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RESEARCH ARTICLE

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Reliability prediction and its validation for nuclear power units in service

Abstract In this paper a novel method for reliability prediction and validation of nuclear power units in service is proposed. The equivalent availability factor is used to measure the reliability, and the equivalent availability factor deducting planed outage hours from period hours and maintenance factor are used for the measurement of inherent reliability. By statistical analysis of historical reliability data, the statistical maintenance factor and the undetermined parameter in its numerical model can be determined. The numerical model based on the maintenance factor predicts the equivalent availability factor deducting planed outage hours from period hours, and the planed outage factor can be obtained by using the planned maintenance days. Using these factors, the equivalent availability factor of nuclear power units in the following 3 years can be obtained. Besides, the equivalent availability factor can be predicted by using the historical statistics of planed outage factor and the predicted equivalent availability factor deducting planed outage hours from period hours. The accuracy of the reliability prediction can be evaluated according to the comparison between the predicted and statistical equivalent availability factors. Furthermore, the reliability prediction method is validated using the nuclear power units in North American Electric Reliability Council (NERC) and China. It is found that the relative errors of the predicted equivalent availability factors for nuclear power units of NERC and China are in the range of –2.16% to 5.23% and –2.15% to 3.71%, respectively. The method proposed can effectively predict the reliability index in the following 3 years, thus providing effective reliability management and maintenance optimization methods for nuclear power units.

Keywords nuclear power units in service, reliability, reliability prediction, equivalent availability factors

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1 Introduction

Generally, the reliability prediction of generators is conducted according to the statistical analysis of historical operation data, such as the USA standard of ANSI/IEEEStd762 [1] and the Chinese Standard of Reliability Evaluation Procedure for Power Generation Equipment (DL/T793) [2]. In these standards the reliability statistics are obtained by analyzing the historical operation data in the past one or several years. Besides, in the Generating Unit Statistical Brochure used by North American Electric Reliability Council (NERC) and the China Electric Reliability Management Annual Report offered by the China Electric Reliability Management Center, reliability predictions are both conducted with the historical operation data used. The reliability prediction method for nuclear power units used today focuses on dealing with the operation data. However, this method does not pay much attention to the outage scheduler in the future. Moreover, it cannot obtain the equivalent availability factor in the next few years. Therefore, a new reliability prediction method for the next few years is of great importance to nuclear power units in service. It can play an important role in reliable management, and safe and economic operation of nuclear power units.

2 Reliability index of nuclear power units

2.1 Calculations of equivalent availability factor and planed outage factor

The equivalent availability factor E_{AF} and planed outage factor P_{OF} are the main reliability index for nuclear power units [1,2], which are defined as

$$E_{AF} = \frac{t_{AH} - t_{EUNDH}}{t_{PH}} \times 100\% = \frac{t_{AH} - t_{EUNDH}}{t_{AH} + t_{UH}} \times 100\%$$

$$= \frac{t_{\mathrm{AH}} - t_{\mathrm{EUNDH}}}{t_{\mathrm{AH}} + t_{\mathrm{UOH}} + t_{\mathrm{POH}}} \times 100\%, \tag{1}$$

$$P_{\mathrm{OF}} = \frac{t_{\mathrm{POH}}}{t_{\mathrm{PH}}} \times 100\%, \tag{2}$$

where t_{AH} is the available hours, which is the sum of service hours and reserve shutdown hours. t_{EUNDH} is the equivalent unit derated hours, t_{POH} is the planed outage hours, t_{UOH} is the un-planed outage hours, t_{PH} is the period hours which can be expressed as $t_{\mathrm{PH}} = t_{\mathrm{AH}} + t_{\mathrm{UH}} = t_{\mathrm{AH}} + t_{\mathrm{UOH}} + t_{\mathrm{POH}}$, and t_{UH} is the unavailable hours which is the sum of t_{UOH} and t_{POH}.

The unavailable hours of nuclear power units consist of the planed outage hours and un-planed outage hours. t_{UOH} is a measure of the impact of unplanned outage event caused by equipment failure on the reliability of nuclear power units, and t_{POH} measures the impact of maintainability on the unit operation. A larger t_{UOH} corresponds to a lower reliability, and a larger t_{POH} corresponds to a worse maintainability. Besides, for the nuclear power units in service, a larger E_{AF} indicates a higher reliability. Traditionally, Eq. (1) is for calculating the equivalent availability factor E_{AF}, and the planed outage hours t_{POH} is considered in the denominator. For a single nuclear power unit, in the year with A class repair, the values of t_{POH} and P_{OF} are relatively higher, and that of E_{AF} is relatively lower. The value of t_{POH} has a notable effect on E_{AF}.

