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A Study on the Optimal Replacement Periods of Digital Control Computer's Components of Wolsung Nuclear Power Plant Unit 1

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월성 원자력 발전소 1호기의 디지탈 제어컴퓨터 부품들의 최적교체주기에 관한연구

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Abstract

Due to the failure of the instrument and control devices of nuclear power plants caused by aging, nuclear power plants occasionally trip. Even a trip of a single nuclear power plant (NPP) causes an extravagant economical loss and deteriorates public acceptance of nuclear power plants. Therefore, the replacement of the instrument and control devices with proper consideration of the aging effect is necessary in order to prevent the inadvertent trip. In this paper we investigated the optimal replacement periods of the control computer's components of Wolsung nuclear power plant Unit 1. We first derived mathematical models for optimal replacement periods to the digital control computer's components of Wolsung NPP Unit 1 and calculated the optimal replacement periods analytically. We compared the periods with the replacement periods currently used at Wolsung NPP Unit 1. The periods used at Wolsung is not based on mathematical analysis, but on empirical knowledge. As a consequence, the optimal replacement periods analytically obtained and those used in the field show a little difference.

요 약

원자력 발전소의 제어계측 장비의 노후화 때문에, 원자력 발전소에서는 제어계측 장비의 고장으로 인한 발전소 불시정지가 가끔 일어난다. 원자력 발전소의 불시정지는 커다란 경제적 손실과 발전소의 신뢰도를 떨어뜨리고 대중적인 인식을 좋지 않게 한다. 그러므로 불필요한 불시정지를 방지하기 위해서 제어계측 부품의 노후화를 고려한 부품교체를 해주는 것이 필요하다. 이 논문은 월성 원자력 발전소의 제어 컴퓨터 부품의 최적교체주기에 대해 연구했다. 우리는 먼저 월성 디지탈 제어 컴퓨터 부품의 최적교체주기에 대한 수학적 모델을 유도했고, 해석적으로 최적교체주기를 계산했다. 우리는 그결과를 현재 월성 원자력 발전소에서 쓰이는 방법과 비교했다. 월성에서 사용되는 방법은 수학적 분석 방법이 아닌 경험적 지식을 토대로 한것이다. 결과적으로 해석적으로 얻어진 최적 교체주기와 월성에서 사용되는 교체주기와는 약간의 차이를 보이고 있다.

1. Introduction

Wolsung nuclear power plant Unit 1 is the only facility of all existing nuclear power plants in Korea that has overall plant monitoring and control capability by using computer control devices. Since the computer control devices control many power systems of Wolsung NPP unit 1, however, it is impossible to control the nuclear power plant when computer control devices fail. It causes the trip of the nuclear power plant which results in economic loss and degradation of the availability of the nuclear power plant. Therefore, the replacement of the components of computer control devices with proper consideration of aging effect is necessary in order to prevent the inadvertent trip and to improve the reliability of the computer control devices.

The computer control devices of Wolsung nuclear power plant Unit 1 consists of DCCX(Digital Control Comparator X), DCCY and DCCZ[1]. DCCX and DCCY take charge of the control of the Wolsung NPP Unit 1. DCCZ is used for the purpose of training of the operators, for experiments and for spare one. Main digital control computer is DCCX. DCCX controls the power system of Wolsung NPP Unit 1 at normal condition. DCCY is in hot standby state. When DCCX fails, the mission of the main DCC is transferred to DCCY and DCCY controls the nuclear power plant immediately. Therefore, the computer control devices are failed at the following cases:

case 1 : DCCX and DCCY are both in failed states.

