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Article

Reliability Analysis Models for Differential Protection Considering Communication Delays and Errors

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Abstract: This paper proposes three probability models to assess the impact of communication delays and bit errors on differential protection. First, the mechanism of relay protection malfunction caused by communication delays and bit errors is introduced. In general, a channel's consistent delay or bit error results in refuse-operations, while a channel's inconsistent delay normally causes false trips. Based on the analysis of the probability distributions of communication delays and bit errors, probabilistic models of false trips and refuse-operations are proposed. Simulation results, using typical parameters, are implemented to investigate the effects of communications on the malfunction probability of differential protection.

Keywords: communication delay; bit error; current differential protection; false trip; refuse-operation; probability

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1. Introduction

Electrical transmission systems are continuously evolving and growing larger. Moreover, the systems are now being operated closer to their limits more frequently and as a result power systems today are more vulnerable to disturbances than ever before. In order to enhance the reliability and security of bulk power transmission, protections are commonly utilized in modern high voltage transmission networks for fault detection/location.

Conventionally, *current differential protection* is one of the commonly used techniques in the protection of transmission lines [1–4]. In principle, differential protection is heavily dependent on the quality of the communication system. It uses the signals from both ends of the protected component, which need to be transmitted through communication channels, to locate faults. Thus, when differential protection is used to protect transmission lines, a number of communication problems due to the impact of the external environment, equipment operating conditions or other factors, could cause performance degradation. At 50 Hz an uncompensated communication delay of 1 ms will translate into an error of approximately 13 degrees in the phase angle computation [5]. Any protection performance degradation may threaten the security of and cause stability problems in the power system. For instance, in June 2003, when a fault happened to a 500 kV transmission line in the China Southern grid, one differential protection unit failed to trip this line because of a long *communication delay*. Therefore, with considering communication problems, it seems clear that there is a need to evaluate the reliability of differential protection so that the high security inherent in protection systems can be maintained. Recently, data driven/model free solutions for reliability, control and monitoring issues of complicated systems have been developed in the research literature [6–9].

Existing references have been mainly focusing on three communication issues: *inconsistent communication delays*, *consistent communication delays*, and *bit errors* [10]. To study the effects of communication delays and bit errors on differential current protection, the presently used methods are mainly qualitative or experimental methods. A simulation method applied in [11] to study the effects of delays showed that any significant inconsistent communication delays may cause errors in data synchronization, which may result in a *false trip* of the relay protection. It has been proved that long consistent communication delays may cause *refuse-operation* errors in relay protection [12]. In fact, protection systems are time delay systems which have been an active research area for the last few decades. There have been a great number of research results concerning time delay systems scattered in the literature due to the ever-increasing expectations of dynamic performance [13]. In [14], several tests results are provided which showed that a large number of communication bit errors could cause refuse-operation relay protection faults. Generally, the effects of communication issues on differential protection can be summed up as: inconsistent communication delay causes data synchronization problems, which may result in false trips; consistent communication delays lead to the loss of speed, which may result in refuse-operation faults; and communication bit errors cause incorrect current signals and cause synchronization problems, which may result in refuse-operation faults. However, in all previous references no reliability analysis models for differential protection have been introduced.

This paper studies the impact of communication delays and bit errors on current differential protection. First, the mechanism of how the communication delays and bit errors impact the differential protection is revealed. According to the *probability* distributions of communication delays and bit errors and the implied threshold of the current differential protection, malfunction probability models of the current differential protection are proposed. Using the probability from the proposed models together with the consequences to the power system resulting from protection malfunctions, the risk faced by the current differential protection can be calculated.

The remainder of the paper is structured as follows: Section 2 presents some definitions related to current differential protection. The main discussion begins in Section 3 with general observations on the relationships between communication problems and protection malfunctions. Then three probabilistic evaluation models for protection are developed. In Section 4, we present simulations with typical protection data and parameters showing that the communication problems affect the performance of differential protection. We conclude the paper in Section 5.

2. Definitions

Some important terms used in this paper are defined as follows:

Refuse-operation: A communication delay or bit error causes the relay protection to lock, and as a result, the relay protection doesn't start when a given fault occurs within the protection range.

False trip: A communication delay or bit error causes the relay protection device activation when no fault has occured within the protection range.

The communication delay is commonly measured by the "poll and answer" method which is based on the IEEE1588 network time synchronization technology [15–18]. This technique measures the time delay by transmitting "poll and answer" signals across the communication medium. The limitation of this technique is that it can provide only accurate delay measurements if the outgoing and return channel delay times are the same. If these times differ, then an error is introduced.

