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Impacts of Life Distributions on Reliability Analysis of Smart Substations

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Abstract

Most of the existing reliability analysis is based on exponential distribution which is convenient to calculation, whereas most intelligent electronic devices exhibit Weibull distribution. What kind of influence will life distribution have on the reliability and availability of a smart substation? This paper compares the reliability and availability of systems with different life distributions based on reliability block diagram and Monte-Carlo simulation, by treating the smart substations as non-repairable and repairable systems respectively. Simulation results proves the feasibility of substituting Weibull distribution with exponential distribution in engineering practice when the smart substations are treated as repairable systems, thus the life data estimation as well as the reliability analysis and calculation will be greatly simplified.

Keywords: *life distribution, reliability, availability, smart substation.*

1. Introduction

China has become one of the most experienced countries in the practice of smart substations. Over 500 smart substations have been constructed in recent years, and at least 5000 more will be constructed during “the Twelfth Five Years”. As the fundamental criteria for the implementation of smart substations are high reliability and availability, hence reliability analysis on the smart substations is necessary [1]. Determining the life data and life distributions of the components in the smart substation is an essential prerequisite for reliability analysis. The most commonly used life distribution models include exponential distribution and Weibull distribution. According to the bathtub curve, new type of IEDs (Intelligent Electronic Devices) should be at the start of the bathtub curve while conventional IEDs should be at the end of the bathtub curve considering the device aging [2]. Therefore, from theoretical point of view, when analyzing the reliability and availability of smart substations, Weibull distribution is recommended to be utilized. However, two problems appear during the analyzing process.

First, from the perspective of life estimation, two parameters need to be estimated when it comes to using Weibull distribution. For the lack of life data that can be collected, life estimation would be much simpler if either of the two parameters can be left out.

Second, from the perspective of reliability and availability analysis, IEDs like protective relays belong to repairable systems in which the Markov model is an efficient approach to reliability analysis. Unfortunately, the precondition of adopting the Markov model is that the system exhibits exponential distribution.

Taking the above two problems into consideration synthetically, how much error will be brought if exponential distribution is adopted while the genuine distribution of a component is Weibull distribution?

By combining reliability block diagram and Monte-Carlo simulation, this paper compares the system reliability and availability of both the non-digital and digital smart substations with different life distributions and proves the feasibility of substituting Weibull distribution with exponential distribution in engineering practice.

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2. Architectures of Smart Substations

The common feature of smart substations is that their station level buses are compliant with the IEC 61850 standard [3]. However, significant differences exist on the process level. According to whether digitalization is implemented on the process level, smart substations can be divided into two categories, i.e. non-digital smart substations and all-digital smart substations. Taking the protection system as an example, the structures of the two categories of smart substations are illustrated below.

2.1. Non-digital Smart Substations

The feature of a non-digital smart substation is that sampling and tripping signals will be transmitted by electric cables and the transmitted signals are analog. The architecture of a typical power transformer bay in a 110kV substation is shown in Figure 1. Note that the redundancy for the protection system is omitted for the sake of figure concision.

