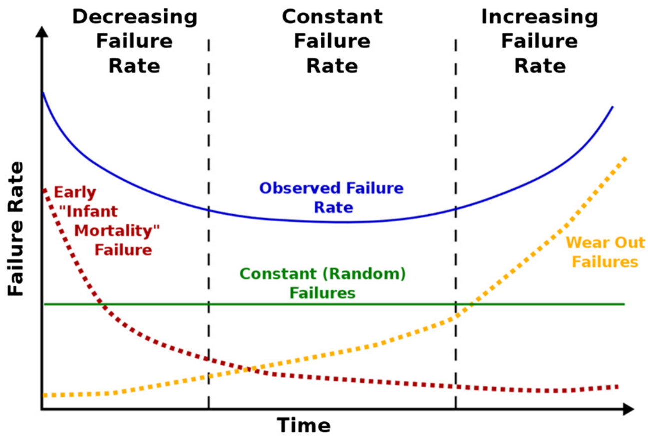

Fig. 4. Bathtub curve failure rate at three important regions.

Table 1
Shape parameter in Weibull distribution.

β = 1	Exponential distribution
β < 1	Decreasing Failure Rate (DFR)
β > 1	Increasing Failure Rate (IFR)
β = 3.5	Normal Distribution

and the shape factor. Reliability curve can be deduced as follow:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

Considering both the random failure ad wear-out failure, Table 2 lists 5 main components and 33 sub-components with the failure rate and Weibull parameters in the entire power conditioner.

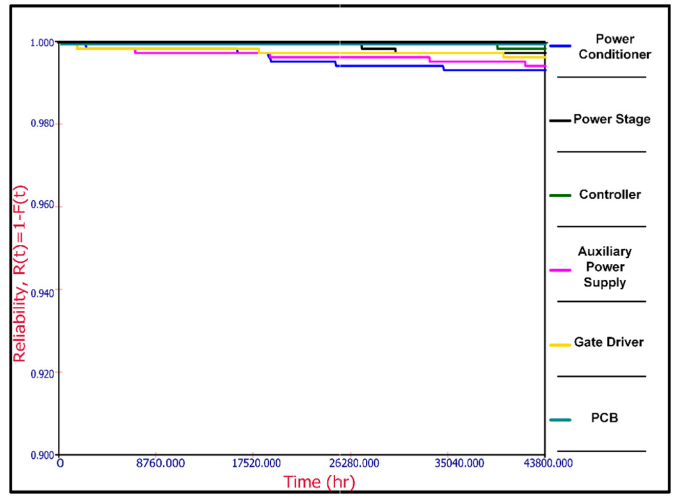

Fig. 5. Reliability comparison of five main components in the case of the random failure.

3.2. Reliability comparison between random and wear-out failure

After performing the FTA and assigning parameters of Weibull distribution to the power conditioner, the reliability curve of 5 main components can be calculated within 43,800 h (5 years), where 1000 times of Monte Carlo simulation is used. As shown in Figs. 5 and 6, it is noted that the random failure mode and the wear-out failure mode are represented by the exponential distribution (β = 1) and Weibull

Table 2
Weibull parameters for all the sub-components in the cases of random failure and wear-out failure.