Figure 1 shows the process of the signal transmission in current differential protection. Assuming the slave sends a frame packet to the host to measure the channel delay. T_{d1} is the channel delay when the packet is sent from the slave to host, T_{d2} is the channel delay when the packet is sent from host to slave. Then the *inconsistent delay* is defined as the difference between T_{d1} and T_{d2}:

$$T_{cd} = \left| T_{d1} - T_{d2} \right| \quad (1)$$

and the *consistent delay* is defined as the average of T_{d1} and T_{d2}:

$$T_d = \frac{T_{d1} + T_{d2}}{2} \quad (2)$$

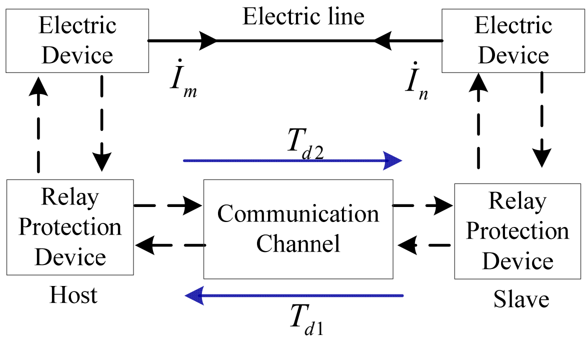

Figure 1. Signal transmission in current differential protection.

3. Malfunction Probability Models for Communication Delays and Bit Errors

Existing research shows that relay protection has implied thresholds for communication delay and bit error, beyond which protection malfunctions may result [19]. The probability reflects the uncertainty of the whole process, including communication delays and bit errors, measurement errors and other factors. This section analyses the malfunction probability of relay protection considering communication problems.

3.1. False Trip Probability Model for Inconsistent Delays

Protection would be activated by an inconsistent delay when it exceeds the implied threshold while no fault occurs within the protection range [20,21]. In this paper, we mainly consider the inconsistent delays caused by the uncertainty of the current measurement error.

3.1.1. Relationship between Inconsistent Delay and Protection Action Criterion

(1) The action criterion of the current differential protection

Currently, the following two criteria are commonly used for the activation of transmission line phase current differential protection [5,22]:
Start criterion: $I_{cd} \geq I_{op}$, I_{cd} is the differential current; I_{op} is a constant determined offline. The threshold of the relay protection is $I_{\max}$:

$$I_{\max} = I_{op} \tag{3}$$

Braking ratio criterion: $I_{cd} \geq kI_{res}$; k is the braking coefficient; I_{res} is the amount of braking current. Two typical forms of I_{res} are:

(a) $I_{res} = \left|\dot{I}_m - \dot{I}_n\right|$. The relationship between the currents of two ends and measured current is depicted in Figure 2. According to the braking ratio criterion, the threshold for this criterion can be expressed as:

$$I_{\max} = kI_{res} = 2kI_L \cos\left(\frac{t_{cd}\omega}{4}\right) \tag{4}$$

where I_L is load current, ω is synchronous angular velocity.

(b) $I_{res} = \left|\dot{I}_m\right| + \left|\dot{I}_n\right|$. The threshold of the relay protection using this criterion is:

$$I_{\max} = kI_{res} = 2kI_L \tag{5}$$

(2) The relationship between the differential current and inconsistent delay

The inconsistent delay t_{cd} causes the sampling time error ($t_{cd}/2$) between the two ends [23]. This produces a differential current I_{cd} when there no fault is happening or the fault is out of protection area. From Figure 2a, the angle difference between $-I_n$ and I_m can be obtained:

$$\theta = t_{cd} \times \omega/2 \tag{6}$$

Therefore, the differential current is:

$$I_{cd} = \left|\dot{I}_m + \dot{I}_n\right| = 2I_L \sin(\frac{t_{cd}\omega}{4}) \quad (7)$$

Equation (7) shows the relationship between the differential current and the inconsistent delay.

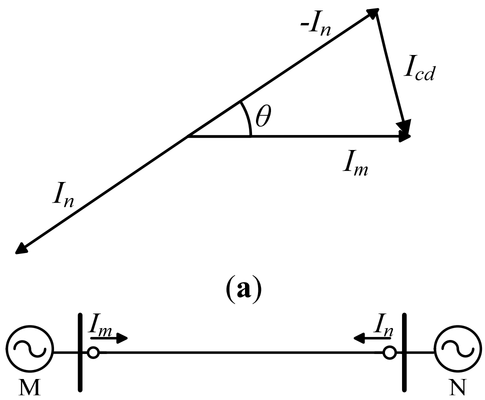

Figure 2. Current vector changes caused by inconsistent delay. (**a**) Vector diagram of currents; (**b**) current differential protection.

3.1.2. False Trip Probability for Inconsistent Delays

For the current differential protection, the directly measured electric quantities are the currents of both ends, and then the differential current can be calculated. In a normal state, in theory the differential current is equal to zero or an expected small value I_{cd}. However, due to communication delays, the currents at both ends used in the calculation may not correspond to the same time instant, which results in a relatively large differential current in a normal state. According to [24], the practically observed differential current of protection shows a normal distribution. Assuming that the differential current follows the normal distribution $N(0, \sigma^2)$, then the differential current is:

$$I'_{cd} = I_{cd} + \alpha + \beta \sim N(I_{cd}, 2\sigma^2) \quad (8)$$

where $2\sigma^2$ is the variance; I_{cd} is the expected small value of the differential current; and α and β are the errors caused by communication delay. The probability density function of the differential current I'_{cd} is shown in Figure 3.

