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Comprehensive Evaluation of Reliability of Protection System in Smart Substation

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Abstract

The reliability of smart substations has a great significance on the safety and stability of smart grid operation. Taking the protection system in smart substation as an example, this paper constructs comprehensive reliability models to evaluate the reliability of smart substations with different architectures. The paper first illustrates two important aspects which affect the reliability of the protection system, namely the network architecture and the maintenance strategy. To satisfy these two aspects, the paper then adopt the Monte Carlo simulation combined with the Reliability Block Diagram method to make quantitative reliability analysis. At last, reliability of four power transformer protection systems applying different maintenance strategies with alternative architectures are evaluated. The simulation results show clearly that advanced maintenance strategies such as conditional maintenance will play a critical role in enhancing the reliability and availability of smart substation.

Keywords: *smart substation, protection, reliability, Monte-Carlo simulation, condition-based maintenance*

1. Introduction

China has become the country to put the largest number of smart substations into operation. New technologies such as Gigabit Ethernet communication, synchronized sampling with microsecond accuracy, nonconventional transducers are widely used in smart substations. These new technologies bring tremendous changes to smart substation, whereas the reliability issue has also aroused widespread concern at the same time.

Smart substation reliability should be analyzed from two aspects. The first aspect is the network architecture of the system. Because of the LAN-based feature of the smart substations, a variety of architectures have been designed to meet deifferent requirements in practice. The key difference in the alternative architectures is that whether the network architecture depends on Ethernet switches. Existing reliability analyses are all focused on a particular network architecture [1-3], therefore there is a lack of horizontal comparison of different network architectures.

The second aspect is the maintenance strategy of the system. A smart substation system is a repairable system and the maintenance strategy applied has a great impact on system reliability. Currently the periodic maintenance strategy is widely used for the power system. More advanced maintenance strategies such as conditional maintenance have been studied in recent years. Compared to conventional substations, the system architectures of smart substations become more complex which adversely affect the system reliability. However, the possibility to apply more advanced maintenance strategies in smart substations will definitely compensate the shortcomings in terms of structural complexity, correspondingly their reliability may reach or even exceed that of conventional substations. Existing reliability studies either simplify smart substation systems to non-repairable systems [1-3], or merely consider periodic maintenance strategy [4-5]. The study which considers and compares different maintenance strategies for the smart substations is still limited.

To satisfy these two aspects of reliability analysis, reliability simulation method needs to be studied. The simulation method has to adapt to the complexity of the system structure of smart substations, and handle various maintenance strategies. Among the existing studies, reliability block diagram (RBD) [1-3] and fault tree analysis [6] methods have been widely used, but these methods are only suitable for non-repairable systems. For repairable systems, Markov

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state space [7] method is widely used. However, due to the structural complexity of smart substations, applying this method is prone to leading to state space explosion problem which decreases the availability of the method.

Focusing on the protection system in smart substation, this paper analyzes and compares the reliability and availability of smart substations with typical alternative network architectures and different maintenance strategies. In order to meet the analytical requirements of smart substations, RBD method and Monte-Carlo simulation are combined to form a practical approach. The effectiveness of the approach is demonstrated by detailed examples, and the reliability of different protection systems are evaluated comprehansively.

2. Alternative Architectures of Smart Substations

The network of smart substations consists of substation-level network and process-level network. As the process-level network is responsible for the transmission of sampling values and tripping signals which are of critical importance to protection function, this paper only discusses the network architecture of process level. According to the practices in China, this paper discusses the following alternative network architectures [8]:

1) "Network-sampling-network-tripping". The sampling value (SV) [9] and the Generic Object Oriented Substation Events (GOOSE) are both transmitted through the Ethernet switches. This architecture is consistent with the IEC 61850 standard and has the simplest network structure, but its reliability has always been questioned as it relies on Ethernet switches and external time source required for synchronized sampling.

2) "Direct-sampling-network-tripping". The optical fibers of SV use point-to-point connections, while the transmission of GOOSE still depends on Ethernet switches. In this architecture, the voltage and current signals from different merging units are time aligned via resampling technology thus eliminating the dependence on external time source.