case 2 : The mission of main DCC is not transferred to DCCY

Nowadays, the replacement periods of the components of DCCX and DCCY of Wolsung NPP Unit 1 are calculated by the method that the replacement period is determined at the point of 5% confidence level of chi-square distribution. We consider a certain component of the computer control devices. Assume the name of this component is A. Further assume that A is operated during T years and the number of failure during T years is n. Then the chi-square density distribution function is as follows[2] :

$$f(x^2)=\frac{1}{2^{\frac{\nu}{2}}\Gamma(\frac{\nu}{2})}(x^2)^{\frac{\nu}{2}-1}e^{-\frac{x^2}{2}} \qquad (x^2>0)$$

$$= \quad 0 \qquad\qquad (\text{otherwise}) \qquad (1.1)$$

If the component A has failed n times during t years, A has degrees of freedom of 2n-2[3]. Therefore the chi-square distribution of this component is

$$f(x^2)=\frac{1}{2^{n+1}\Gamma(n+1)}(x^2)^{n}e^{-\frac{x^2}{2}} \qquad (x^2>0) \qquad (1.2)$$

$$= \quad 0 \qquad\qquad (\text{otherwise})$$

and

$$\int_0^{x_\alpha} f(x')dx' = 1-\alpha \qquad (1.3)$$

When α is 0.05, we can determine the value x_α. We can find replacement time with 5% confidence level as follows[4].

$$T_{replace}(\text{replacement time})=\frac{2T}{x_a} \qquad (1.4)$$

For an example, if the core memory is used for 30 years and the number of failure during 30 years is 3, then T=30, n=3, and degrees of freedom is 8. In this case $x_{0.05}$ is 15.507 and therefore $T_{replace}(\text{replacement time})=\frac{2\times 30}{15.507}=3.87$years.

The above method, however, neither considers the economical loss nor the failure density function of the hot standby system. In this paper, we consider the loss caused by the trip of nuclear power plant, the cost due to the replacement of old component, and the failure probability density function of the computer control devices. We propose the method that finds the optimal replacement periods of the components in a view of engineering economics, that is minimizing the cost. This method is described in the following section.

2. Methodology

In this section, we developed the methodology for derivation of failure probability density function of the control devices and the optimal replacement periods of the components of DCC.

Control devices are failed in the following three cases :

case 1) DCCX fails at time t and transfers mission of main digital control computer from DCCX to DCCY, and DCCY fails during the repair time of DCCX.

case 2) DCCX fails at time t and fails to transfer of mission of DCCX to DCCY.

case 3) DCCY fails at time t and DCCX fails during the repair time of DCCY.

If component i of DCCX fails at t, this component may be the first fail or the second, and so on. Similarly, if DCCX fails at t, this may be the first fail or the second, and so on.

$f_{ntk}(t)$ denotes the probability that the events occur sequentially. Assume component i of DCCX has the n–th fail at time t, transfer mission of main digital control computer from DCCX to DCCY, and DCCY has the k–th fail during the repair time of DCCX. Then, $f_{ntk}(t)$ is obtained by multiplying $f_{xi-n}(t)$, $(1-\lambda_d)$, $F_{y-k}(t \sim t+T_{rep})$, and $P_{sur-ntk}(t)$, that is,

$$f_{ntk}(t) = f_{xi\_n}(t)(1-\lambda_d)^n F_{y\_k}(t \sim t + T_{rep}) P_{sur\_ntk}(t). \quad (2.1)$$

$f_{xi-n}(t)$ is the probability per unit time that component i of DCCX has the n–th fail at time t. $f_{xi-n}(t)$ is called n–th renewal density function. $F_{y-k}(t \sim t+T_{rep})$ is the probability that DCCY has the k–th fail between t and $t+T_{rep}$. $(1-\lambda_d)^n$ is the probability that carry out n times transfer to DCCY successfully. $f_{ntk}(t)$ implies that DCCX and DCCY have been failed (n–1) times and (k–1) times during time t, respectively, and the fails of DCCX and DCCY have not been concurrent during time t. Therefore $P_{sur-ntk}(t)$ is the probability that control devices survive until time t, in spite of (n–1) times down time of DCCX and (k–1) times down time of DCCY.