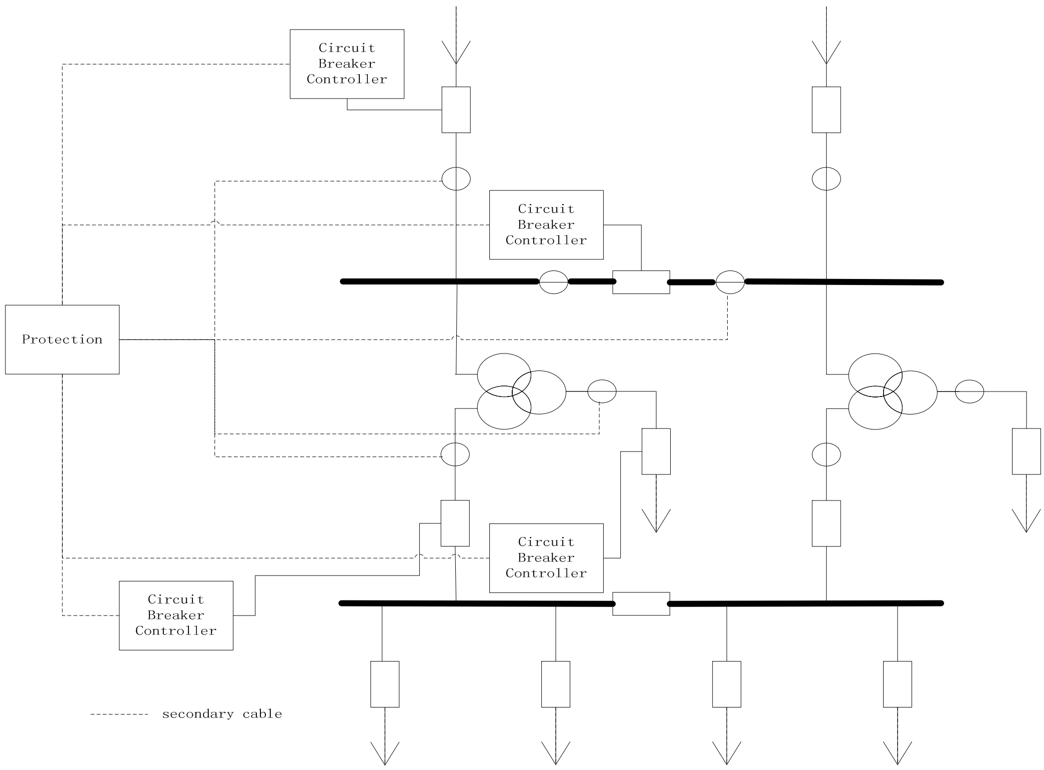

Figure 1. System Architecture of a Non-Digital Smart Substation

2.2. All-Digital Smart Substations

In an all-digital smart substation, the electrical cables on the process level are replaced by optical fibres. The protection system thus become so called all-digital protection system, which is composed of nonconventional instrument transducers, merging units (MU), circuit breaker controllers (CBCTR), Ethernet switches (SW), Ethernet communication media (EM), external time sources(TS) and protective relay(PR) [4]. The sampled values assembled by the merging units are transmitted to the IEC 61850-9-2 [3] process buses, and the tripping commands are published through Genric Object-oriented Substation Events (GOOSE) [3]. Because of the LAN-based feature of the ADPS, it is possible to design numerous alternative architectures to meet different requirements.

For comparison purpose, this paper merely considers the commonly used system architecture in China known as “point-to-point fibre connection” which is similar to the non-digital smart substation in topology. The key point of the architecture is that the Ethernet switches will not be involved in the process bus, thus the precise time synchronization between the merging units can be achieved via resampling technology rather than external time sources. The architecture of a similar power transformer bay is shown in Figure 2. Note again that the redundancy for the protection system is not shown in the figure for the same purpose.

