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Analytical model for unavailability due to aging failures in power systems

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ABSTRACT

Power system component failures can generally be classified into two categories: repairable random failures and aging failures. An essential step in power system reliability evaluation is the calculation of component unavailability. The paper presents a new model for calculating the unavailability due to aging failures using the normal distribution. It is based on the strictly mathematical derivation and can be used more easily with high accuracy compared to the traditional model. An example of seven generating units and two test systems of the RBTS and the IEEE-RTS were used to demonstrate effectiveness of the proposed model and its applications in power system reliability evaluation.

1. Introduction

Power system component failures are affected by a variety of factors, such as preventive and corrective maintenance practices, designed useful life and variations in operation environment and conditions. These failures can generally be classified into two categories: repairable random failures and non-repairable aging failures (end-of-life) resulting from wear-out [1,2].

Only repairable failures have been considered and aging failures have been excluded in most of power system reliability evaluation methods. Ignoring the aging failures will most likely result in underestimation of power system risk [2–4], particularly for an aged system. In this case, ignorance of aging failures may create a misleading conclusion in the component reliability performance and system risk. Equipment aging has gradually become a major concern in many utilities [2–10]. The aging failures of major system components (such as generating units, transformers, cables and breakers) is a driving factor in system planning of many utilities since more and more system components are approaching their wear-out stage [2,4]. Therefore the aging failure mode of components should be incorporated in reliability evaluation when the components approach to end-of-life.

Several references discussed power system reliability analysis techniques considering aging failures of components. The basic concept of incorporating aging failures in power system reliability evaluation was addressed in Ref. [1]. A method to calculate the unavailability due to aging failures, which can be modeled using either a normal distribution or a Weibull distribution, was proposed in Refs. [3,4]. The model considering aging failures was used to evaluate the reliability of bulk power system and HVDC system [5]. Based on a Bayesian approach applied to a novel Weibull stress–strength probabilistic model, a method for evaluating the reliability of aged electrical components in the presence of overstresses is proposed in Ref. [6]. The cable-failure model taking aging failures into account was presented in Ref. [7] for the reliability calculation of electric distribution systems. The effect of adverse weather and component aging on power system reliability was modeled using time-varying failure rates in Ref. [8]. A Monte Carlo simulation is performed to analyze the impacts of increased component failure rates in the aging period on the distribution system reliability in Ref. [9].

An essential step in power system reliability evaluation considering aging failures is the modeling of component unavailability due to aging failures. The concept of probability of transition to aging failure has been developed long time ago [2]. Unfortunately, this concept cannot be directly used to describe an average probability that a component is found unavailable due to aging failures during a specified time period. As well known, the unavailability due to repairable failures is a basic modeling data in power system reliability evaluation. Hence, the modeling concept of the unavailability due to aging failures must be developed so that it can be combined with the unavailability due to repairable failures in performing power system reliability assessment.

Aging failures are assumed to be non-repairable end-of-life failures in this paper. Therefore an aging failure does not have a

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concept of repair time. If there is a replacement activity for a non-repairable failure, some conventional techniques may be used to evaluate reliability of power systems by treating the replacement time as the traditional repair time. However, it should be appreciated that a replacement is conceptually different from a repair in real life. The time span for an aging failure is much longer than that for a repairable failure. In other wards, it may be difficult to consider both the replacement process for aging failures and the repair process for repairable failures on the same timeframe. The paper presents a novel method for evaluating the unavailability due to aging failures so that both repairable and aging failures can be considered in one single reliability evaluation. The major advantage of the proposed method is that it is a fully analytical model and can be used more easily with higher accuracy compared to the conventional model of aging failure unavailability in a discrete expression [1].

The rest of the paper is organized as follows. The calculation model and analytical formula for the unavailability due to aging failures are presented in Sections 2 and 3, respectively. A method of applying the composite unavailability due to both repairable and aging failures in power system reliability evaluation is briefly summarized in Section 4. The numerical examples are given in Section 5, followed by conclusions in Section 6.

2. Calculation model for unavailability due to aging failures

Assume that T is the age and t is a specified subsequent period to be considered. As shown in Fig. 1, x is an arbitrary time point within T and $T+t$.