The derivation of renewal density function[5] of DCCX is as follows :

$$f_{xi-1}(t) = f_{xi-1}(t)$$

$$f_{xi-2}(t) = \int_0^{t-T_{rep}} f_{xi-1}(x) f_{xi\ 1}(t-x-T_{rep})dx \qquad (t > T_{rep})$$

$$= 0 \qquad (t > T_{rep})$$

$$\approx \int_0^t f_{xi-1}(x) f_{xi-1}(t-x)dx$$

$$f_{xi\_3}(t) = \int_{T_{rep}}^{t-T_{rep}} f_{xi-2}(x) f_{xi-1}(t-x-T_{rep})dx \qquad (t > T_{rep})$$

$$= 0 \qquad (t > T_{rep})$$

$$\approx \int_0^t f_{xi-2}(x) f_{xi-1}(t-x)dx$$

$$\vdots$$

$$f_{xi-n}(t) \approx \int_0^t f_{xi-(n-1)}(x) f_{xi-1}(t-x)dx \qquad (2.2)$$

Laplace transform of $f_{xi-b}(t)$ is denoted by $\phi_{xi-n}(s)$ or $L\{f_{xi-n}(t)\}$.

$\phi_1(s) = L\{f_{xi-1}(t)\} = [\phi_{xi-1}(s)]$, $\phi_n(s) = L\{f_{xi-n}(t)\} = [\phi_{xi-1}(s)]^n$.

Therefore, $f_{xi-n}(t)$ can be also obtained by inverse Laplace transform of $[\phi_1(s)]^n$[6].

$$f_{xi-n}(t) = L^{-1}\{[\phi_{xi-1}(s)]^n\}. \qquad (2.3)$$

Similarly, $f_{y-k}(t) \approx \int_0^t f_{y-(k-1)}(x) f_{y-1}(t-x)dx \qquad (2.4)$

$$f_{y-k}(t) = L^{-1}\{[\phi_{y-1}(s)]^k\}. \qquad (2.5)$$

Therefore, the probability that the k–th fail of DCCY occurs between t and $t-T_{rep}$ is as follows :

$$F_{y-1}(t \sim t + T_{rep}) = \int_t^{t+T_{rep}} f_{y-1}(x)dx$$

$$F_{y-2}(t \sim t + T_{rep}) = \int_0^{t-T_{rep}} f_{y-1}(x) \int_t^{t+T_{rep}} f_{y-1}(u-x-T_{rep})dudx \qquad (t > T_{rep})$$

$$F_{y-3}(t \sim t + T_{rep}) = \int_{T_{rep}}^{t-T_{rep}} f_{y-2}(x) \int_t^{t+T_{rep}} f_{y-1}(u-x-T_{rep})dudx \qquad (t > 2T_{rep})$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$F_{y-k}(t \sim t+T_{rep}) = \int_{(k-2)T_{rep}}^{t-T_{rep}} f_{y-(k-1)}(x) \int_{t}^{t+T_{rep}} f_{y-1}(u-x-T_{rep})\,du\,dx \quad (t > (k-1)T_{rep}) \tag{2.6}$$

$$F_{y-k}(t \sim t+T_{rep}) \approx \int_{t}^{t+T_{rep}} f_{y-k}(x)dx \qquad \text{if } T_{rep} \ll t \tag{2.7}$$

Because the repair time is too short, it is seldom that two components are in failed states. Therefore we can consider as follows :

$P_{sur-ntk}(t) \approx 1.0$ if $T_{rep} < t$

$f_{nxk}(t)$ denotes the probability that the events occur sequentially. Component i of DCCX has the n–th fail at time t, and fails to transfer the mission of DCCX to DCCY, and DCCY have failed k times during the time t. Therefore, $f_{nxk}(t)$ is obtained by multiplying $f_{xi-n}(t)$, $(1-\lambda_d)^{n-1}$, λ_d, $F_{y-k}(t)$, and $P_{sur-nxk}(t)$.