2.2 Calculation of equivalent availability factor deducting planed outage hours from period hours

To eliminate the effect of planed outage, an equivalent availability factor deducting planed outage hours from period hours E_{AP} is proposed. E_{AP} can be used as the reliability evaluation index for nuclear power units in service, which can be expressed as

$$\begin{aligned} E_{\mathrm{AP}} &= \frac{t_{\mathrm{AH}} - t_{\mathrm{EUNDH}}}{t_{\mathrm{PH}} - t_{\mathrm{POH}}} \times 100\% \\ &= \frac{t_{\mathrm{AH}} - t_{\mathrm{EUNDH}}}{t_{\mathrm{AH}} + t_{\mathrm{UOH}}} \times 100\% = \frac{E_{\mathrm{AF}}}{1 - P_{\mathrm{OF}}} \times 100\%. \end{aligned} \tag{3}$$

The difference between Eq. (1) and Eq. (3) is the deduction of planed outage hours t_{POH} in the denominator. E_{AP} can effectively indicate the effect of unplanned outage event caused by the equipment failure on the reliability of nuclear power units, which is the inherent reliability evaluation index. In practical applications, the inherent reliability of nuclear power units in service varies in a certain extent. The planed outage hours are arranged by 3 years in advance. As a result, the planed outage factor P_{OF} can be determined in advance. By determining the variation of inherent reliability E_{AP}, the variation of E_{AF} can be obtained. According to Eq. (3), E_{AF} can be expressed as

$$E_{\mathrm{AF}} = (1 - P_{\mathrm{OF}}) \times E_{\mathrm{AP}}. \tag{4}$$

2.3 Calculation of maintenance factor

In the study by Shi et al. [3], a maintenance factor ρ was proposed to express the variation of equivalent availability factor deducting planed outage hours from period hours E_{AP}, which is defined as

$$\rho = \frac{t_{\mathrm{UOH}} + t_{\mathrm{EUNDH}}}{t_{\mathrm{AH}} - t_{\mathrm{EUNDH}}}. \tag{5}$$

The relationship between maintenance factor ρ and E_{AP} can be expressed as

$$\rho = \frac{1 - E_{\mathrm{AP}}}{E_{\mathrm{AP}}}, \tag{6}$$

$$E_{\mathrm{AP}} = \frac{1}{1 + \rho}. \tag{7}$$

Substituting Eq. (3) into Eq. (6), there is

$$\rho = \frac{1 - P_{\mathrm{OF}} - E_{\mathrm{AF}}}{E_{\mathrm{AF}}}. \tag{8}$$

For a nuclear power unit in service, the values of E_{AF}, E_{AP} and P_{OF} are different in different years, and the maintenance factor ρ varies with the year t_i. The value of $\rho(t_i)$ can be expressed as

$$\rho(t_i) = \frac{1 - P_{\mathrm{OF}}(t_i) - E_{\mathrm{AF}}(t_i)}{E_{\mathrm{AF}}(t_i)}, \tag{9}$$

where $E_{\mathrm{AF}}(t_i)$ is the statistical equivalent availability factor in the year t_i, and $P_{\mathrm{OF}}(t_i)$ is the statistical planed outage factor in the year t_i.

3 Numerical model of reliability

3.1 Numerical model of maintenance factor

In the study by Shi [4], a reliability growth model was proposed, and it is reported that the maintenance factor can be expressed as a power function. Power function, polynomials, exponential function and Weibull distribution are all used for the curve fitting of statistical reliability data. However, it is found that the curve fitting with the power function used shows the best agreement with the maintenance factor. The function of $\rho(t)$ can be expressed as

$$\rho(t) = \eta_i t^{-m_i}, \tag{10}$$

where t is the operating years of nuclear power units in service, η_i is the scale parameter, and m_i is the growth factor.

3.2 Numerical model of equivalent availability factor deducting planed outage hours from period hours

Substituting Eq. (10) into Eq. (7), the equivalent availability factor deducting planed outage hours from period hours can be obtained.

$$E_{\mathrm{AP}}(t) = \frac{1}{1+\eta_i t^{-m_i}}. \tag{11}$$

3.3 Numerical model of equivalent availability factor

After obtaining the numerical models of equivalent availability factor deducting planed outage hours from period hours $E_{\mathrm{AP}}(t)$ and planed outage factor $P_{\mathrm{OF}}(t)$, Eq. (11) can be substituted into Eq. (4) to get the equivalent availability factor $E_{\mathrm{AF}}(t)$,

$$E_{\mathrm{AF}}(t) = \frac{1-P_{\mathrm{OF}}(t)}{1+\eta_i t^{-m_i}}. \tag{12}$$

4 Reliability prediction method for nuclear power units

The first step for reliability prediction of the nuclear power units is to analyze the multiple power units and the single power unit history data of nuclear power units to present the inherent-reliability change of nuclear power units. The next step is to determine the parameters m and η, so as to predict the equivalent availability factor deducted planed outage hours from period hours E_{AP} of nuclear power units. The third step is to predict the equivalent availability factor E_{AF} of power units based on the arrangement of planed repair days in advance.

4.1 Statistical analysis of operation data

For the nuclear power units in service, the maintenance factor $\rho(t_i)$ can be calculated according to Eq. (9) with the statistical value of $E_{\mathrm{AF}}(t_i)$ and $P_{\mathrm{OF}}(t_i)$, which can be obtained using the historical reliability data in the past n years ($n \geqslant 3$). The scale parameter η_i and the growth factor m_i in Eq. (10) can be obtained using the least squares method [4,5].