Sub-system of PEMFC	Components	Sub-components	Failure rate (λ)	Weibull parameters	
				Scaling parameter (η) with β = 1	Scaling parameter (η) with β = 2
Power conditioner	Power stage	Fuse	0.02E-6	5E7	5.64E7
		Electrolytic capacitor	0.12E-6	8.33E6	9.4E6
		Transformer	0.15E-8	6.66E8	7.52E8
		Choke	0.16E-9	6.25E9	7.05E9
		Power MOSFET	0.52E-6	1.92E6	2.17E6
		Shunt resistor	0.43E-9	2.32E9	2.62E9
		VDR	0.43E-9	2.32E9	2.62E9
		SMD capacitor	0.69E-9	1.45E9	1.63E9
		Heatsink	0.06E-6	1.66E7	1.88E7
	Auxiliary power supply	MOSFET	0.52E-6	1.92E6	2.17E6
		Electrolytic capacitor	0.12E-6	8.33E6	9.4E6
		Driver IC	0.38E-8	2.63E8	2.97E8
		Isolation transformer	0.15E-6	6.66E6	7.52E6
		SMD capacitor	0.69E-9	1.45E9	1.63E9
		SMD transistors	0.44E-5	2.27E5	2.56E5
		SMD diodes	0.02E-6	5E7	5.64E7
		SMD resistors	0.39E-9	2.56E9	2.89E9
	Controller	DSP	0.12E-6	8.33E6	9.41E6
		CPLD	0.32E-8	3.12E8	3.53E8
		Crystal	0.11E-6	9.09E6	1.03E7
		Miscellaneous ICs	0.38E-8	2.63E8	2.97E8
		SMD transistors	0.44E-5	2.27E5	2.57E5
		SMD diodes	0.02E-6	5E7	5.64E7
		SMD photo-couplers	0.16E-6	6.25E6	7.05E6
	Gate driver	Driver IC	0.38E-8	2.63E8	2.97E8
		Driver transformer	0.15E-6	6.66E6	7.05E6
		Miscellaneous ICs	0.38E-8	2.63E8	2.97E8
		SMD capacitors	0.69E-9	1.45E9	1.63E9
		SMD transistors	0.44E-5	2.27E5	2.56E5
		SMD diodes	0.02E-6	5E7	5.64E7
		SMD resistors	0.39E-9	2.56E9	2.89E9
	PCB	PCB board	0.18E-5	5.55E5	6.27E5
		Connectors	0.38E-6	2.63E6	2.97E6

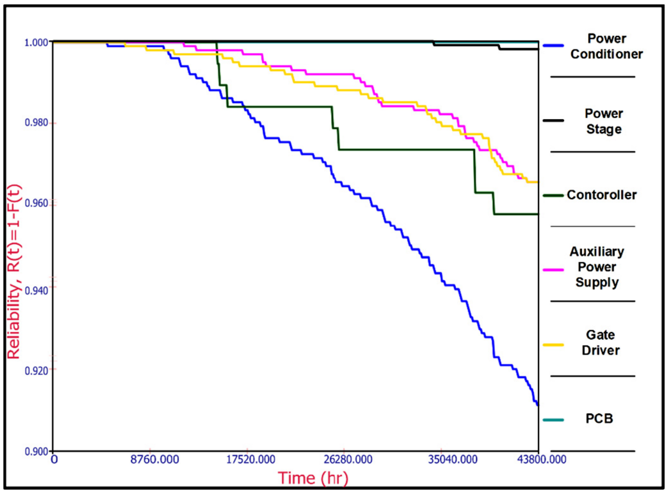

Fig. 6. Reliability comparison of five main components in the case of the wear-out failure.

renewal

distribution (β = 2), respectively.

In fact, these figures are the comparison between the random and wear-out behavior of the power conditioner sub-system. The top three reliability-critical components are the gate driver, the auxiliary power supply, and the controller, respectively. Moreover, it is evident that the wear-out failure mode is more significant than the random failure. The designed 5-year operation causes the damage < 1% for the random failure, while it leads to the damage much > 10% in the case of wear-out failure. In other words, proper maintenance needs to be applied in order to guarantee the lifetime demand.

4. Reliability, maintainability, and availability

4.1. Concept of maintenance

Maintenance is the ability to maintain or restore a system in functioning state, which contains inspections and repairs. In this paper, it involves the repair and inspection conditions in 9 critical sub-components among 33 basic sub-components of all system. These components, including transistors, capacitors, transformers, diodes, DSP, CPLD, crystal, and PCB, are identified through the sensitivity analysis. Maintenance can affect the maintainability directly by shortening the time spent on the repair (Mean Time To Repair MTTR). With the decreasing MTTR and increasing the average time interval between repairs (Mean Time Between Failure MTBF) at the optimum point, the availability can be increased using its definition:

$$Availability = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{3}$$

Since the repair or inspection time can be changed according to different conditions, a normal distribution with standard deviation 10% is modeled with the mean of 720 h and standard deviation of 72 h. Fig. 7 demonstrates the comparison of the reliability curve in the power conditioner without repair and with inspection and repair every 720 h in five years. By assuming a Weibull distribution and the wear-out of the system, it is noted 1% increase in reliability within the 5-year operation.