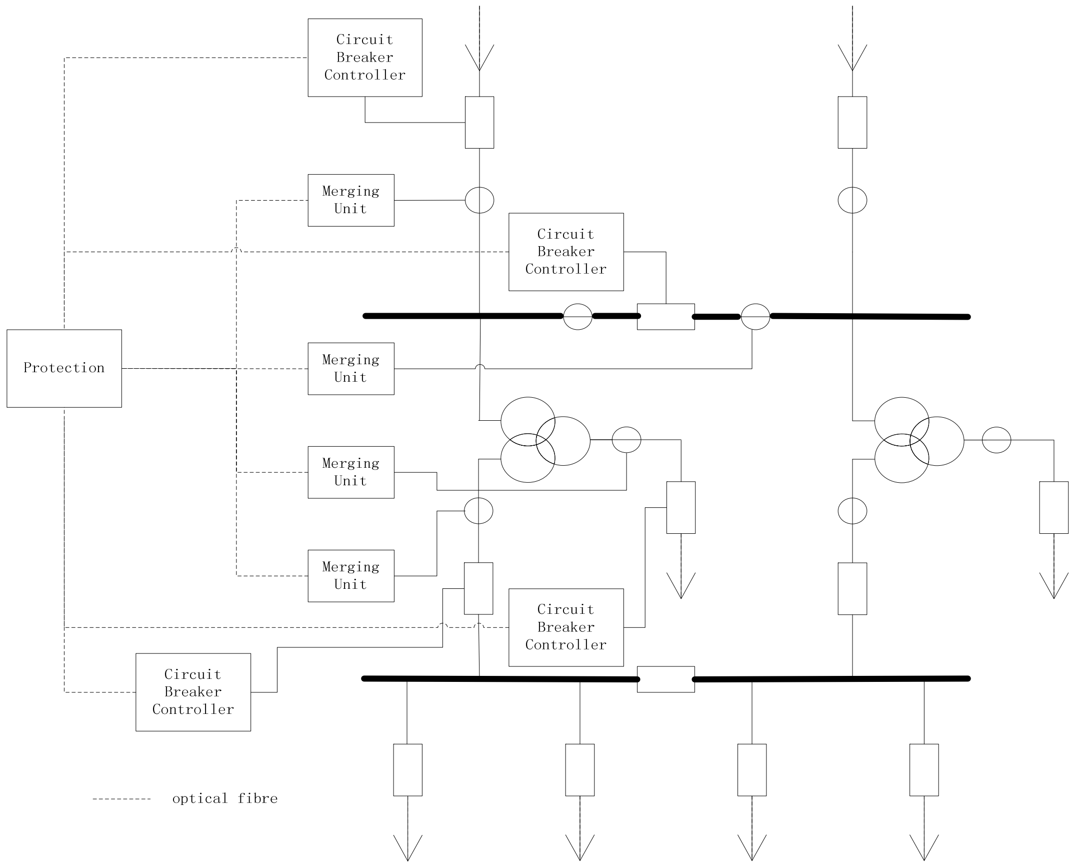

Figure 2. System Architecture of Point-To-Point Smart Substations

3. Life Distributions

3.1. Exponential Distribution.

The exponential distribution is commonly used for components or systems with a constant failure rate. Due to its simplicity, it has been widely employed, even in cases where it doesn't apply.

In its most general case, the probability density function of the 2-parameter exponential distribution is defined by:

$$f(t) = \lambda e^{-\lambda(t-\gamma)}, t \geq 0, \lambda > 0 \quad (1)$$

Where λ is the constant failure rate in failures per unit of measurement and γ is the location parameter. In addition, $\frac{1}{\lambda} = MTTF - \gamma$, where MTTF indicates the mean time to failure.

By setting $\gamma = 0$, the distribution becomes the 1-parameter exponential distribution shown as follows:

$$f(t) = \lambda e^{-\lambda t}, t \geq 0, \lambda > 0 \quad (2)$$

3.2. Weibull Distribution.

The Weibull distribution is a general purpose reliability distribution used to model material strength, times-to-failure of electronic and mechanical components, equipment or systems.

In its most general case, the probability density function of the 3-parameter Weibull distribution is defined by:

$$f(t)=\frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}e^{-(\frac{t-\gamma}{\eta})^{\beta}},t\geq 0,\beta>0,\eta>0 \quad (3)$$

Where β is the shape parameter, η is the scale parameter, γ is the location parameter.

By setting $\gamma=0$, the distribution becomes the 2-parameter Weibull distribution shown as follows:

$$f(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}e^{-(\frac{t}{\eta})^{\beta}},t\geq 0,\beta>0,\eta>0 \quad (4)$$

3.3. Problem of Small Samples in Reliability Parameter Estimation

As the protection system has a very high level of reliability, system failure events fairly happen, thus the system has typical characteristic of small samples which will result in difficulty with parameter estimation. The parameter estimation problem for Weibull distribution is more difficult than that for exponential distribution, as there are more parameters to be estimated for the former [6]. In order to resolve the problem, researchers have proposed Bayes-Weibull parameter estimation by using apriori knowledge of life parameter or shape parameter to reduce the number of parameters to be estimated. Nevertheless, the apriori knowledge is equally difficult to obtain, and the accuracy of parameter estimation may be even worth when the apriori knowledge is not reliable.

The problem to be solved in this study is: if the exponential distribution is adopted while the life distribution of the devices is Weibull distribution indeed, how much impact will be brought with regard to the analysis of system reliability? In other word, is there any sense via simplifying Weibull distribution to exponential distribution? If such kind of simplification does not have an obvious bad effect on the accuracy of reliability analysis, the difficulty in estimating parameters will be decreased by such kind of simplification evidently. Further, the Markov chain approach that accepts only exponential distribution can be applied in reliability analysis of smart substations and get accuracy results.

To analyze the problem above, the following analysis method is applied:

1. Considering the smart substation protection system as a non-repairable system and a repairable system respectively, analyze the system from the perspective of reliability and availability.

2. Making the shape parameter of Weibull distribution range from 0.5 to 1.5 with a step of 0.1, analyze the system reliability and availability. Known from Equation (4), when the shape parameter equals to 1, the 2-parameter Weibull distribution is simplified to the 1-parameter exponential distribution by coincidence. Therefore, there is no need to discuss the exponential distribution separately. When the shape parameter is smaller than 1, the start of the bathtub curve can be simulated to express new IEDs such as all-digital protections. On the opposite, when the shape parameter is larger than 1, the end of the bathtub curve can be simulated to express conventional IEDs.