4.2 Equivalent availability factor deducting planed outage hours from period hours E_{AP}

The numerical model of E_{AP} can be obtained with the historical reliability data in the past n years. Given $t = n+1$, $n+2$ and $n+3$, the value of E_{AP} in the very year ($t = n+1$), the next year ($t = n+2$) or two ($t = n+3$) can be expressed as

$$E_{\mathrm{AP}}(n+1) = \frac{1}{1+\eta_i (n+1)^{-m_i}}, \tag{13}$$

$$E_{\mathrm{AP}}(n+2) = \frac{1}{1+\eta_i (n+2)^{-m_i}}, \tag{14}$$

$$E_{\mathrm{AP}}(n+3) = \frac{1}{1+\eta_i (n+3)^{-m_i}}. \tag{15}$$

4.3 Prediction of planed outage factor P_{OF}

The maintenance plan of the nuclear power units in service is conducted according to the standard of DL/T8384 (Guide of Maintenance for Power Plant Equipment) [6]. The planned maintenance days M_1 in the very year can be determined at the beginning of the year, and the planned maintenance days in the following one and two years can also be obtained. According to Eq. (2), the planed outage factor P_{OF} in the very year and the next one and two years can be written as

$$P_{\mathrm{OF}}(n+1) = \frac{24 \times M_1}{8760}, \tag{16}$$

$$P_{\mathrm{OF}}(n+2) = \frac{24 \times M_2}{8760}, \tag{17}$$

$$P_{\mathrm{OF}}(n+3) = \frac{24 \times M_3}{8760}. \tag{18}$$

4.4 Prediction of equivalent availability factor E_{AF}

After obtaining the equivalent availability factor deducting planed outage hours from period hours E_{AP} and the planed outage factor P_{OF}, the equivalent availability factor E_{AF} in the next few years can be obtained using Eq. (4).

$$E_{\mathrm{AF}}(t) = [1-P_{\mathrm{OF}}(t)] \times E_{\mathrm{AP}}(t). \tag{19}$$

Based on the value of $E_{\mathrm{AP}}(n+1)$, $E_{\mathrm{AP}}(n+2)$, and $E_{\mathrm{AP}}(n+3)$ and $P_{\mathrm{OF}}(n+1)$, $P_{\mathrm{OF}}(n+2)$, and $P_{\mathrm{OF}}(n+3)$, the equivalent availability factor E_{AF} in the next few years can be obtained by using

$$\begin{aligned} E_{\mathrm{AF}}(n+1) &= [1-P_{\mathrm{OF}}(n+1)] \times E_{\mathrm{AP}}(n+1) \\ &= \left(1-\frac{24 \times M_1}{8760}\right) \times \frac{1}{1+\eta_i (n+1)^{m_i}}, \end{aligned} \tag{20}$$

$$\begin{aligned} E_{\mathrm{AF}}(n+2) &= [1-P_{\mathrm{OF}}(n+2)] \times E_{\mathrm{AP}}(n+2) \\ &= \left(1-\frac{24 \times M_2}{8760}\right) \times \frac{1}{1+\eta_i (n+2)^{m_i}}, \end{aligned} \tag{21}$$

$$E_{\mathrm{AF}}(n+3)=[1-P_{\mathrm{OF}}(n+3)]\times E_{\mathrm{AP}}(n+3)$$
$$=\left(1-\frac{24\times M_3}{8760}\right)\times\frac{1}{1+\eta_i(n+3)^{m_i}}. \tag{22}$$

5 Reliability Validation methods for nuclear power units

5.1 Validation method for the predicted value

By statistically analyzing the historical reliability data of the nuclear power units in service, the statistical value of equivalent availability factor $E_{\mathrm{AF}}(t_i)$ and planed outage factor $P_{\mathrm{OF}}(t_i)$ in a certain year can be obtained. There are certain differences between the statistical planed outage factor of the nuclear power units in service and the predicted value using Eqs. (16) to (18). As a result, the validation for the reliability prediction cannot be conducted based on the comparison between the $E_{\mathrm{AF}}(t)$ obtained from Eqs. (20) to (22) and the statistical value of $E_{\mathrm{AP}}(t_i)$. However, during the operation of nuclear power units, the prediction of equivalent availability factor $E_{\mathrm{AF}i}(t)$ can be conducted with the predicted value of $E_{\mathrm{AP}}(t)$ obtained from Eqs. (13) to (15) and the statistical value of $P_{\mathrm{OF}}(t_i)$ used. Under the condition of using the same planed outage factor $P_{\mathrm{OF}}(t_i)$, the validation for the reliability prediction of nuclear power units in service can be realized based on the comparison between the predicted value of $E_{\mathrm{AF}i}(t)$ and the statistical value of $E_{\mathrm{AF}}(t_i)$.

5.2 Prediction of the equivalent availability factor

According to Eq. (4), the predicted value of equivalent availability factor $E_{\mathrm{AF}i}(t)$ in a certain year can be written as

$$E_{\mathrm{AF}i}(t)=[1-P_{\mathrm{OF}}(t_i)]\times E_{\mathrm{AP}}(t), \tag{23}$$

where $E_{\mathrm{AP}}(t)$ is the predicted value of equivalent availability factor deducting planed outage hours from period hours using Eqs. (13) to (15), and $P_{\mathrm{OF}}(t_i)$ is the practical statistical value of planed outage factor for nuclear power units.