According to the definition of reliability function and the conditional probability concept, the probability of transition to aging failure of a component in the interval $[T, T+x]$ after having survived for T years can be calculated by [1,2]

$$P(T,x) = \frac{\int_T^{T+x} f(t)dt}{\int_T^{\infty} f(t)dt} \tag{1}$$

where $f(t)$ is the failure density probability function, which can be represented using a normal or Weibull distribution.

Let

$$Q(x) = \int_x^{+\infty} f(t)dt \tag{2}$$

Eq. (1) can be rewritten as follows

$$P(T,x) = \frac{Q(T) - Q(T+x)}{Q(T)} \tag{3}$$

The probability density function of transition to aging failure of a component at the time point x after having survived for T years can be obtained

$$d(T,x) = \frac{dp(T,x)}{dx} = \frac{f(T+x)}{Q(T)} \tag{4}$$

When a component dies of aging failure at the time point x, the unavailable duration is $(t-x)$. The component can fail at any time point x within the specified period t. Therefore, the expected value of the unavailable duration in the period t is

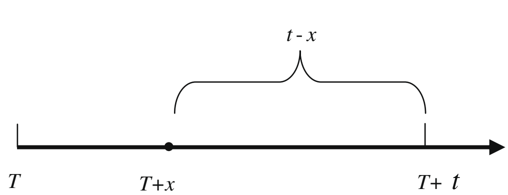

Fig. 1. Aging failure concept.

$$t_{Ua} = \int_0^t d(T,x)(t-x)dx \tag{5}$$

The unavailability due to aging failure is defined as a ratio of the expected value of the unavailable duration with regard to the specified subsequent period (t) given that the component has survived for T years [1]. With this definition and by substituting Eq. (4) into (5), the unavailability due to aging failure of a component in the period t is given by

$$\begin{aligned} U_a &= \frac{t_{Ua}}{t} = \frac{1}{Q(T)}\int_0^t f(T+x)\left(1-\frac{x}{t}\right)dx \\ &= \frac{1}{Q(T)}\int_0^t f(T+x)dx - \frac{1}{Q(T)t}\int_0^t f(T+x)xdx \end{aligned} \tag{6}$$

3. Analytical formulas for the unavailability model

By letting $s = T + x$, and considering the similar derivation from Eq. (1) to Eq. (3), the first term in Eq. (6) can be calculated as follows

$$\frac{\int_0^t f(T+x)dx}{Q(T)} = \frac{1}{Q(T)}\int_T^{T+t} f(s)ds = \frac{Q(T)-Q(T+t)}{Q(T)} \tag{7}$$

As mentioned earlier, a normal or Weibull distribution can be used to represent the failure density probability function for aging failures [1,2]. In this paper, a normal distribution is considered. It can be seen from the following derivation that a similar derivation process can be conducted if a Weibull distribution is assumed as this is only associated with a different expression of the failure density probability function. With the normal distribution, the failure density probability function is given by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) \tag{8}$$

where μ and σ are the mean life and its standard deviation of a component respectively.

Denoting the integral part of the second term in Eq. (6) as $F(T, t)$ and substituting Eq. (8) into it yields

$$F(T,t) = \int_0^t f(T+x)xdx = \int_0^t \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(T+x-\mu)^2}{2\sigma^2}\right]xdx \tag{9}$$

By denoting $x = (T + x-\mu) + (\mu-T)$, Eq. (8) can be rewritten as

$$\begin{aligned} F(T,t) &= \int_0^t \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(T+x-\mu)^2}{2\sigma^2}\right](x-\mu+T)dx \\ &+ \int_0^t \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(T+x-\mu)^2}{2\sigma^2}\right](\mu-T)dx \end{aligned} \tag{10}$$

Using the following substitutions for the first term and second term in Eq. (7)

$$y = T + x - \mu \tag{11}$$

$$z = T + x \tag{12}$$

Eq. (7) is rewritten as

$$\begin{aligned} F(T,t) &= \int_{T-\mu}^{T+t-\mu} \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{y^2}{2\sigma^2}\right]ydy + (\mu-T)\int_T^{T+t}\frac{1}{\sigma\sqrt{2\pi}} \\ &\times \exp\left[-\frac{(z-\mu)^2}{2\sigma^2}\right]dz \end{aligned} \tag{13}$$

It is known from the integral theory that

$$\int \exp\left(\frac{x^2}{a}\right)xdx = \frac{a}{2}\exp\left(\frac{x^2}{a}\right) + C \tag{14}$$