3. The reliability block diagram (RBD) and Monte-Carlo simulation methods are employed for reliability analysis when considering the smart substation as non-repairable and repairable systems respectively.

4. Simulation Method

4.1. Non-repairable System

A reliability block diagram is a success-oriented network describing the function of the system. It shows the logical connections of components needed to fulfill a specified system function. If the system has more than one function, each function must be considered individually, and a separate reliability block diagram has to be established for each system function [5].

Having established the reliability block diagrams, the minimal path sets method can be used to calculate the exact system reliability. For a given architecture, when all the minimal path sets $P_1, P_2, \ldots, P_p$ are determined, the structure function may be written as:

$$\Phi(X) = \prod_{j=1}^{p} \prod_{i \in P_j} X_i \tag{5}$$

The structure function is thus written as a multi-linear form. $\Phi(X)$ is then expanded, and all exponents should be omitted since $X_i, i = 1, 2, \ldots, n$ are binary. The system reliability $R_{sys}(t)$ is obtained by replacing all the X_i's in the structure function by the corresponding p_i's, where p_i is the reliability of component i. If component i has a constant failure rate λ_i:

$$p_i(t) = e^{-\lambda_i t} \tag{6}$$

The Mean Time To Failure (MTTF) is then defined as

$$MTTF = \int_0^{\infty} R_{sys}(t)\,dt \tag{7}$$

Reliability block diagrams are suitable for systems with non-repairable components and where the order in which failures occur does not matter.

4.2. Repairable System

4.2.1. Maintenance Strategy

Maintenance strategies may be classified in many different ways. Some of the most common designations include preventive maintenance (PM), corrective maintenance (CM) and failure-finding maintenance [7-8]. PM tasks can be classified into four categories, i.e. age-based maintenance, clock-based maintenance, condition-based maintenance, and opportunity maintenance. As the clock-based maintenance is the most common practice for today's substations, it is selected as the maintenance strategy in our study.

4.2.2. Monte-Carlo Simulation

Monte-Carlo simulation is a technique in which the failures and repairs of a system are simulated by the use of random number generators [9]. For large systems with a huge state space, Monte-Carlo simulation is a more practical and efficient approach in contrast to the traditional analysis methods such as Markov chain [10]. Moreover, the Monte-Carlo simulation can accept any kinds of life distributions. As a result, it is selected as the simulation method in our study.

Suppose $F_T(t)$ is the distribution function of random variable T. If $F_T(t)$ is a monotone increasing function, $F_T^{-1}(y)$ is ascertained singly for all $y \in (0,1)$. Set $Y = F_T(t)$, the distribution function of random variable Y is [5]:

$$\begin{aligned} F_Y(y) &= \Pr(Y \le y) = \Pr[F_T(T) \le y] \\ &= \Pr[T \le F_T^{-1}(y)] \\ &= F_T[F_T^{-1}(y)] = y, 0 < y < 1 \end{aligned} \tag{8}$$

Evidently, if random variable Y exhibits the uniform distribution on $(0,1)$, $T = F_T^{-1}(y)$ will has a distribution function illustrated by $F_T(t)$.

Base on the above principle, we propose a Monte-Carlo simulation method, the flow chart of which is shown as follows:

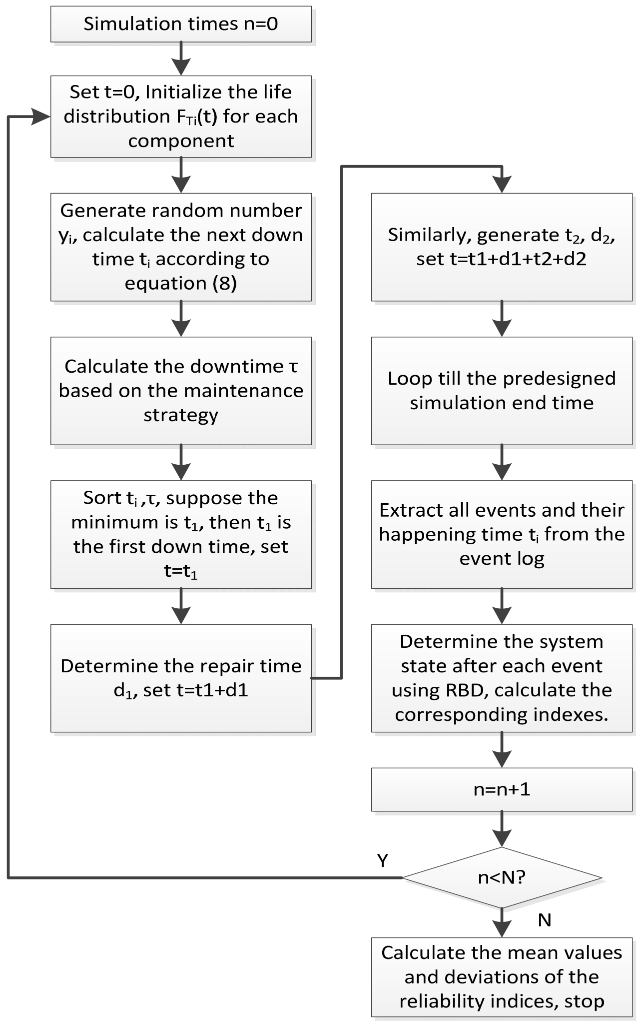

Figure 3. Flow Chart of Monte-Carlo Simulation

Other benefits of Monte-Carlo simulation are listed as follows [11]:
1) Outputs provide more information than deterministic point estimate calculations,
2) The accuracy of the results can be increased by running more trials,
3) Random selection process is repeated many times which can imitate system behavior in the field.

5. Case Study

Reliability parameters are the fundamental of reliability analysis [12]. The specific parameter settings are adopted for the components in Figure 1 and Figure 2 as shown in Table 1, correspondingly analysis and simulation based on the settings are done in the study. Please note the Ethernet media in this paper refers to communication port and optical fibre. The life cycle reliability of optical fibre is evaluated in [13].

Table 1. Parameter Settings of the Components

Component	Failure Rate(times per year)
Protective Relay	0.01
Merging Unit	0.01
Circuit Breaker Controller	0.01
Ethernet Media	0.0033
Instrument Transducer	0.005~0.2

For the purpose of comparison, merging units and protective relays exhibit the 2-parameter Weibull distribution with the scale parameter equaling to 0.01 and the shape parameter ranging from 0.5 to 1.5 with a step of 0.1.

5.1. Reliability Study

For the non-repairable case, analysis based on reliability block diagram can be done directly and the result concerning MTTF is shown as follows:

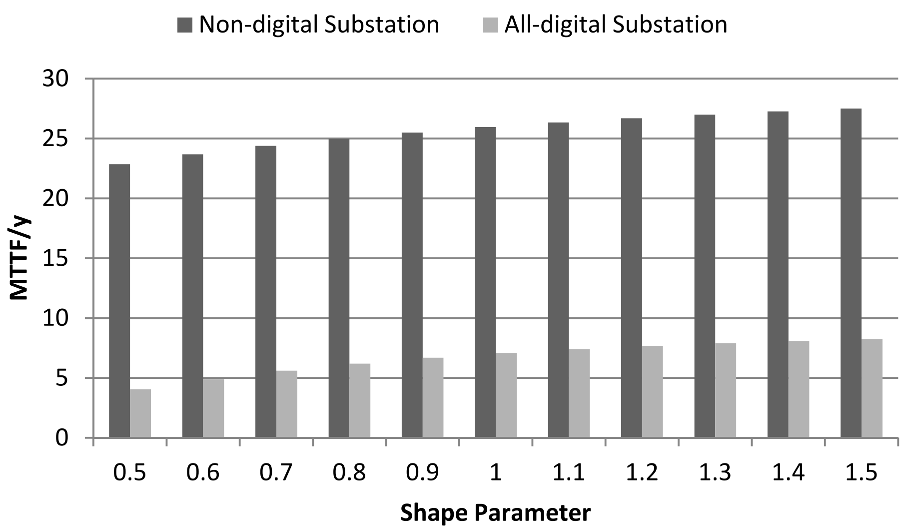

Figure 4. Mean Time to Failure of the Non-Repairable Case

Via comparing the data in Figure 4, it is obvious that MTTF is positively correlated with the shape parameter both in the conventional and smart substation, whereas the difference is not too much and the MTTF data can be considered roughly in the same level.