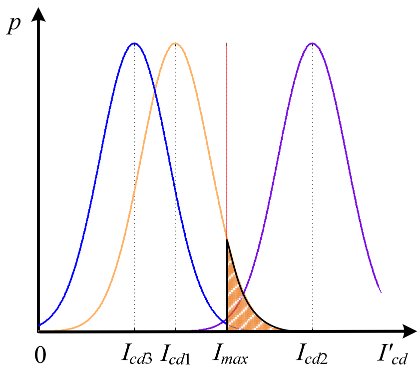

Figure 3. The probability density function of the differential current.

In Figure 3, the horizontal axis represents the differential current, and the vertical axis represents the probability. The orange area represents the probability of the differential current exceeding the current threshold I_{max} in the case of the expected small value being I_{cd1}:

$$P(I_{cd1}) = p(I'_{cd} \geq I_{\max}) \tag{9}$$

where I_{max} is the current threshold of the relay protection. A false trip will happen if the differential current is larger than the current threshold I_{max} while there is no fault happening or the fault is out of protection area. Therefore, $P(I_{cd1})$ is the false trip probability of the protection due to inconsistent communication delays.

Generally, for a protection with an expected small value I_{cd}, its false trip probability is:

$$P_f(I_{cd}) = 1 - \varphi(\frac{I_{\max} - I_{cd}}{\sqrt{2}\sigma}) \tag{10}$$

where $\varphi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{t^2}{2}} dt$ is the standard normal distribution function. Figure 4 gives the false trip probability caused by the differential current.

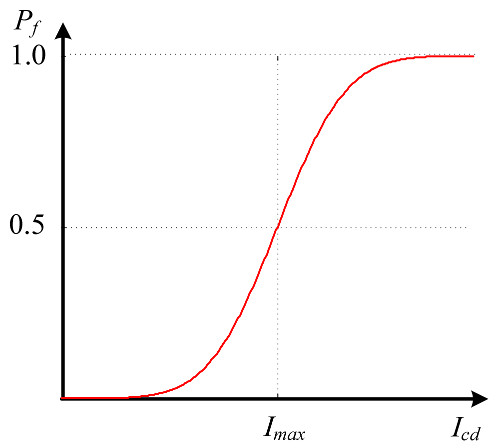

Figure 4. False trip probability caused by the differential current.

Then the false trip probability following the start criterion ($I_{cd} \geq I_{op}$) can be expressed as:

$$P_{f1}(t_{cd}) = 1 - \varphi(\frac{I_{op} - 2I_L \sin(\frac{t_{cd}\omega}{4})}{\sqrt{2}\sigma}) \tag{11}$$

There are two forms for false trip probability following the braking ratio criterion ($I_{cd} \geq kI_{res}$) depending on how I_{res} is calculated:

(a) If $I_{res} = \left|\dot{I}_m - \dot{I}_n\right|$, then the probability can be expressed as:

$$P_{f2}(t_{cd}) = 1 - \varphi(\frac{2kI_L \cos(\frac{t_{cd}\omega}{4}) - 2I_L \sin(\frac{t_{cd}\omega}{4})}{\sqrt{2}\sigma}) \tag{12}$$

(b) If $I_{res} = \left|\dot{I}_m\right| + \left|\dot{I}_n\right|$, then the probability can be expressed as:

$$P_{f3}(t_{cd}) = 1 - \varphi\left(\frac{2kI_L - 2I_L \sin(\frac{t_{cd}\omega}{4})}{\sqrt{2}\sigma}\right) \tag{13}$$

In China, the first form of braking ratio criterion and the start criterion are jointly used to determine the action of the current differential protection, while in some other countries, the second form of braking ratio criterion and the start criterion are jointly used [25].

Then the false trip probability of the relay protection with the first form of braking ratio criterion and the start criterion can be obtained:

$$P_f(t_{cd}) = \begin{cases} P_{f1}, & t_{cd} \geq \frac{4}{\omega}\arccos(\frac{I_{op}}{2kI_L}) \\ P_{f2}, & t_{cd} < \frac{4}{\omega}\arccos(\frac{I_{op}}{2kI_L}) \end{cases} \tag{14}$$

where P_{f1} and P_{f2} are defined in (11) and (12). Figure 5 gives the false trip probability of relay protection with the first form of braking ratio criterion and start criterion.