3) "Direct-sampling-direct-tripping". This architecture is similar to that of conventional substations except for the electrical cables are replaced by optical fibers. This architecture eliminates the need for Ethernet switches and external time source, at the expense of sacrificing the simplicity of network.

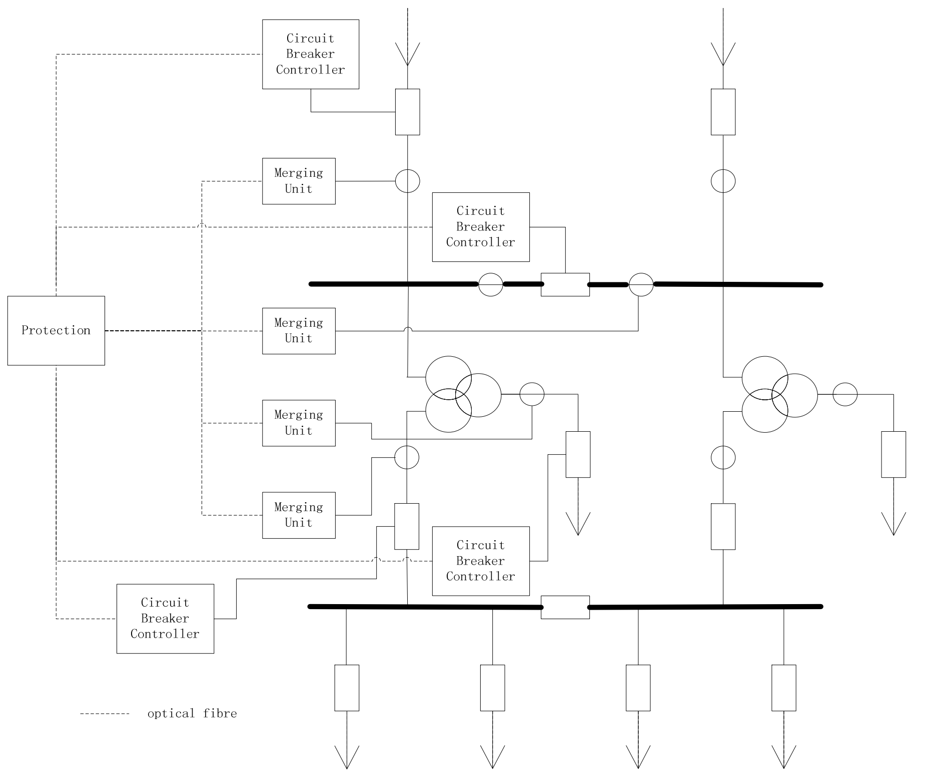


Figure 1. Structure Diagram of a Power Transformer Protection System

In order to carry out a horizontal contrast with conventional substations, this paper takes conventional substations as the baseline for comparison. Later in this paper, a typical transformer protection system in a 110kV smart substation is used as an example. The system structure while adopting "direct-sampling-direct-tripping" is shown in Figure 1.

3. Maintenance Strategies for Smart Substations

3.1. Primary Maintenance Methods

The following primary maintenance methods [10] may be applied in smart substations:

1) Operational inspection. It includes inspections conducted by both maintenance crew and online monitoring system.

2) Corrective maintenance (CM). It is also known as repair after failure. Since the system has already failed when executing the maintenance task, this method may seriously threaten the safety of devices and maintenance personnel.

3) Time-based maintenance. It schedules maintenance program based on time which belongs to preventive maintenance (PM). Such maintenance method requires optimized maintenance cycle, otherwise it will lead to either a lack of maintenance or repair surplus.

4) Condition-based maintenance (CBM). Based on condition monitoring and fault diagnosis of device, this method arranges maintenance tasks before device failure by analyzing device status and developing trend. This maintenance method requires that the degradation of device function is detectable, and there is a definable potential failure condition.

Comparisions of the above maintenance methods are shown in Table 1. Note that in this paper outages caused by time-based and condition-based maintenance are called planned outages, while outages caused by corrective maintenance are called unplanned ones.