4.2. Availability curve

Reliability curve calculated the probability that the system is in an available state, without ever having entered an unavailable state, at a certain point in time. Availability curve is the probability that a system (or component) is operational at any random time. This is very similar to the reliability function, which gives a probability that a system can function at the given time. Unlike the reliability, the instantaneous availability measure incorporates maintainability information. At any given time, the system is operational with the following conditions:

1. It functions properly during time with probability *R(t)*, or,
2. It functions properly since the last repair at time *u*, 0 < u < t, with probability:

$$\int_0^t R(t-u)m(u)du \tag{4}$$

With *m(u)* being the renewal density function of the system. The point of availability is the summation of these two probabilities, or:

$$A(t) = R(t) + \int_0^t R(t-u)m(u)du \tag{5}$$

Fig. 8 shows availability curve of power conditioner, which considering effects of maintenance on the availability of the system for a 5-

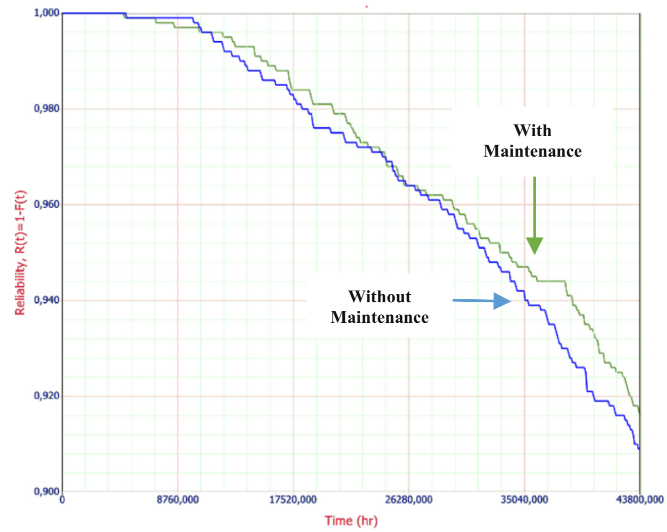

Fig. 7. Reliability of power conditioner without repair and inspection (blue) and with repair and inspection (green) considering Weibull distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

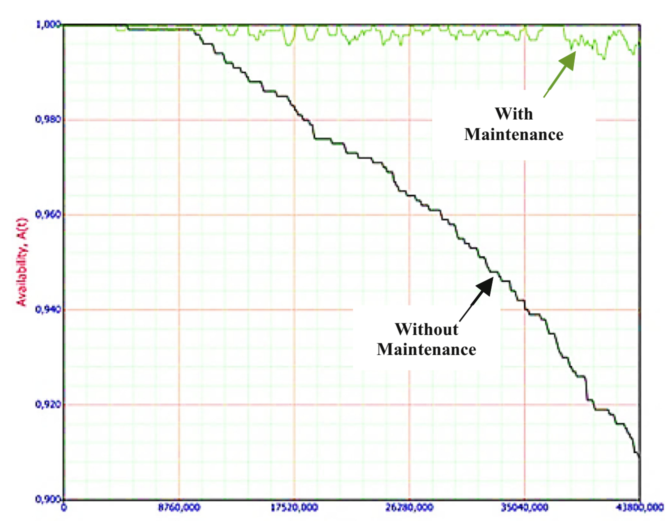

Fig. 8. Availability of power conditioner without maintenance (black) and with maintenance (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

year period. It can be seen that the availability of the system significantly increases by using maintenance scheme.

5. Conclusion

In this paper, the reliability and availability issues of power conditioner system in the PEM fuel cell is studied according to the relationship among all key components. With the help of fault tree analysis, the reliability of the power conditioner is calculated within 5 years. Random failure and wear-out failure are compared in order to have a better understanding of the real behavior of the system, where the wear-out issue is more significant compared to the random failure. Considering maintenance intervals, the availability of the system increases in accordance with planned maintenance. Taking into account the inspection intervals, another solution for decision makers to optimize maintenance interval is to look at the inspection or monitoring systems. The repair actions for critical components could make a huge difference in the availability of the system. On the other hand, the optimum maintenance intervals could be further investigated.

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