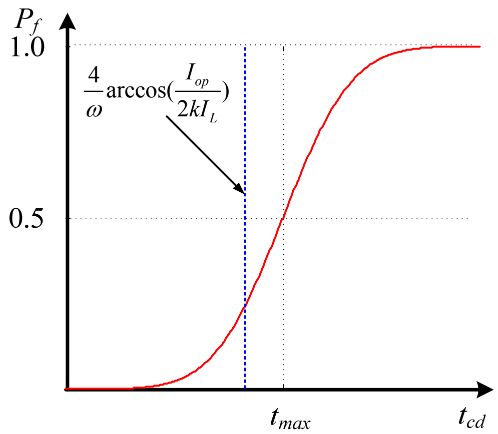

Figure 5. False trip probability follows the first form of braking ratio criterion and start criterion.

The false trip probability of the relay protection with the second form of braking ratio criterion and the start criterion can be obtained similarly.

3.2. Refuse-Operation Probability Model for Consistent Delays

It has been proved that there is a consistent delay threshold t_{max} [19,26,27]. If the consistent delay t_d is larger than t_{max}, the relay protection would be blocked. In this case, a refuse-operation would occur if there is a fault happing within the protection area. This section will analyze the refuse-operation probability considering the uncertainty of communication delays.

According to [24], the practically observed consistent delay shows a normal distribution. Considering the uncertainty of environment impacts, the measurement errors and communication condition variations, the measured consistent delay t follows the normal distribution $t \sim N(t_d, \sigma_1^2)$. t_d is the expected value of the consistent delay t, and $2\sigma^2$ is the variance. The probability density function of the consistent delay t is expressed as:

$$f(t)=\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(t-t_d)^2}{2\sigma_1^2}} \tag{15}$$

Figure 6 shows the probability density of the consistent delay. The orange area represents the probability of consistent delay exceeding the threshold $t_{\max}$ when the expected value of the consistent delay is t_{d1}.

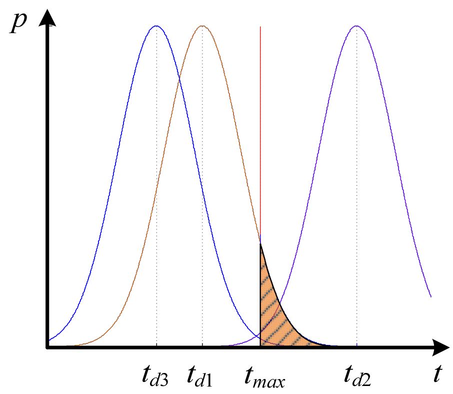

Figure 6. The probability density function of the consistent delay.

Refuse-operation would occur if the measured consistent delay t is larger than $t_{\max}$ and a fault happens within the protection area. Therefore, the refuse-operation probability can be expressed as:

$$P_{rd}(t_d)=1-\varphi(\frac{t_{\max}-t_d}{\sigma_1}) \tag{16}$$

where $\varphi(x)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x}e^{\frac{t^2}{2}}dt$ is the standard normal distribution function.

Figure 7 gives the refuse-operation probability of relay protection caused by consistent delays.

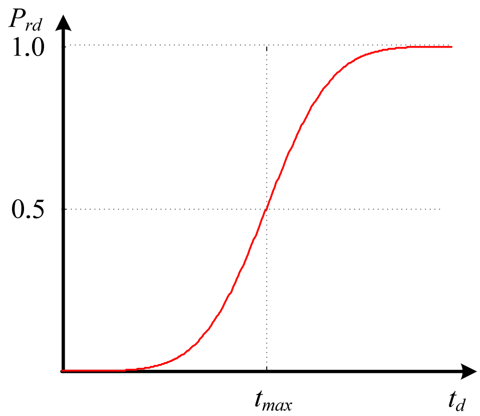

Figure 7. Refuse-operation probability for consistent delay.

3.3. Refuse-Operation Probability Model for Bit Errors

When communication conditions deteriorate, the bit error rate w increases. If the bit error rate exceeds the threshold w_{max}, the relay protection would refuse to operate [14]. This section will analyze the refuse-operation probability considering communication errors.

Assuming that each bit error probability is independent, and the average bit error rate is w_1, then the distribution of bit error can be represented by a binomial distribution. Because the average bit error rate w_1 is usually very small, the distribution of bit error can be represented by the Poisson distribution. Thus the probability density of bit error rate during a period of time (for example 1 second) can be expressed as:

$$p(x=k)=\frac{(nw_1)^k e^{-nw_1}}{k!} \tag{17}$$

where k is the number of bit error; n is the total bit number transmitted during the period of time.

Rewriting Equation (17) as the form that takes bit error rate as variable:

$$p(w)=\frac{(nw_1)^{nw} e^{-nw_1}}{(nw)!} \tag{18}$$

The probability density of the bit error rate is shown in Figure 8. The orange area represents the probability of bit error rate exceeding the threshold w_{max} in the case of the expected value of the bit error rate being w_2.