Table 1. Comparisons of the Primary Maintenance Methods

Item	Inspection	CM	PM	CBM
Will cause component failure?	N	Y	Y	Y
Will cause unplanned system outage?	N	Y	N	N
Will cause planned system outage?	N	N	Y	Y

3.2. Maintenance Strategies

Through combination of the above primary maintenance methods, two maintenance strategies called periodic maintenance and conditional maintenance are constituted, as shown in Table 2. For example, the periodic maintenance strategy uses inspection and time-based maintenance methods; as these methods cannot guarantee exploring all faults of devices, the periodic maintenance strategy needs to include corrective maintenance method as well.

Table 2. Maintenance Strategies for Smart Substations

Strategy \ Method	Inspection	CM	PM	CBM
Periodic maintenance	√	√	√	
Conditional maintenance	√	√		√

4. Reliability Analysis Method

In order to cope with the complex system structure of smart substations and consider various maintenance strategies, this paper combines the RBD and Monte-Carlo simulation methods to constitute a practical reliability simulation method.

4.1. Reliability Block Diagram

The RBD method can describe the logical connections among all the components to perform specific system functions. It is suitable for systems where components are failure independent and non-repairable [11].

Suppose $P_1, P_2, \ldots, P_p$ are the minimal path sets of the system, X_i is the state variable of the i-th component in the system. As the whole system is connected by the minimal path sets in parallel, the structure function of the system is [11]:

$$\Phi(\boldsymbol{X}) = 1 - \prod_{j=1}^{p} (1 - \Phi_{P_j}(\boldsymbol{X})) \quad (1)$$

Assume the failure time of all the components exhibits exponential distribution, then for any component, the reliability function is:

$$R_i(t) = p_i(t) = e^{-\lambda_i t} \quad (2)$$

Replacing the corresponding state variable X_i in equation (1) with the reliability function p_i of each component, the system reliability function $R_{sys}(t)$ is obtained.

4.2. Monte-Carlo Simulation

Suppose $F_T(t)$ is the distribution function of random variable T. If $F_T(t)$ is a monotonically increasing function, then for all $y \in (0,1)$, $F_T^{-1}(y)$ is uniquely determined. Let $Y = F_T(T)$, then the distribution function of random variable Y is [11]:

$$\begin{aligned} F_Y(y) &= \Pr(Y \le y) = \Pr[F_T(T) \le y] \\ &= \Pr[T \le F_T^{-1}(y)] \\ &= F_T[F_T^{-1}(y)] = y, 0 < y < 1 \end{aligned} \quad (3)$$

Clearly, if random variable Y exhibits the uniform distribution on $(0,1)$, $T = F_T^{-1}(Y)$ will have the distribution function $F_T(t)$.

According to the above principle, the Monte-Carlo simulation method can be used to calculate the reliability of the protection systems by using repeated statistical experiment and the system structure function defined in (1). The process is illustrated in more details in [12]. For complex systems like smart substations, Monte-Carlo simulation is a more practical and efficient approach in contrast to the traditional analysis methods such as Markov chain.

5. Case Study

5.1. Reliability Parameters

In view of the lack of long-term statistics of reliability parameters of components in smart substation, this paper adopts the following hypotheses:

1) The failure and repair rates of all components exhibit exponential distribution.

2) The reliability of protection IED in smart substation should not be lower than that of conventional substation. The new protection IED in smart substation replaces the transformer input (analogue) modules by SV modules, and replace the input/output (binary) modules by GOOSE modules, therefore the reliability parameters can and should be close to that of conventional protection. According to [13], this paper set the failure rate to 0.01/y.

3) The reliability of merging units, circuit breaker IED, Ethernet switches and synchronization clock should not be less than that of protection IED.

4) Communication media contains optical fiber and optical transceiver. The protection and merging unit need less optical transceivers to transmit SV and GOOSE for network architecture using Ethernet switch than those using point-to-point fiber connection. Considering the fact that the more optical transceivers in the same IED, the higher temperature of the

GOOSE/SV module, and the higher bit error rate, the failure rate of communication media is set to 0.0033/y [14-15] when using Ethernet switch, and 0.005/y for point-to-point connection.

5) As the reliability of nonconventional transducer is still low now, the failure rate is set to twice that of protection IED. On the contrary, as the conventional transducer is mature enough, its failure rate is set to half of protection IED.