Probability that DCCY has the k–th fail at time t, is denoted by $F_{y-k}(t)$.

$$F_{y-1}(t) = \int_0^{t-T_{rep}} f_{y-1}(x)\left(1-\int_0^{t-x-T_{rep}} f_{y-1}(u)du\right)dx \qquad (t>0)$$

$$F_{y-2}(t) = \int_{T_{rep}}^{t-T_{rep}} f_{y-2}(x)\left(1-\int_0^{t-x-T_{rep}} f_{y-1}(u)du\right)dx \qquad (t>T_{rep})$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$F_{y-k}(t) = \int_{(k-1)T_{rep}}^{t-T_{rep}} f_{y-k}(x)\left(1-\int_0^{t-x-T_{rep}} f_{y-1}(u)du\right)dx \qquad (t>(n-1)T_{rep}) \tag{2.8}$$

$$F_{y-k}(t) \approx \int_0^{t} f_{y-k}(x)\left(1-\int_0^{t-x} f_{y-1}(u)du\right)dx \qquad \text{if } T_{rep} \ll t \tag{2.9}$$

As mentioned above, $P_{sur-nxh}(t) \approx 1$

Therefore, $f_{nxk}(t)$ is described by the following equation :

$$f_{nxk}(t) = f_{xi-n}(t)\lambda_d F_{y-k}(t). \tag{2.10}$$

$f_{nk}(t)$ is the probability that the following event occurs sequentially.

DCCY has the k–th fail at time t, and DCCX has the n–th fail during repair time of DCCY. Therefore, $f_{nk}(t)$ is obtained by multiplying $f_{y-k}(t)$, $(1-\lambda_d)^{n-1}$, $F_{xi-n}(t \sim t+Trep)$, and, $P_{sur-nk}(t)$.

$$f_{nk}(t) = f_{y-k}(t)(1-\lambda_d)^{n-1}F_{xi-n}(t \sim t+T_{rep})P_{sur-nk}(t). \tag{2.11}$$

$$f_{y-k}(t) \approx \int_0^{t} f_{y-(k-1)}(x) f_{y-1}(t-x)dx, \tag{2.12}$$

$$F_{xi-n}(t \sim t+T_{rep}) \approx \int_t^{t+T_{rep}} f_{xi-n}(x)dx, \text{ if } T_{rep} \ll t. \tag{2.13}$$

As mentioned above, $P_{sur-nk}(t) \approx 1.0$, if $T_{rep} \ll t$.

Therefore, failure probability density function of control devices, f(t), is the summation of $f_{1t1}(t)$, $f_{2t1}(t)\cdots\cdots$, $f_{nt1}(t)$, $f_{1t2}(t)$, $f_{2t2}(t)\cdots\cdots$ $f_{nt2}(t)\cdots\cdots$, $f_{1tk}(t)$, $f_{2tk}(t)\cdots\cdots$, $f_{ntk}(t)$, $f_{1x0}(t)$, $f_{2x0}(t)\cdots\cdots$, $f_{nx0}(t)$, $f_{1x1}(t)$, $f_{2x1}(t)\cdots\cdots$, $f_{nx1}(t)\cdots\cdots$, $f_{1xk}(t)$, $f_{2xk}(t)\cdots\cdots$, $f_{nxk}(t)$, $f_{11}(t)$, $f_{21}(t)\cdots\cdots$, $f_{n1}(t)$, $f_{12}(t)$, $f_{22}(t)\cdots\cdots$, $f_{n2}(t)\cdots\cdots$, $f_{1k}(t)$, $f_{2k}(t)\cdots\cdots$, and $f_{nk}(t)$, that is,

$$f(t) \approx \sum_{n=1}^{R}\left(\sum_{k=1}^{R} f_{ntk}(t)\right) + \sum_{n=1}^{R}\left(\sum_{k=0}^{R} f_{nxk}(t)\right) + \sum_{n=1}^{R}\left(\sum_{k=1}^{R} f_{nk}(t)\right), \text{ where } R = \frac{t}{T_{rep}}. \tag{2.14}$$