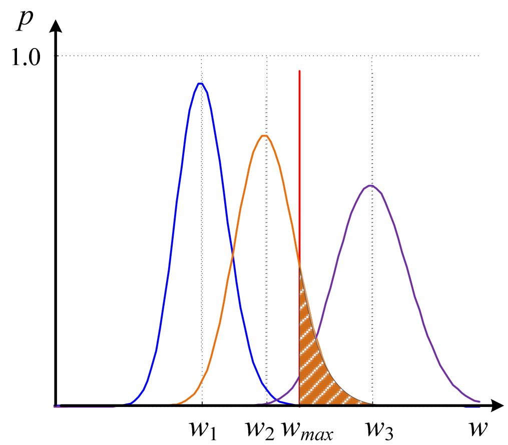

Figure 8. The probability density function for bit error rate.

Refuse-operation would occur if the measured bit error rate w is larger than w_{max} and a fault happens within the protection area. Therefore, the refuse-operation probability can be expressed as:

$$P_{rb}(w)=1-\sum_{nw=0}^{nw_{max}}\frac{(nw_1)^{nw} e^{-nw_1}}{(nw)!} \tag{19}$$

Figure 9 gives the refuse-operation probability of relay protection caused by bit errors.

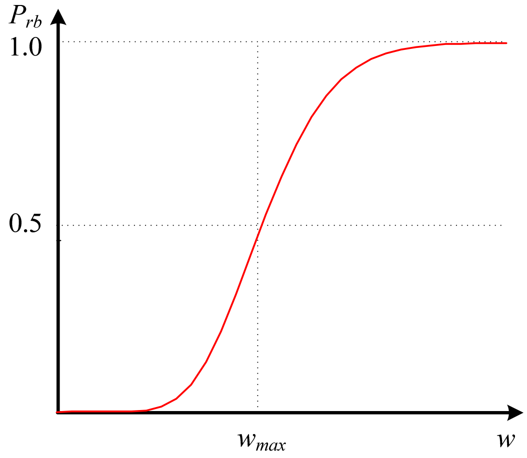

Figure 9. Refuse-operation probability for bit error.

3.4. Refuse-Operation Probability Model for Consistent Delays and Bit Errors

The two reasons for the refuse-operation of the current differential protection, the consistent delay and bit error, are independent [14,26]. The progress of refuse-operation of differential protection is shown in Figure 10.

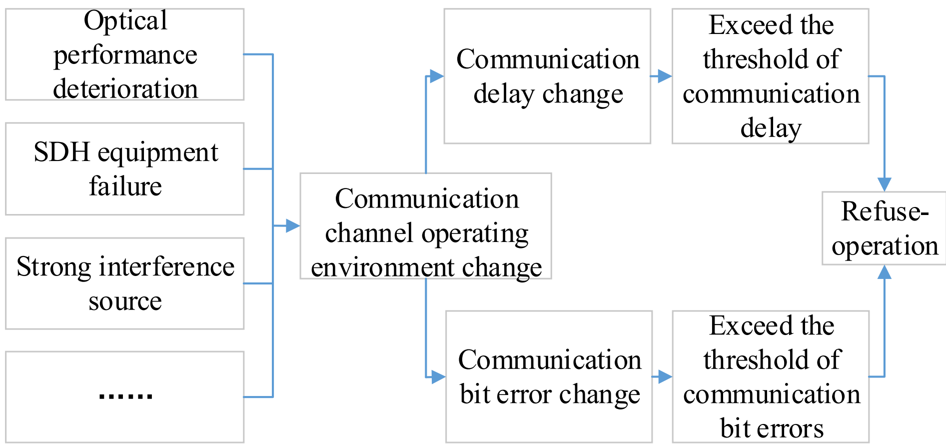

Figure 10. The progress of refuse-operation.

Therefore, the total refuse-operation probability can be obtained:

$$P_r = 1-(1-P_{rd})(1-P_{rb}) \tag{20}$$

Applying (16) and (19) into (20), the total refuse-operation probability of the protection caused by the consistent delays and bit errors can be represented as:

$$P_r = 1-\varphi(\frac{t_{\max}-t_d}{\sigma_1})\times\sum_{nw=0}^{nw_{\max}}\frac{(nw_1)^{nw}e^{-nw_1}}{(nw)!} \tag{21}$$

Figure 11 gives the total refuse-operation probability of relay protection caused by consistent delays and bit errors.

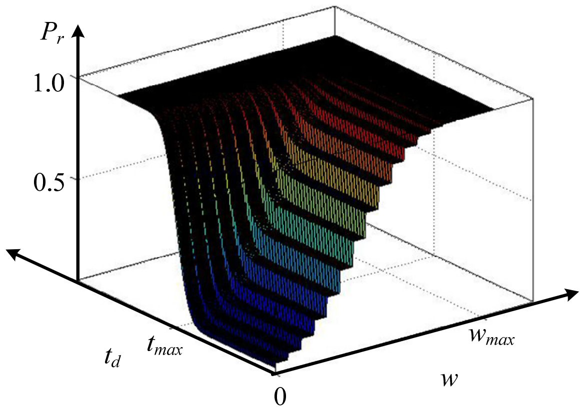

Figure 11. Refuse-operation probability for consistent delays and bit errors.