The statistical value of planed outage factor in the year t_i is $P_{\mathrm{OF}}(t_i)$. The predicted value of equivalent availability factor $E_{\mathrm{AF}i}(n+1)$ in the year t_i using the scale parameter η_i and the growth factor m_i in the year t_i–1 can be expressed as

$$E_{\mathrm{AF}i}(n+1)=[1-P_{\mathrm{OF}}(t_i)]\times E_{\mathrm{AP}}(n+1)$$
$$=\frac{1-P_{\mathrm{OF}}(t_i)}{1+\eta_i(n+1)^{-m_i}}. \tag{24}$$

The predicted value of equivalent availability factor $E_{\mathrm{AF}i}(n+2)$ in the year t_i using the scale parameter η_i and the growth factor m_i in the year t_i–2 can be expressed as

$$E_{\mathrm{AF}i}(n+2)=[1-P_{\mathrm{OF}}(t_i)]\times E_{\mathrm{AP}}(n+2)$$
$$=\frac{1-P_{\mathrm{OF}}(t_i)}{1+\eta_i(n+2)^{-m_i}}. \tag{25}$$

The predicted value of equivalent availability factor $E_{\mathrm{AF}i}(n+3)$ in the year t_i using the scale parameter η_i and the growth factor m_i in the year t_i–3 can be expressed as

$$E_{\mathrm{AF}i}(n+3)=[1-P_{\mathrm{OF}}(t_i)]\times E_{\mathrm{AP}}(n+3)$$
$$=\frac{1-P_{\mathrm{OF}}(t_i)}{1+\eta_i(n+3)^{-m_i}}. \tag{26}$$

5.3 Relative error of the reliability prediction

The absolute errors of the predicted and statistical equivalent availability factor Δ_1 and Δ_2 can be written as

$$\Delta_1=\max\left\{\begin{array}{l}[E_{\mathrm{AF}}(n+1)-E_{\mathrm{AF}}(t_j)],\\ [E_{\mathrm{AF}}(n+2)-E_{\mathrm{AF}}(t_j)],\\ [E_{\mathrm{AF}}(n+3)-E_{\mathrm{AF}}(t_j)]\end{array}\right\}, \tag{27}$$

$$\Delta_2=\min\left\{\begin{array}{l}[E_{\mathrm{AF}}(n+1)-E_{\mathrm{AF}}(t_j)],\\ [E_{\mathrm{AF}}(n+2)-E_{\mathrm{AF}}(t_j)],\\ [E_{\mathrm{AF}}(n+3)-E_{\mathrm{AF}}(t_j)]\end{array}\right\}. \tag{28}$$

At $\Delta_1>0$ and $|\Delta_1|\geqslant|\Delta_2|$, the relative error E_{r} can be expressed as

$$E_{\mathrm{r}}=\frac{\Delta_1}{E_{\mathrm{AF}}(t_i)}\times 100\%. \tag{29}$$

At $\Delta_2<0$ and $|\Delta_1|<|\Delta_2|$, the relative error E_{r} can be expressed as

$$E_{\mathrm{r}}=\frac{\Delta_2}{E_{\mathrm{AF}}(t_i)}\times 100\%. \tag{30}$$

5.4 Maintenance optimization

In the reliability prediction of nuclear power units, the planned maintenance days are suggested to be the ceiling value in the standard DL/T838 (Guide of Maintenance for Power Plant Equipment). If the predicted value of equivalent availability factor is not up to the required target value, the lower limit of planned maintenance days should be gradually reduced according to the rules of DL/T838. Reliability prediction can be conducted using the method introduced in this paper until the predicted equivalent availability factor of the nuclear power unit meets the required reliability target value.

For example, for a 1000 MW nuclear power unit, it takes 70 to 80 days to conduct A class repair in the rules of DL/T838, while it takes 35 to 50 days, 26 to 30 days and 9 to 15 days, respectively to perform B, C, and D class repair. The planned maintenance days can be optimized by using the reliability prediction method proposed in this paper. In this way, the reliability management can be realized and the reliability index of the nuclear power units will be under control.

If the planned maintenance days of a nuclear power unit are in the range of the rules of DL/T838 introduced above, the un-planed outage hours t_{UOH} will not increase with the decreasing planned maintenance days. The original maintenance plan needs to be changed, and a more efficient maintenance schedule can be obtained.

6 Reliability prediction and validation examples of multiple nuclear power units

For application examples of multiple nuclear power units, reliability prediction error could be validated based on the reliability history data from NERC.

6.1 Statistical reliability data of NERC nuclear power units

The statistical data of $E_{AF}(t_i)$ and $P_{OF}(t_i)$ for nuclear power units in 2004 and 2013 are listed in Table 1, which is provided by the North American Electric Reliability Council (NERC) [7]. In 2004 totally 103 units were statistically analyzed, including 62 pressurized water reactor (PWR) units and 30 boiling water reactor (BWR) units. In 2013 totally 104 units were statistically analyzed, including 65 PWR units and 33 BWR units.

6.2 Reliability prediction and validation examples of multiple nuclear power units

The statistical data of equivalent availability factor $E_{AF}(t_i)$ and planed outage factor $P_{OF}(t_i)$ in 2004 and 2013 provided by NERC are tabulated in Tables 1 and 2. Given that t_i = 1 in 2004 and t_i = 10 in 2013, the growth factor m_i and scale parameter η_i (Table 2) can be obtained by using the statistical reliability data in the past n years. Besides, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$ and $E_{AF}(n+3)$ and the relative error E_r for the very year ($t = n + 1$) and the following years are also presented in Table 2.