If component i is replaced with periodic T years, then total expected cost per unit time is given with the following equation[6] :

$$C(T) = \frac{C_f F(T) + C_p(1-F(T))}{\int_0^T (1-F(x))dx} \tag{2.15}$$

Optimal replacement period is determined by T that minimize right hand side of the equation (2.15). We can obtain the optimal replacement period, T, that satisfy the equation, $\frac{dC(T)}{dT}=0$.

3. Results

We calculated the replacement periods of the components of DCCX by using the method described in the previous section and compared them with those obtained from the Wolsung NPP Unit 1. We assumed that the failure probability density function of DCCX follows the Weibull distribution as follows[2] :

$$f_{DCCX}(t) = \alpha\beta t^{\beta-1}e^{-\alpha t^{\beta}}. \quad (t > 0)$$

The values of α and β of the Weibull distribution are obtained by fitting the failure data of Wolsung NPP1 on Weibull distribution probability paper. We assume that the failure probability density function of DCCY follows the exponential distribution as follows :

$$f_{DCCY}(t) = \lambda_y \exp(-\lambda_y t).$$

We obtained the results by using the following values of parameters :
C_f=700 million won, C_p=2 million won, λ_d=0.005, λ_y 4.1 per year and T_{rep}=8 hours. Table 2 shows the optimal replacement periods of DCC's board obtained using the value of above parameters.

4. Sensitivity Analysis

Above results can be altered by changing value of the parameters, i.e., C_p, C_f, T_{rep}, λ_d , etc. The total cost at the equation (2.15) is dependent on the parameters, C_p, C_f, T_{rep}, λ_d , etc. In this paper, we investigated the sensitivity that each parameter affects the total cost at the equation (2.15). We obtained the above results by using Cf 700 million won, C_p=2 million won, λ_d=0.005, and T_{rep}=8 hours. We calculated the optimal replacement periods by changing the values of parameters. We changed the values of each parameter by ±40%, that is, the range of the value of the repair time is from 4.8 hours to 11.2 hours, that of λ_d from 0.003 to 0.007, that of C_f from 420 million won to 980 million won, and that of C_p from 1.2 million won to 2.8 million won. The results are shown in Fig.1. In Fig. 1, the slopes of parameters C_f and C_p are more steeper than those

Table 1. Failure Data for the Components of DCCX of Wolsung NPP Unit 1.

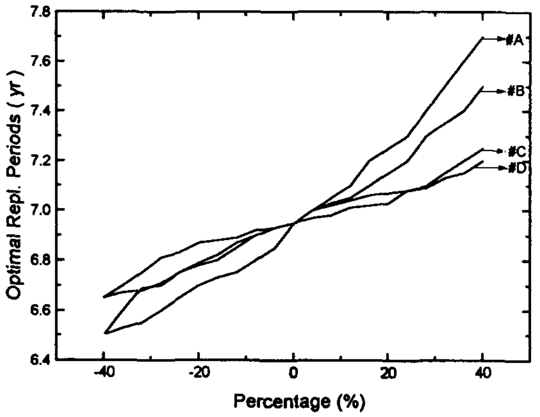
Component Name	Number of Failure	Operating Time	Number of Component
Processor	2	26.25years	3
OPTION	2	26.25	3
Core Memory	8	105	12
Auto Restart	3	26.25	3
Decoding Receiver	2	35	4
Megaram Controller	1	26.25	3
BIC	3	52.5	6
BICO	2	35	4
IOBIC	3	96.25	11
PIM	3	78.75	9
Non Inverter Receiver	2	96.25	11

Table 2. Comparing the Analytically Obtained Optimal Replacement Periods and Those Used in the Field.