4. Simulations

This paper studies the malfunction probability of current differential protection devices in power systems. The communication type is optical fiber. The relevant parameters used in the simulation studies are shown in Table 1 [19,21,28]. The simulation tries to analyze the effects of key factors on the malfunction probability of optical fiber current differential protection. A comparison of the malfunction probabilities of protection in normal and abnormal communication conditions will also be provided.

Table 1. Parameters used in the simulation.

Parameters	Name	Value	Description
$t_{\max}$	Consistent delay threshold	12 ms	If the measured consistent delay t is larger than $t_{\max}$, the relay will refuse to operate when internal fault occurs.
σ_1	Normal distribution standard deviation of consistent delay	1/6 ms	(1) Considering the uncertainty of environment impacts and communication condition variations, the consistent delay t follows the Normal distribution. (2) Assuming 99.7% of consistent delay is less than 1 ms, then according to the probability theory the consistent delay fluctuation standard deviation is 1/6 ms.
$w_{\max}$	Communication bit error rate threshold	2×10^{-6}	(1) If the measured bit error rate w is larger than the $w_{\max}$, the relay will refuse to operate when internal fault occurs. (2) The value of communication bit error rate threshold is relative fuzzy, it may be related to the types of relay protection and the distribution of the communication bit error. Here we select a typical value 2×10^{-6}.
I_{op}	Current start threshold for start criterion	$0.5 \times I_N$	Protection operates when the differential current is larger than I_{op}.
σ	Normal distribution standard deviation of differential current caused by inconsistent delay	$0.26 \times I_N$	The selected value $0.26 \times I_N$ is calculated from the reliable coefficient of current different protection.
k	Braking coefficient	0.6	Braking coefficient in braking ratio criterion.

4.1. Key Factors Affecting the Malfunction Probability

(1) False trip probability for inconsistent delays

In this simulation, the false trip probability follows the braking ratio criterion ($I_{cd} \geq kI_{res}$) with I_{res} being calculated as $I_{res} = |\dot{I}_m| + |\dot{I}_n|$. From Equation (13), it can be found that the key factors affecting the false trip probability are the differential current's standard deviation σ and the inconsistent delay t_{cd}.

Figure 12 shows the changes of the false trip probability with t_{cd} ranging from 0 ms to 8 ms and σ ranging from 0 to 1.0.

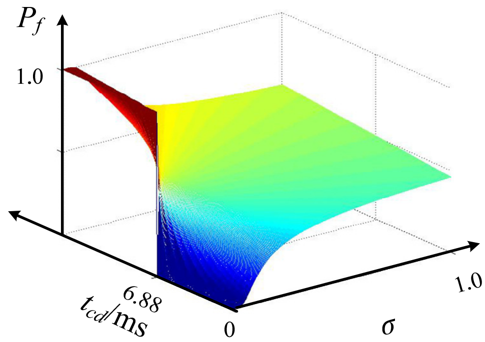

Figure 12. Key factors affecting false trip probability.

From Figure 12, we can conclude that when the standard deviation of differential current is equal to 0, the false trip probability experiences a step change at an inconsistent delay of 6.88 ms. Hence, the observation that the maximum inconsistent delay is 6.88 ms is supported by China industry's practical application which indicates the maximum inconsistent delay of differential protections ranges from 5.9 ms to 8.2 ms [25].

Furthermore, with the increase of σ, the probability changes with respect to inconsistent delay becomes slower. Especially, for $t_{cd} = t_{max}$, the probability changes dramatically at σ = 0, while it remains almost constant at σ = 1. This means that a larger σ indicates less differential protection sensitivity.

(2) Refuse-operation probability for consistent delays

According to (13), the refuse-operation probability is mainly dependent on the distribution of the consistent delay (the normal distribution standard deviation of consistent delay σ_1, the expected value of consistent delay t_d) and the threshold of the consistent delay t_{max}.

According to the real industrial experience in China, we selected the threshold of consistent delay t_{max} as 12 ms. Figure 13 shows the changes of the refuse-operation probability with the expected consistent delay t ranging from 0 ms to 20 ms and the standard deviation of consistent delay σ_1 ranging from 0 ms to 15 ms.

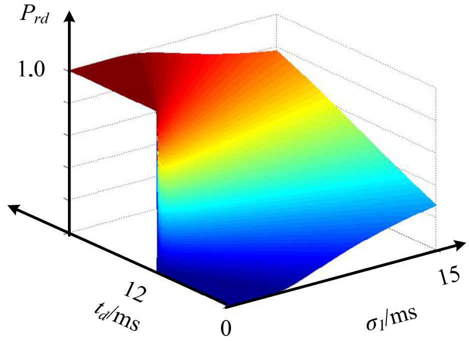

Figure 13. Refuse-operation probability considering consistent delay distribution.