The predicted equivalent availability factor $E_{AFi}(n+3)$ in 2013 can be obtained by using the growth factor m_i and scale parameter η_i in 2010 (n = 7) used.

$$\begin{aligned} E_{AFi}(n+3) &= [1-P_{OF}(t_i)] \times E_{AP}(n+3) \\ &= \frac{1-P_{OF}(10)}{1+\eta_i(n+3)^{-m_i}} \\ &= \frac{1-0.0639}{1+0.058300 \times 10^{-0.151293}} \\ &= 89.91\%. \end{aligned}$$

With the growth factor m_i and scale parameter η_i in 2011 ($n=8$) used, the predicted equivalent availability factor $E_{AFi}(n+2)$ in 2013 can be obtained as

$$\begin{aligned} E_{AFi}(n+2) &= [1-P_{OF}(t_i)] \times E_{AP}(n+2) \\ &= \frac{1-P_{OF}(t_i)}{1+\eta_i(n+2)^{-m_i}} \\ &= \frac{1-0.0639}{1+0.054965 \times 10^{-0.072899}} \\ &= 89.45\%. \end{aligned}$$

Table 1 Statistical reliability data of nuclear power units provided by NERC

Year	Power								
	Results for all units			800–999 MW			1000 MW Plus		
	Number of units	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	Number of units	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	Number of units	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%
2004	103	87.53	7.59	38	89.74	5.97	49	88.03	8.05
2005	104	87.06	7.20	38	87.97	5.97	48	89.93	6.47
2006	108	88.77	6.95	38	89.54	6.95	49	89.13	6.93
2007	99	90.24	6.30	33	91.77	6.03	50	89.30	7.10
2008	99	89.40	7.26	34	91.08	5.67	51	89.67	7.06
2009	99	88.21	7.70	34	89.96	7.03	51	88.40	6.48
2010	99	88.53	6.73	34	87.40	6.63	51	90.58	5.39
2011	97	86.37	8.36	32	86.89	6.14	50	88.40	7.00
2012	101	83.50	8.97	33	87.10	7.03	51	84.24	7.95
2013	104	87.66	6.39	33	90.44	5.71	54	88.55	5.90

With the growth factor m_i and scale parameter η_i in 2012 ($n = 9$) used, the predicted equivalent availability factor $E_{AFi}(n+1)$ in 2013 can be obtained as

$$\begin{aligned} E_{AFi}(n+1) &= [1 - P_{OF}(t_i)] \times E_{AP}(n+1) \\ &= \frac{1 - P_{OF}(t_i)}{1 + \eta_i (n+1)^{-m_i}} \\ &= \frac{1 - 0.0639}{1 + 0.049651 \times 10^{0.04978}} \\ &= 88.67\%. \end{aligned}$$

The statistical equivalent availability factor in 2013 provided by NERC is $E_{AF}(t_i) = 87.66\%$, thus $\Delta_1 = 89.91\%–87.66\% = 2.25\%$, $\Delta_2 = 88.67\%–87.66\% = 1.01\%$. The relative error of the predicted equivalent availability factor is

$$E_r = \frac{\Delta_1}{E_{AF}(t_i)} \times 100\% = \frac{2.25}{87.66} \times 100\% = 2.57\%.$$

According to Table 2, the relative error of the predicted equivalent availability factor varies in the range of –1.32% to 5.13%. The error of reliability prediction of year 2012 is relatively big which is related to a large un-planed outage hours for NERC nuclear power units in that year.

6.3 Reliability prediction and validation examples of 800–999 MW nuclear power units

The statistical data of $E_{AF}(t_i)$ and $P_{OF}(t_i)$ of 800–999MW nuclear power units in 2004 and 2013 are listed in Tables 1 and 3, respectively. Given that $t_i = 1$ in 2004 and $t_i = 10$ in 2013, the growth factor m_i and scale parameter η_i (Table 3) can be obtained by using the statistical reliability data in the past n years. The predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$ and $E_{AF}(n+3)$, and the relative error E_r for the very year ($t = n + 1$) and the following years are also given in Table 3. It is found that the relative error of the predicted equivalent availability factor for 800–999 MW nuclear power units varies in the range of –2.16% to 5.23% since 2007. The error of reliability prediction of year 2011 is relatively big which is related to a large un-planed outage hours for NERC 800–999 MW nuclear power units in that year.

6.4 Reliability prediction and validation examples of 1000 MW nuclear power units

The statistical data of $E_{AF}(t_i)$ and $P_{OF}(t_i)$ for 1000 MW nuclear power units in 2004 and 2013 are presented in Tables 1 and 4, respectively. Given that $t_i = 1$ in 2004 and $t_i = 10$ in 2013, the growth factor m_i and scale parameter η_i can be obtained by using the statistical reliability data in the past n years, as given in Table 4. The predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$ and $E_{AF}(n+3)$, and the relative error E_r for the very year ($t = n + 1$) and the following years are also listed in Table 4. It is found that the relative error of the predicted equivalent availability factor for 1000MW nuclear power units has been varying in the range of -0.52% to 4.53% since 2007. The error of reliability prediction of year 2012 is relatively big which is related to a large un-planed outage hours for NERC 1000 MW nuclear power units in that year.

7 Reliability prediction and validation examples of a single nuclear power unit

For application examples of the single nuclear power unit, reliability prediction error could be validated based on the reliability history data from China Electric Reliability Management Annual Report (CERMAR) .