Component Name	New Method	Method used in Wolsung NPP
Processor	6.7year	4.2year
OPTION	6.7	4.2
Core Memory	6.7	7.3
Auto Restart	4.4	3.4
Decoding Receiver	9.0	5.6
IBC	9.0	6.8
BICO	9.0	5.6
IOBIC	15.0	12.5
PIM	15.2	10.0
Non Inverter Receiver	15.0	15.0

Table 3. Comparing the Analytically Obtained Optimal Replacement Periods Using Real Cost of DCC'S Boards and Those Used in the Field.

Component Name	New Method	Method used in Wolsung NPP	The Costs of Board
Processor	10.0year	4.2year	$10780
OPTION	8.9	4.2	$5600
Core Memory	8.5	7.3	$8700
Auto Restart	8.7	3.4	$32000
Decoding Receiver	7.0	5.6	$1500
BIC	5.2	6.8	$500
BICO	6.2	5.6	$900
IOBIC	15.0	12.5	$5100
PIM	7.6	10.0	$500
Non Inverter Receiver	15.0	15.0	$1100



#A ; the optimal replacement periods with various values of C_f.

#B ; the optimal replacement periods with various values of C_p.

#C ; the optimal replacement periods with various values of λ_d.

#D ; the optimal replacement periods with various values of T_{rep}.

Fig. 1. The Sensitivity of the Optimal Replacement Periods to Each Parameter, that is, C_f, C_p, λ_d, and T_{rep}.

of λ_d and T_{rep}. Therefore, the results are more sensitive to the parameter C_f and C_p than to those λ_d and T_{rep}.

5. Conclusion

In this paper we have developed an analytic method that calculates the optimal replacement period of hot standby system. Because the system of DCC consists the two parallel units of which one unit is in operation at a time and the other is in hot standby, the reliability of DCC is larger than that of a single unit system. The method used in Wolsung is not based on mathematical analysis, but on empirical knowledge. When we compare the results obtained using the method proposed in this work with those used in Wolsung NPP 1, we can conclude that the replacement periods used in Wolsung NPP 1 could be extended in view of economics. The method developed in this paper also can be applied to any 2 out of 3 logic system with the slight modifications of the equations shown in this paper.

Nomenclature

C(T)	total cost per unit time if component i is replaced with periodic T years
C_f	total expected economical loss during down time of Wolsung NPP 1 that is caused by the trip of NPP
C_p	cost of a replacement of DCC component i
$f_{xi-n}(t)$	Probability per unit time that component i of DCCX has the n–th fail at time t. $f_{xi-n}(t)$ is called n–th renewal density function of component i of DCCX
$f_{y-k}(t)$	Probability per unit time that DCCY has the k–th fail at time t. $f_{y-k}(t)$ is called k–th renewal density function of DCCY
F(T)	failure probability density function of control devices, that is, $F(T)=\int_0^T f(t')dt'$
$F_{xi}(t)$	cumulative failure probability density function of a component i of DCCX
F_{xi-n} $(t\sim t-T_{rep})$	Probability that component i of DCCX has the n–th fail between t and $t-T_{rep}$ time
$F_y(t)$	cumulative failure probabilfunction of DCCY
F_{y-k} $(t\sim t-T_{rep})$	Probability that DCCY has the k–th fail between t and $t-T_{rep}$ time
n_{-i}	total number of failure of component i of DCCX during T_{i-op}
n_{-y}	number of failure of DCCY during T_{-y}
T_{i-op}	total operating time of component i

	of DCCX
T_{rep}	repair time
χ_α	chi square value of the 5% confidence level
α	the shape parameter of Weibull distribution
β	the scale parameter of Weibull distribution
λ_d	probability that fails to transfer the mission of DCCX to DCCY when DCCX fails
λ_y	failure rate of DCCY, where $\lambda_y = \frac{n_{-y}}{T_{-y}}$
T_{-y}	operating time of DCCY

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