In Figure 13, when the normal distribution standard deviation of differential current is equal to 0, the refuse-operation probability experiences a step change at a consistent delay of 12 ms. This is in agreement with the fact that the threshold of consistent delay $t_{\max}$ was selected as 12 ms. Hence, with the increase of σ_1, the probability changes with respect to consistent delay becomes slower. This means that a larger σ_1 indicates less differential protection sensitivity. We seclected consistent delay t_d as 10 ms and σ_1 as 1 ms, then the refuse-operation probability change with the threshold ranging from 0 to 20 ms was obtained as shown in Figure 14.

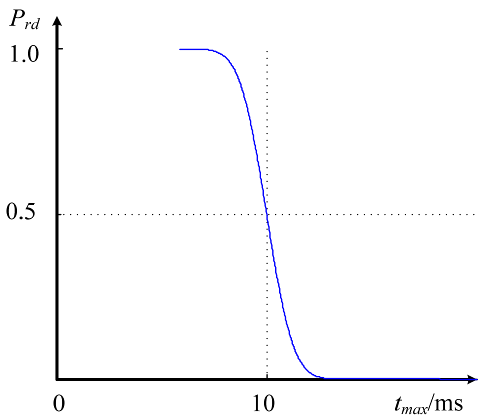

Figure 14. Refuse-operation probability with threshold.

Figure 14 shows that the larger the threshold is, the smaller the probability of refuse-operation is. When the consistent delay is equal to the threshold, the probability of refuse-operation is equal to 0.5.

(3) Refuse-operation probability for bit errors

According to (16), the threshold of bit error rate $w_{\max}$ and the real time bit error rate w_1 are two relevant factors to the refuse-operation probability. We selected the real time bit error rate w_1 as 5×10^{-4}, then the relationship between $w_{\max}$ and refuse-operation probability was obtained as shown in Figure 15.

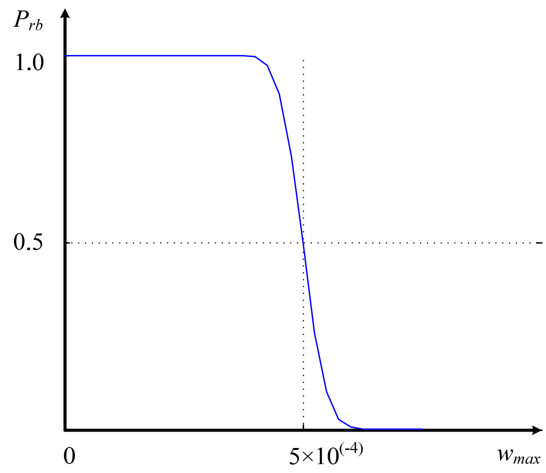

Figure 15. The relationship between the threshold and refuse-operation probability.

From Figure 15, we find that the larger the threshold is, the smaller the refuse-operation probability is. When the real time bit error rate is equal to the threshold, the probability of refuse-operation is equal to 0.5.

4.2. Comparison of Mal-Function Probabilities in Normal and Abnormal Communication Conditions

(1) False trip probability

In normal communication conditions, the expected inconsistent delay is relatively small and acceptable. The current differential protection operates correctly. In other words, the false trip probability is very low under normal communication conditions. However, when a disturbance occurs in the communication channel, the inconsistent delay may increase and fluctuate. The change of inconsistent delay will affect protection's false trip probability.

The inconsistent delay during a period of time is shown in Figure 16. At $t = 1$ s, a fault occurs to the communication channel, which results in an inconsistent delay increase. Accordingly, during the period of time, the real time false trip probability of the protection was obtained as shown in Figure 17.

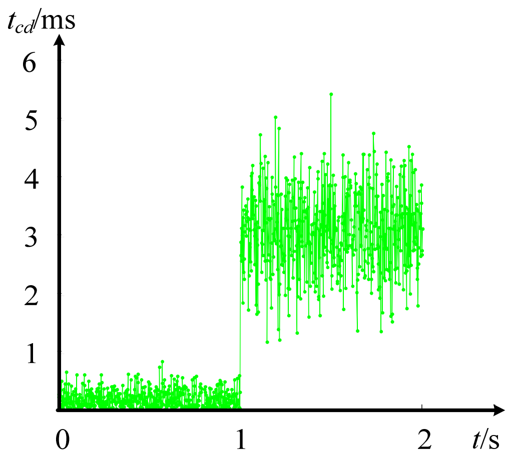

Figure 16. Inconsistent delay sequence.

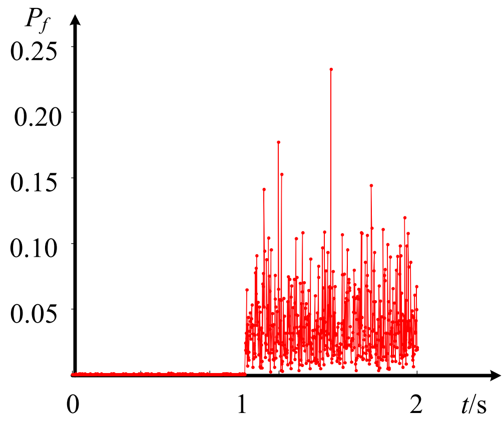

Figure 17. Real time false trip probability for inconsistent delay.

