Estimation of Remaining Useful Life of Electronic Components in the OPERA DCS Platform depending on Time-varying Temperature and Electrical Stress

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1. Introduction

Traditionally, the failure rates (λ) of the electronic components in NPP I&C systems have been calculated based on the MIL-HDBK-217F standard ('Reliability Prediction of Electronic Equipment') Notice 2 [1]. After that, the failure rates of control modules (CMs) such as OPERA DCS including the various kinds of the electronic components are predicted by a summation of the failure rates of the electronic components under the conservative assumption that the electronic components in CMs are connected in series as shown in Equation (1).

$$\lambda_{CM} = \sum_{n=i} \lambda_i \quad (1)$$
$$(i = i_{th}\ electronic\ components\ constituting\ the\ CM)$$

In addition, mean time to failure (MTTF) of the electronic components or CMs are estimated by the inverse of failure rate which is the expectation of an exponential distribution of the failure rates (λ) as shown in Equation (2) [2].

$$MTTF = \frac{1}{\lambda} \quad (2)$$

In order to obtain the failure rates of the electronic components based on the MIL-217F, various input parameters according to the types of electronic components should be identified. In case of a microprocessor or transistor, its manufacturing technology, number of bits, package type, number of pins, thermal resistance, ambient temperature, power dissipation, operating voltage and others should be defined in advance [3].

Among these parameters, ambient temperature and operating voltage can be dynamically varied according to conditions of electrical equipment room. However, reliability analysts predict the failure rates and/or MTTF of electronic components by assuming that the ambient temperature and electrical stress are static constants until the predetermined replacement period of the system which is the current limitation of failure rate/MTTF predictions.

In order to overcome this limitation, Jang [4] proposed the remaining useful life (RUL) prediction method of the electronic component under NPP dynamic stress conditions and applied this method to the electronic components in the POSAFE-Q PLC which is the platform of the safety I&C systems.

In this paper, the RUL prediction method of the electronic component depending on time-varying temperature and electrical stress is introduced and this RUL prediction method is applied to the electronic components in the OPERA DCS which is the platform of the non-safety I&C systems

2. Electronic Component Failure Rate Database of the OPERA DCS Platform

The objective of collecting of an electronic component failure rate database reflecting various stress conditions (temperature and electrical stress conditions) in Section 2 is to use the database to predict the RUL of electronic components of OPERA DCS under dynamic stress conditions of NPPs in Section 3.

In order to obtain the electronic component failure rate database, various parameters, which are the input parameters to the failure rate prediction model in MIL-217F, should be defined first as briefly stated in Section 1 based on the corresponding datasheet of the electronic component. Considering various types of electronic components in MIL-217F, these parameters generally contain the manufacturing technology, number of bits, memory size, package type, connection type, number of years in production, number of pins, case-to-ambient thermal resistance, junction-to-case thermal resistance, power dissipation, rated voltage, operating voltage, quality, ambient temperature, environment, and so on. After that, depending on the detailed type of electronic component, the *application parameters* that can dynamically change during NPP operation are determined to assign them as stress factors affecting the electronic component failure rates. In this study, *temperature and electrical load* are determined as stress factors. Finally, based on the combinations of predetermined stress factors *(temperature–electrical stress*), the electronic component failure rate database is collected by predicting the electronic component failure rates and changing the levels of stress conditions based on the MIL-217F [3-4].

Table 1 and 2 show that the part of electronic component failure rate database of digital input module (DIM) of OPERA DCS (here, 'fpmh' as a unit stands for failure per million hours). Note that only 1 out of the 40 stress conditions in Table 1 and 2 is typically considered in traditional and current reliability predictions of electronic equipment.

Table 1: Failure rates of DIM24A-52 (integrated circuit) to stress conditions (unit: fpmh)

		Electrical Stress (Ratio)				
		0.1	**0.3**	**0.5**	**0.7**	**0.9**
Temp Stress (°C)	**30**	1.04	1.04	1.04	1.04	1.04
	40	1.609	1.609	1.609	1.609	1.609
	50	2.44	2.44	2.44	2.44	2.44
	60	3.63	3.63	3.63	3.63	3.63
	70	5.307	5.307	5.307	5.307	5.307
	80	7.631	7.631	7.631	7.631	7.631
	90	10.8	10.8	10.8	10.8	10.8
	100	15.08	15.08	15.08	15.08	15.08

Table 2: Failure rates of DIM24A-16 (transistor) according to stress conditions (unit: fpmh)