7.1 Reliability prediction and validation examples of 1000 MW nuclear power units in China

Two 1000MW PWR units [8] in China are studied. Units 1 and 2 began their commercial operation days on May 17, 2007 and Aug. 16, 2007, respectively. Tables 5 and 6 lists the statistical data of $E_{AF}(t_i)$, $P_{OF}(t_i)$, m_i, and η_i, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$, and $E_{AF}(n+3)$, and the

Table 2 Predicted equivalent availability factor E_{AF} of nuclear power units

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	1	87.53	7.59	0.05575						
2005	2	87.06	7.20	0.06593						
2006	3	88.77	6.95	0.04821	0.091931	0.059341				
2007	4	90.24	6.30	0.03834	0.260758	0.062810	89.05			–1.32
2008	5	89.40	7.26	0.03736	0.301046	0.063990	89.06	88.22		–1.31
2009	6	88.21	7.70	0.04637	0.232249	0.061528	88.98	88.80	87.88	0.87
2010	7	88.53	6.73	0.05354	0.151293	0.058300	89.76	90.06	89.87	1.73
2011	8	86.37	8.36	0.06102	0.072899	0.054965	87.90	88.29	88.61	2.59
2012	9	83.50	8.97	0.09018	–0.04978	0.049651	86.96	87.38	87.79	5.13
2013	10	87.66	6.39	0.06788	–0.08222	0.048222	88.67	89.45	89.91	2.57

Table 3 Predicted equivalent availability factor E_{AF} of 800–999 MW nuclear power units

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	1	89.74	5.97	0.04780						
2005	2	87.97	5.97	0.06889						
2006	3	89.54	6.95	0.03920	0.104420	0.053792				
2007	4	91.77	6.03	0.02397	0.466539	0.060763	89.79			–2.16
2008	5	91.08	5.67	0.03568	0.378336	0.058337	91.70	90.23		–0.94
2009	6	89.96	7.03	0.03346	0.339708	0.057066	90.30	90.58	89.00	–1.07
2010	7	87.40	6.63	0.06831	0.122156	0.049372	90.70	90.83	91.14	4.27
2011	8	86.89	6.14	0.08022	–0.03878	0.043749	90.40	91.29	91.43	5.23
2012	9	87.10	7.03	0.06739	–0.10372	0.041456	88.74	89.59	90.52	3.93
2013	10	90.44	5.71	0.04257	–0.06894	0.042774	89.57	89.99	90.90	–0.96

Table 4 Predicted equivalent availability factor E_{AF} of 1000 MW nuclear power units

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	1	88.03	8.05	0.04453						
2005	2	89.93	6.47	0.04003						
2006	3	89.13	6.93	0.04421	0.022500	0.043452				
2007	4	89.30	7.10	0.04031	0.046397	0.043803	89.15			–0.17
2008	5	89.67	7.06	0.03647	0.090231	0.044699	89.31	89.20		–0.52
2009	6	88.40	6.48	0.05792	–0.04301	0.041429	90.09	89.90	89.77	1.92
2010	7	90.58	5.39	0.04449	–0.03981	0.041517	90.53	91.19	90.97	0.67
2011	8	88.40	7.00	0.05204	–0.07095	0.040557	88.99	88.97	89.68	1.44
2012	9	84.24	7.95	0.09271	–0.19654	0.036547	87.88	88.06	88.04	4.53
2013	10	88.55	5.90	0.06268	–0.21077	0.036082	88.99	89.81	90.00	1.64

Table 5 Predicted equivalent availability factor E_{AF} of Unit 1 (1000 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2008	1	71.38	27.26	0.01909						
2009	2	74.83	24.51	0.00884						
2010	3	87.25	12.75	0.00000	8.125370	0.070797				
2011	4	100.00	0.00	0.00000	8.072653	0.069552	100.00			0.00
2012	5	86.91	13.12	0.00000	7.329061	0.049334	86.88	86.88		–0.04
2013	6	90.00	9.15	0.00947	3.693418	0.006206	90.85	90.85	90.85	0.95

Table 6 Predicted equivalent availability factor E_{AF} of Unit 2 (1000 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2008	1	81.45	18.16	0.00475						
2009	2	80.53	19.46	0.00015						
2010	3	82.69	17.13	0.00214	1.187275	0.002326				
2011	4	100.00	0.00	0.00000	4.520036	0.007139	99.96			–0.04
2012	5	87.91	12.12	0.00000	5.165162	0.009617	87.88	87.85		–0.07
2013	6	88.48	10.54	0.01107	2.190137	0.001763	89.46	89.46	89.43	1.11

relative error E_r of Units 1 and 2, respectively. It can be found that the relative error of the predicted equivalent availability factors for Units 1 and 2 vary in the range of –0.04% to 0.95% and –0.07% to 1.11%, respectively, indicating that the prediction accuracy for equivalent availability factors is high.

7.2 Reliability prediction and validation examples of 990 MW nuclear power units in China

Two 990MW PWR units [8] in China are studied. Units 1 and 2 began their commercial operation days on May 28, 2002 and Jan. 8, 2003, respectively. Tables 7 and 8 give the statistical data of $E_{AF}(t_i)$, $P_{OF}(t_i)$, m_i, and η_i, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$, and $E_{AF}(n+3)$, and the relative error E_r of Unit 1 and 2, respectively. As observed, the relative error of the predicted equivalent availability factors for Units 1 and 2 vary in the range of –0.23% to 2.66% and –0.23% to 2.66%, respectively, indicating that the prediction accuracy for equivalent availability factors is also high.