5.2 Availability Study

For the repairable case, we consider clock based maintenance with an interval of two year, assuming that all components will be repaired as new and the downtime is a workday. Monte-Carlo simulation is executed 1000 times with an interval of 10 days between every two adjacent points. The results concerning mean time to first failure (MTTFF) and system availability are shown as follows:

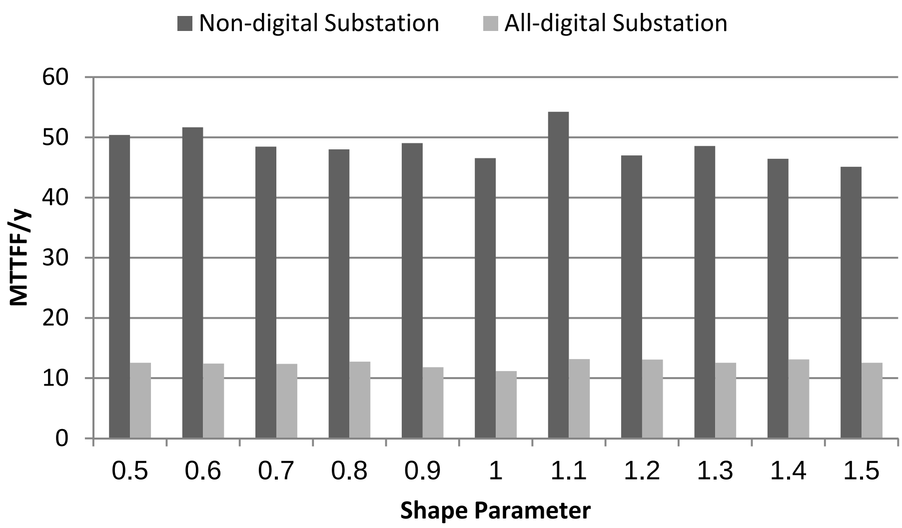

Figure 5. Mean Time to First Failure of he Repairable Case

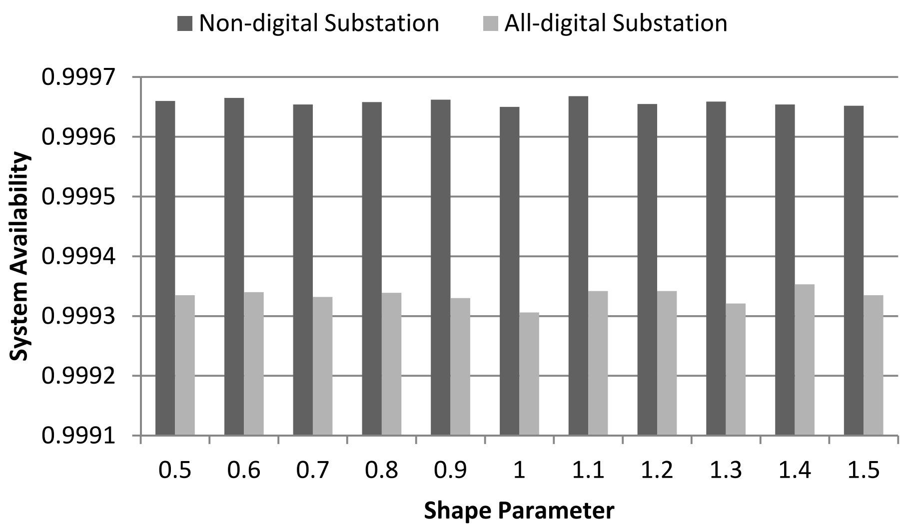

Figure 6. System Availability of the Repairable Case

Via comparing the data in the above two figures, it can be seen that unlike the non-repairable case there are no obvious correlations between the shape parameter and the reliability indices. It can also be observed that the difference brought by applying different life distributions is even less than that in the non-repairable case.

6. Summary

The following conclusions are made based on the simulation results:

1) If smart substations are treated as non-repairable systems, utilizing Weibull distribution and exponential distribution will have some difference on the analyzing result of reliability. Analysis indicates that, system reliability is positively correlated with the shape parameter.

2) If smart substations are treated as repairable systems, the correlation between life distribution and system reliability is weak. As a result, although the Weibull distribution is

theoretically more accurate, the exponential distribution can be used to substitute Weibull distribution with regard to the repairable smart substation system in engineering practice. Furthermore, it's feasible to use exponential distribution in parameter estimation as well.

3) It is shown in [10] that, if an all-digital protection system is indeed repairable but is modeled in a non-repairable manner for analysis, the calculated values for the MTTF and the MTTFF could be grossly different. A smart substation is a typical repairable system, it's not suitable to treat it as a non-repairable system. The error brought by the non-repairable assumption might be far more severe than that brought by inaccurate parameter estimation.

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