		Electrical Stress (Ratio of operating to rated voltage)				
		0.1	**0.3**	**0.5**	**0.7**	**0.9**
Temp Stress (°C)	**30**	0.04464	0.08298	0.1543	0.2868	0.5331
	40	0.05488	0.102	0.1896	0.3525	0.6553
	50	0.06664	0.1239	0.2303	0.4281	0.7958
	60	0.08002	0.1487	0.2765	0.514	0.9555
	70	0.09509	0.1768	0.3286	0.6108	1.136
	80	0.1119	0.2081	0.3868	0.7191	1.337
	90	0.1306	0.2428	0.4514	0.8392	1.56
	100	0.1512	0.2811	0.5226	0.9715	1.806

As shown in Table 1 and 2, the failure rate of DIM24A-52 is much larger than that of DIM24A-16 in any stress condition. This is because of the difference of the characteristic of the electronic component itself. Table 1 shows that the failure rates of DIM24A-52, which is an Integrated Circuit (IC), according to stress conditions. Since the failure rate of this electronic component is not affected by electrical stress, it can be confirmed that the failure rates of DIM24A-52 do not change when electrical stress increases. Table 2 shows that the failure rates of DIM24A-16, which is a transistor, according to stress conditions. Since the failure rate of this transistor is affected by both temperature and electrical stress, the failure rates vary depending on the temperature–electrical stress, unlike DIM24A-52.

Based on these results in Table 1 and 2, the RUL of the electronic components under dynamic stress conditions is predicted in Section 3.

3. Prediction of RUL of Electronic Components in the OPERA DCS depending on Time-varying Temperature and Electrical Stress

3.1 RUL prediction method

Basically, a RUL prediction method for electronic components under NPP dynamic stress conditions (time-varying temperature and electrical stress) is proposed by deriving the equations from Fig. 1 and utilizing the electronic component failure rate database collected in Section 2 as input data. However, since this database is a collection of electronic component failure rates under various fixed stress conditions, it should be considered that the RUL prediction method allows for RUL prediction when the stress condition dynamically changes in real time, as shown in the upper side of Fig.1

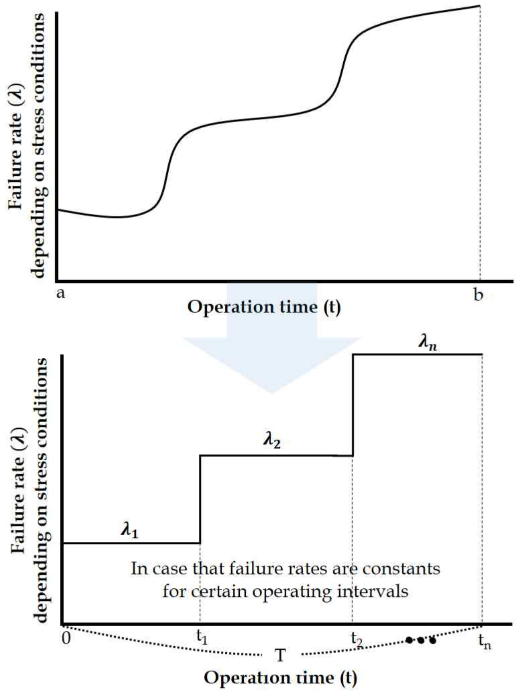

Fig. 1. Failure rates as stress conditions change over time.

In this light, the concept of an average failure rate, which means the average of a component failure rate accumulated over a certain interval is adopted by expressing the upper side of Fig.1 as Equation (3).

$$\lambda_{average} = \frac{1}{b-a}\int_a^b \lambda(t)dt \tag{3}$$

This equation can be interpreted as the average of the component failure rates that change according to the stress conditions between interval *a* and *b*.

If the failure rate that continuously changes by stress condition with operation time (upper side of Fig. 1) can be subdivided and expressed as a constant failure rate for a certain operation interval (lower side of Fig. 1) under a specific stress condition, Equation (3) can be expressed as Equation (4) as follows.

$$\lambda_{average} = \frac{1}{T}\sum_{n=i} \lambda_i t_i \tag{4}$$

$where,\ T = Total\ operation\ time\ (hr)$
$t_i = Operation\ time\ with\ \lambda_i\ (hr)$
$\lambda_i = i_{th}\ \lambda\ under\ specific\ stress\ condition$

Then, Equation (4) allows that the electronic component failure rate database in Section 2 can be used as input data to predict the RUL of the electronic components in the OPERA DCS.