6) For condition-based maintenance, the inspection period is set to one month [16]. It is assumed that if the residual life of a component is less than 50%, the potential failure can be detected by inspection and perfect repair will be performed.

Detailed parameter settings for the reliability analysis are shown in Table 3.

Table 3. Parameters for Reliability Analysis

Component Parameter		μ/d^{-1}	System Parameter	
Component	λ/y^{-1}			
Protection IED	0.01	0.5	PM Cycle	2 years
Merging Unit	0.01		CBM Inspection Cycle	1 month
Circuit Breaker IED	0.01		P-F Residual Life	50%
Synchronization Clock	0.01		Repair Degree	100%
Ethernet Switch	0.01		Simulation End Time	10 years
Communication Media	0.0033		Number of Simulations	1000
Instrument Transducer	0.005~0.02			

For convenience, case 1-4 are defined for different architectures as shown below:
Case 1: Conventional substation,
Case 2: Smart substation with direct-sampling-direct-tripping architecture,
Case 3: Smart substation with direct-sampling-network-tripping architecture,
Case 4: Smart substation with network-sampling-network-tripping architecture.

5.2. Reliability Calculation for Non-repairable Systems

Assuming that the protection system in the smart substation is non-repairable, reliability indexes can be calculated directly by using the RBD method. For different network architectures, the system reliability and MTTF are shown in Figure 2 and Figure 3 respectively.

Figure 2 and Figure 3 show that, the reliability of the protection system in conventional substation (case 1) is significantly higher than those in smart substations (case 2-4). For those in smart substations, the direct-sampling-direct-tripping architecture (case2) has the highest reliability and the network-sampling-network-tripping architecture (case4) has the lowest reliability.

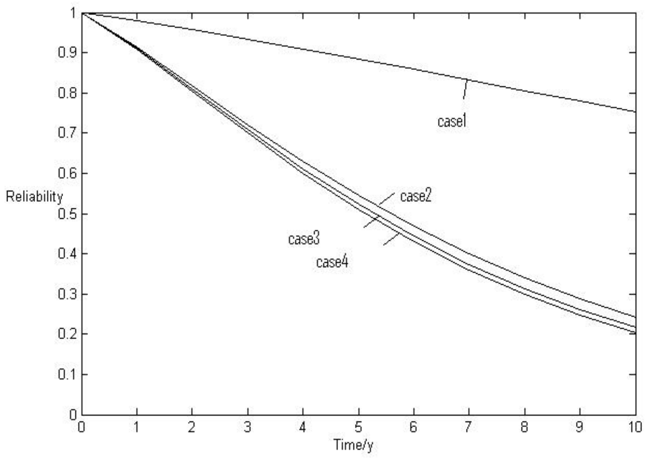


Figure 2. Reliability for Non-repairable Systems

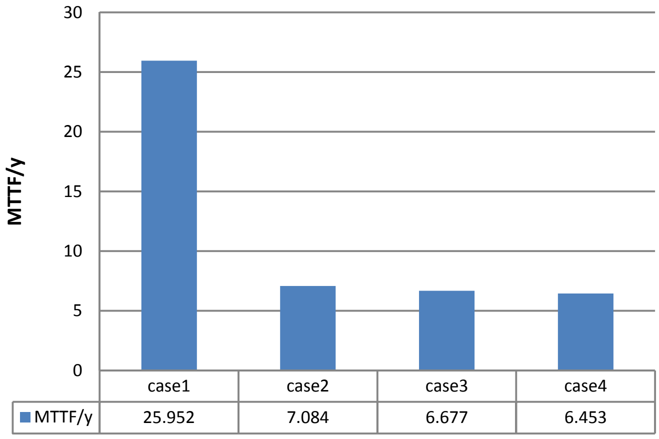


Figure 3. MTTF for Non-repairable Systems

The above results seem to indicate that, the reliability of protection system in smart substation can hardly reach the level of the conventional one. But in fact, the RBD analysis method has the following defects: (1) the self-test capability of optical fiber cannot be expressed in the model, (2) advanced maintenance strategies such as CBM cannot be simulated. In order to fully reflect the advantages of smart substations, and get a more objective result, reliability analysis for repairable system needs to be done.