7.3 Reliability prediction and validation for 700 MW nuclear power units in China

Two 700MW CANDU units [8] in China are studied. Units 1 and 2 began their commercial operation days on Nov. 19, 2002 and Jun. 12, 2003, respectively. Tables 9 and 10 list the statistical data of $E_{AF}(t_i)$, $P_{OF}(t_i)$, m_i, and η_i, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$, and $E_{AF}(n+3)$, and the relative error E_r of Units 1 and 2, respectively. As observed the relative error of the predicted equivalent availability factors for Units 1 and 2 vary in the range of –0.55% to 1.72% and –0.27% to 0.96%, respectively, indicating that the prediction accuracy for equivalent availability factors is high.

7.4 Reliability prediction and validation example of a 310 MW nuclear power unit in China

A 310MW PWR unit (Unit 1) [8] is studied. Unit 1 began its commercial operation day on Dec. 15, 1991. Given t_i = 1 in 1992 and t_i = 13 in 2004, the statistical data of $E_{AF}(t_i)$,

Table 7 Predicted equivalent availability factor E_{AF} of Unit 1 (990 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2003	1	81.89	12.68	0.06631						
2004	2	89.73	10.03	0.00267						
2005	3	84.50	15.02	0.00568	2.494617	0.044477				
2006	4	90.27	9.08	0.00720	1.600860	0.032925	90.79			0.58
2007	5	83.82	16.16	0.00024	2.549497	0.051030	83.63	83.77		–0.23
2008	6	91.93	7.10	0.01055	1.602077	0.029731	92.85	92.73	92.85	1.00
2009	7	91.02	8.04	0.01028	1.070310	0.020867	91.83	91.92	91.82	0.99
2010	8	94.12	5.40	0.00514	0.890892	0.018236	94.39	94.50	94.58	0.49
2011	9	93.20	6.25	0.00592	0.734945	0.016024	93.51	93.57	93.67	0.50
2012	10	91.69	5.71	0.02841	0.363947	0.011476	94.02	94.07	94.13	2.66
2013	11	82.44	16.21	0.01638	0.185429	0.009659	83.39	83.56	83.61	1.42

Table 8 Predicted equivalent availability factor E_{AF} of Unit 2 (990 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	1	81.22	17.94	0.01034						
2005	2	91.94	7.30	0.00824						
2006	3	92.56	6.80	0.00692	0.362202	0.010409				
2007	4	88.16	7.99	0.04363	–0.694066	0.007295	91.43			3.71
2008	5	86.19	13.78	0.00033	1.011887	0.016042	84.34	85.72		–2.15
2009	6	90.46	8.09	0.01603	0.438005	0.011565	91.67	89.64	91.41	1.34
2010	7	91.99	7.40	0.00660	0.362549	0.010998	92.14	92.39	90.06	–2.10
2011	8	93.94	5.45	0.00654	0.311722	0.010586	94.07	94.12	94.37	0.46
2012	9	89.94	7.69	0.02639	0.012525	0.008261	91.82	91.86	91.91	2.19
2013	10	87.47	10.91	0.01848	–0.124085	0.007305	88.38	88.63	88.66	1.36

Table 9 Predicted equivalent availability factor E_{AF} of Unit 1 (700 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2003	1	90.78	0.00	0.10156						
2004	2	77.44	22.14	0.00536						
2005	3	82.85	15.47	0.02030	1.764598	0.063903				
2006	4	96.60	3.40	0.00000	6.468936	0.311159	96.07			–0.55
2007	5	82.67	17.33	0.00000	7.331396	0.463440	82.67	82.36		–0.37
2008	6	88.10	11.93	0.00000	7.303002	0.455997	88.07	88.07	87.83	–0.31
2009	7	92.19	7.81	0.00000	6.997507	0.372079	92.19	92.19	92.19	0.00
2010	8	90.07	9.93	0.00000	6.280064	0.217041	90.07	90.07	90.07	0.00
2011	9	98.14	1.70	0.00160	4.616302	0.054652	98.30	98.30	98.30	0.16
2012	10	94.67	3.70	0.01723	3.064196	0.013520	96.30	96.30	96.30	1.72
2013	11	90.76	8.27	0.01071	2.030372	0.004983	91.73	91.73	91.73	1.07

Table 10 Predicted equivalent availability factor E_{AF} of Unit 2 (700 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	1	94.80	4.14	0.01120						
2005	2	80.21	16.97	0.03521						
2006	3	87.47	12.40	0.00148	1.464810	0.020057				
2007	4	97.69	2.31	0.00000	5.763511	0.085204	97.43			–0.27
2008	5	87.63	12.40	0.00000	6.601611	0.125483	87.60	87.44		–0.22
2009	6	95.42	4.58	0.00001	5.866340	0.082509	95.42	95.42	95.28	–0.14
2010	7	92.79	7.21	0.00004	4.894783	0.043212	92.79	92.79	92.79	0.00
2011	8	89.85	9.29	0.00961	3.006414	0.010458	90.71	90.71	90.71	0.96
2012	9	90.83	9.19	0.00000	3.502394	0.015776	90.80	90.81	90.81	–0.03
2013	10	100.00	0.00	0.00001	3.387580	0.014227	100.00	100.00	100.00	0.00

$P_{OF}(t_i)$, m_i, and η_i, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$, and $E_{AF}(n+3)$, and the relative error E_r of Unit 1 are given in Table 11. As observed, the relative error of the predicted equivalent availability factor for Unit 1 varies in the range of –0.03% to 0.78%, indicating that the prediction accuracy for equivalent availability factors is high.