Finally, the MTTF, which has an expectation of an exponential distribution with $\lambda_{average}$, can be calculated in Equation (5), and then the RUL of electronic components under dynamic stress conditions can be calculated by subtracting the total operation time from the MTTF of the electronic components.

$$MTTF = \frac{1}{\lambda_{average}}, \; RUL = MTTF - T \qquad (5)$$

3.2 Case study

The stress conditions for the two electronic components (IC designated as DIM24A-52, and transistor designated as DIM24A-16) in Table 1 and 2 are divided into a base case and a dynamic case. In the base case, these two electronic components are exposed to a temperature stress of 30 °C and electrical stress of 0.1 for 10 years. On the other hand, in the dynamic case, it is assumed that the electronic components are under the following dynamic stress conditions for 10 years:

- Temperature stress of 30°C and electrical stress of 0.1 for 1 year
- Temperature stress of 60°C and electrical stress of 0.5 for 4 years
- Temperature stress of 90°C and electrical stress of 0.7 for 3 years
- Temperature stress of 100°C and electrical stress of 0.9 for 2 years

Some of the stress conditions in the dynamic case are practically unlikely to occur, but these stress conditions are also assumed to clearly investigate the difference in results when the RUL of electronic components is predicted by Equation (4) and (5) with the electronic component failure rate database in Table 1 and 2.

Table 3 shows that the RUL differences between the base case and dynamic case for the two electronic components are 95 years, and 2,375 years, respectively. For DIM24A-52, in the base case, the RUL of this electronic component is about 99 years (873,938 hours), but under dynamic stress conditions, the RUL is estimated to be about 4 years (38,091 hours) after 10 years of total operation time which shows a significant difference. For DIM24A-16, since the failure rate of the transistor is much lower than that of the IC (Micro, Linear), it can be seen that the MTTF is relatively large in both the base case and the dynamic case (22,401,433 hours, and 1,591,130 hours, respectively). In addition, since the failure rate of the transistor is affected by both temperature stress and electrical stress, the difference in the RUL of the transistor between the base case and the dynamic case is confirmed to be very large as 2,375 years.

Since the MTTFs of electronic components predicted in Table 3 are quite large, it might be thought that the impact of NPP operations on the RUL of the electronic components is not significant. However, if this method is applied to a system such as a CM in which hundreds of electronic components are connected, a more practical level of RUL difference can be derived.

Table 3: Application of the proposed RUL prediction method to two electronic components of DIM24A

	Stress condition[1]	Failure rate[2]	Op. time (hr)	Total op. time (hr)	MTTF (hr)	RUL (hr)	RUL difference(yr)[3]
DIM24A-52 (Micro, Linear)							
Base case	T30-E0.1	1.04	87,600	87,600	961,538	873,938	95
Dynamic case	T30-E0.1	1.04	8,760	87,600			
	T60-E0.5	3.63	35,040				
	T90-E0.7	10.8	26,280				
	T100-E0.9	15.8	17,520				
	$\lambda_{average}$: 7.956				125,691	38,091	
DIM24A-16 (Transistor)							
Base case	T30-E0.1	0.04464	87,600	87,600	22,401,433	22,313,833	2,375
Dynamic case	T30-E0.1	0.04464	8,760	87,600			
	T60-E0.5	0.02765	35,040				
	T90-E0.7	0.8392	26,280				
	T100-E0.9	1.806	17,520				
	$\lambda_{average}$: 0.628484				1,591,130	1,503,530	

1) The stress condition denoted by T30-E0.1 means that temperature stress is 30 °C and electrical stress is 0.1.
2) The failure rate of each stress condition is referred from Table 1 and 2.
3) RUL difference means the difference between the base case RUL and the dynamic case RUL.

4. Conclusions

There is a limitation in reliability prediction of digital I&C systems that certain factors are fixed, such as the ambient temperature and electrical stress affecting the failure rates of electronic components due to changes in the external conditions. To overcome this limitation and predict the RUL of the electronic components of the OPERA DCS platform under dynamic stress conditions, a RUL prediction method for electronic components under dynamic stress conditions was proposed. From the results of the case study, it was confirmed that the RUL differences between the base case and dynamic case of stress conditions were significant based on the RUL of specific electronic components predicted depending on time-varying temperature and electrical stress conditions. It can therefore be said that the RUL of electronic components is possibly estimated under the dynamic stress conditions based on the proposed method.

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