5.3. Availability Calculation for Repairable Systems

Monte-Carlo simulation is adopted to calculate the avaiability for repairable systems. In this part of analysis, two maintenance strategies listed in Table 2 are considered for the three network architectures (case 2-4). As for the conventional one (case 1), only periodic maintenance strategy is considered for reference use.

a) MTTFF

MTTFF indicates mean time to first failure of repairable systems. The system MTTFFs for various systems are shown in Figure 4.

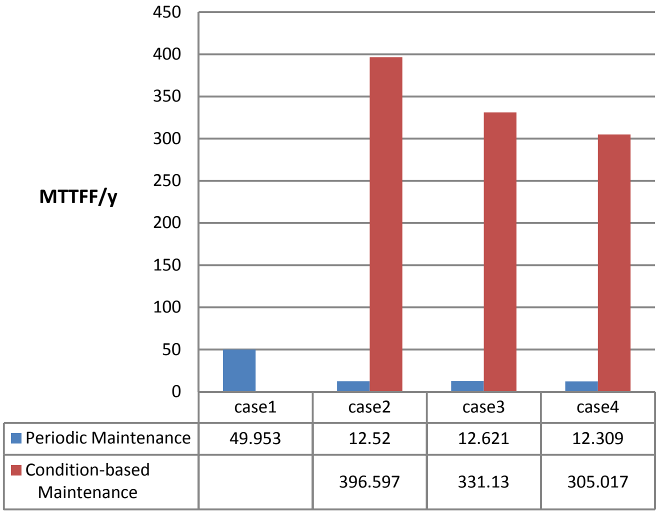
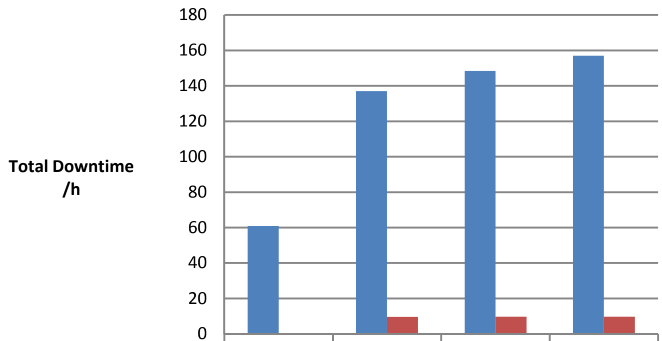


Figure 4. Mean Time to First Failure

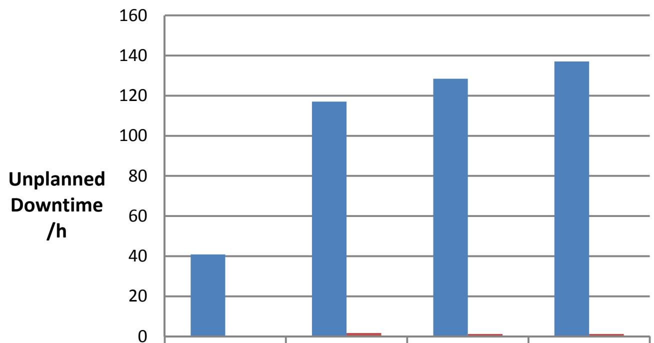
b) Total downtime

The total downtime T_{Down} shown in Figure 5 measures the loss brought by system failure. T_{Down} is made up of planned downtime and unplanned downtime. As the unplanned outage caused by corrective maintenance has a more serious impact, the unplanned downtime $T_{CM_{Down}}$ is used in this paper to indicate the loss of utility brought by unplanned outages.



	case1	case2	case3	case4
Periodic Maintenance	60.886	137.042	148.413	157.025
Condition-based Maintenance		9.613	9.718	9.718

(a) Considering all events, T_{Down}



	case1	case2	case3	case4
Periodic Maintenance	40.896	117.072	128.448	137.031
Condition-based Maintenance		1.728	1.248	1.248

(b) Considering unplanned outages only, $T_{CM_{Down}}$

Figure 5. Total Downtime

c) Availability

When considering all the failure events, availability is defined as:

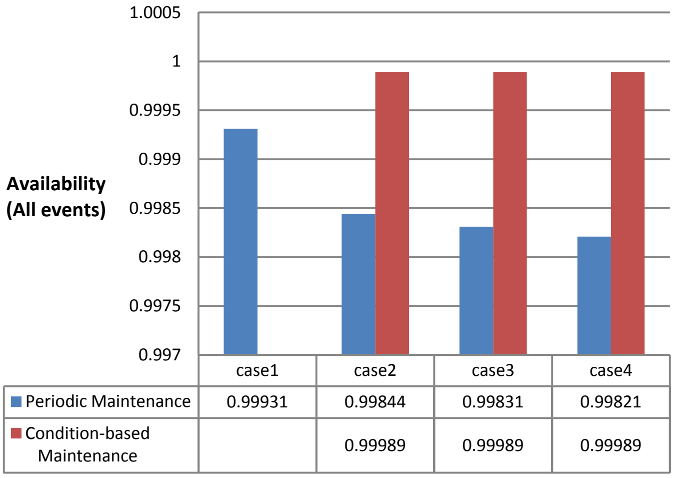
$$A = (T - T_{Down}) / T \quad (4)$$

Where T is the total simulation time, i.e., 10 years in this paper.

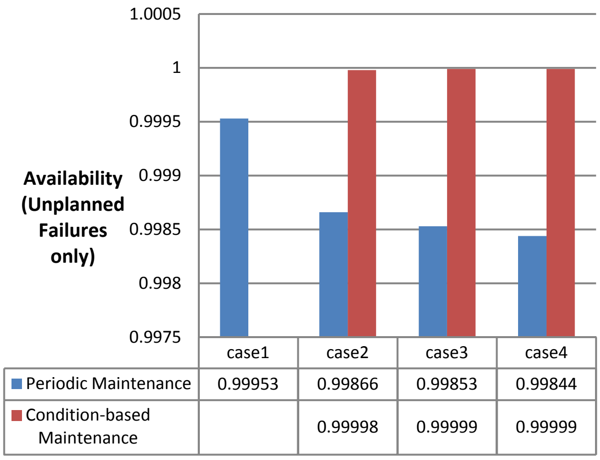
When considering only the unplanned outage events, it is defined as:

$$A = (T - T_{CM_{Down}}) / T \quad (5)$$

The results of availability are shown in Figure 6.



(a) Considering all events



(b) Considering unplanned outages only

Figure 6. System Availability

d). Discussions

Via analyzing Figs. 4~6, it can be concluded that:

1) Maintenance strategy has great impact on system availability. While adopting periodic maintenance, reliability of protection system in smart substation is obviously lower than that in the conventional substation. On the contrary, while adopting conditional maintenance, the availability of protection system in smart substation is generally higher than that of the conventional protection system. This shows that, applying conditional maintenance is the primary method to enhance the reliability of smart substations.

2) When applying periodic maintenance, case2 among different network architectures has the highest availability and case4 is the worst, whereas after applying conditional maintenance, the differences are very little, which implies applying advanced maintenance strategy plays a more critical role than using different network architectures in enhancing the system availability.

3) The key reason why conditional maintenance is able to greatly improve system availability is that it can significantly reduce the probability of unplanned outages and reduce unnecessary planned outages. The fact that MTTFF is greatly improved also owes much to conditional maintenance which can detect potential failures before functional failures, thereby reducing the probability of unplanned outages.

6. Summary

The following conclusions are made based on the simulation results:

(1) While using periodic maintenance strategy, the adopted network architecture significantly affect the availability of the protection system in smart substation. Among different network architectures, the direct-sampling-direct-tripping architecture has the highest availability and the network-sampling-network-tripping architecture is the worst. The results also show that the availabiltiy of the protection system in smart substation is lower than that of the conventional protection system no matter which network architecture is adopted.

(2) Conditional maintenance strategy can greatly improve the availability of the protection system in smart substation. Applying advanced maintenance strategies is more important than adopting optimized network architectures with regard to enhancing the system availability, and improving maintenance strategy is the primary approach to making the availability of the protection system in smart substation exceed that of conventional protection system.

(3) Combination of Monte Carlo simulation and the RBD method can easily consider various maintenance methods, and overcome the state space explosion problem faced when using other methods as Markov chain, thus making it an practical way to analyze the reliability of smart substaions.

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