7.5 Reliability prediction and validation example of a 984 MW nuclear power unit in China

A 984MW PWR unit (Unit 1) [8] is studied. Unit 1 began its commercial operation day on Feb. 1, 1994. However, the statistical reliability data in 1995 and 1998 is not

Table 11 Predicted equivalent availability factor E_{AF} of Unit 1 (310 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
2004	13	99.83	0.00	0.00170						
2005	14	87.86	11.77	0.00422						
2006	15	92.32	7.68	0.00000	5.902193	0.006551				
2007	16	82.40	17.60	0.00000	6.232480	0.007321	82.40			–0.27
2008	17	96.15	3.10	0.00776	2.161159	0.001116	96.90	96.90		–0.22
2009	18	89.60	10.20	0.00225	0.713056	0.000489	89.80	89.80	89.80	–0.14
2010	19	84.42	15.42	0.00187	0.006415	0.000305	84.57	84.58	84.58	0.00
2011	20	88.66	11.34	0.00001	0.730688	0.000526	88.63	88.65	88.66	0.96
2012	21	99.92	0.00	0.00080	0.351586	0.000384	99.99	99.97	99.99	–0.03
2013	22	81.28	18.71	0.00014	0.388548	0.000397	81.28	81.28	81.27	0.00

available. Given t_i = 2 in 1996 and t_i = 19 in 2013, the statistical data of $E_{AF}(t_i)$, $P_{OF}(t_i)$, m_i, and η_i, the predicted $E_{AF}(n+1)$, $E_{AF}(n+2)$, and $E_{AF}(n+3)$, and the relative error E_r of Unit 1 are tabulated in Table 12. It is found that the relative error of the predicted equivalent availability factor for Unit 1 varies in the range of –1.03% to 2.52%, indicating that the prediction accuracy for equivalent availability factors is high.

8 Conclusions

In this paper, a novel method for reliability prediction of nuclear power units in service is proposed. The equivalent availability factor in the next 3 years can be obtained by using the historical equivalent availability factor $E_{AF}(t_i)$ and planed outage factor $P_{OF}(t_i)$ in the past n years ($n \geqslant 3$) and the planned maintenance days in the next 3 years.

The relative errors of the predicted equivalent availability factors for nuclear power units of NERC are in the range of –2.16% to 5.23%. For the 8 nuclear power units in China, the relative errors vary in the range of –2.15% to 3.71%.

If the predicted value of equivalent availability factor is not up to the required target value, the lower limit of planned maintenance days should be gradually reduced according to the rules of DL/T838 until the predicted equivalent availability factor of the nuclear power unit meet the required reliability target value.

The new reliability prediction method proposed in this paper can effectively predict the equivalent availability factor in the next few years, which is of great importance to nuclear power units in service. By optimizing the planned maintenance days, it can effectively satisfy the predicted equivalent availability factor, thus providing a safe and economic reliability management method for nuclear power units.

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Table 12 Predicted equivalent availability factor E_{AF} of Unit 1 (984 MW)

Year	t_i	$E_{AF}(t_i)$/%	$P_{OF}(t_i)$/%	ρ	m	η	$E_{AF}(n+1)$/%	$E_{AF}(n+2)$/%	$E_{AF}(n+3)$/%	E_r/%
1996	2	76.39	18.32	0.06925						
1997	3	82.71	16.83	0.00556						
1999	5	86.92	12.33	0.00863	1.502274	0.042277				
2000	6	86.24	11.12	0.03061	0.597140	0.030977	88.41			2.52
2001	7	88.46	10.42	0.01266	0.541624	0.030188	88.53	89.24		0.89
2002	8	90.45	9.44	0.00122	1.087922	0.041428	89.54	89.61	90.30	–1.01
2003	9	91.21	8.78	0.00011	1.865413	0.070503	90.77	90.27	90.34	–1.03
2004	10	88.52	11.42	0.00068	1.965047	0.076189	88.45	88.20	87.72	–0.90
2005	11	99.96	0.00	0.00040	2.081454	0.084254	99.90	99.88	99.62	–0.34
2006	12	80.93	18.74	0.00408	1.800109	0.064626	81.20	81.19	81.18	0.34
2007	13	92.13	7.84	0.00033	1.905743	0.071937	92.08	92.11	92.10	–0.05
2008	14	99.85	0.00	0.00150	1.785599	0.063176	99.94	99.93	99.95	0.10
2009	15	91.02	8.04	0.01028	1.472167	0.044161	91.90	91.91	91.90	0.97
2010	16	89.31	10.13	0.00625	1.269033	0.034609	89.79	89.82	89.83	0.58
2011	17	99.70	0.00	0.00301	1.169127	0.030535	99.89	99.92	99.95	0.25
2012	18	85.06	14.76	0.00213	1.112881	0.028376	85.14	85.15	85.18	0.14
2013	19	99.94	0.00	0.00060	1.164764	0.030437	99.88	99.89	99.91	–0.06