It can be seen from Figure 17 that the false trip probability is low before the time instant $t = 1$ s, while the false trip probability becomes large after the time instant $t = 1$ s. The probability of stepping from a low level to a high level at the time instant $t = 1$ s is because of the communication condition deterioration. The simulation results suggest that worse communication conditions increase the false trip probability of differential protection.

(2) Refuse-operation probability

In China, under normal conditions, the consistent delay of communication is less than 8 ms, and the communication bit error rate is lower than 10^{-7}. When a fault occurs in the communication channel, the consistent delay and bit error rate may become larger and more volatile.

The consistent delay and communication bit error rate sequence during a period of time are shown in Figures 18 and 19, respectively. At $t = 1$ s, a fault happens in the communication channel, which causes an increase of the consistent delay and communication bit error rates. With these two sequences, the corresponding real time refuse-operation probability was obtained as given in Figure 20.

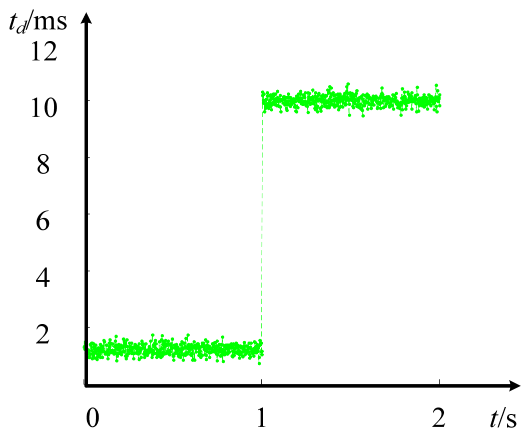

Figure 18. Consistent delay sequence.

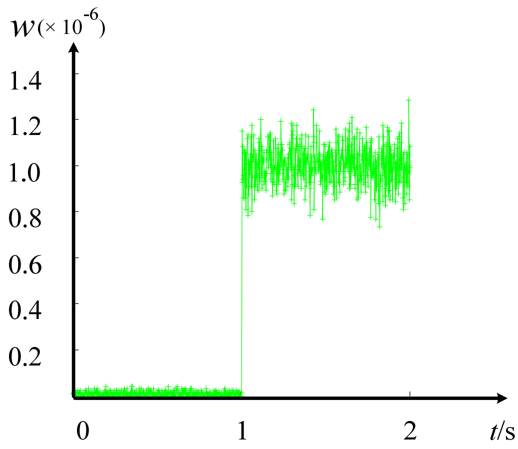

Figure 19. Bit error rate sequence.

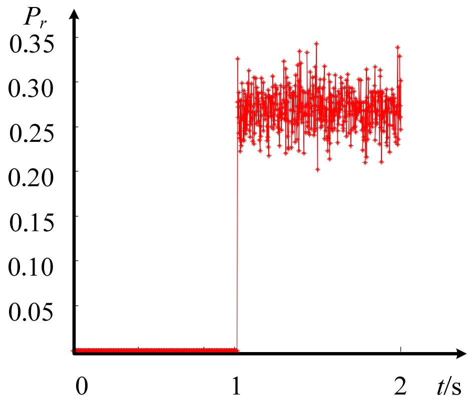

Figure 20. Real time refuse-operation probability.

In Figure 20, before the time instant $t = 1$ s, the refuse-operation probability is relatively low, while the refuse-operation probability becomes larger after the time instant $t = 1$ s. The refuse-operation probability experiences a step change at the time instant $t = 1$ s because a fault happens at that time instant. The simulation results indicate that worse communication conditions increase the refuse-operation probability of differential protection.

5 Conclusions

To enhance the reliability and security of modern power transmission systems, protections are commonly utilized for fault detection/location. It is a well-recognized fact that current differential protection schemes provide sensitive protection with crisp demarcation of the protection zones. Since differential comparison of the local and remote end currents must correspond to the same time instant, inaccuracies in a current differential protection scheme would be inevitable due to communication issues, such as time delays and bit errors. Existing methods for studying the effects of inconsistent communication delays, consistent communication delay, and bit errors on current differential protection are mainly qualitative or experimental methods. This paper provides a quantitative method.

This study presents three probability models to assess the impact of communication delays and bit errors on differential protection. Analysis of the mechanisms of malfunction of relay protection caused by communication delays and bit errors is one of the contributions of this paper. Typically, the analysis of malfunctions of differential protection is mainly experiment-based, which can't fully reveal the underlying causes. In general, a channel's consistent delay or bit error results in refuse-operation incidents, while a channel's inconsistent delay normally causes false trips. In this paper, based on the assumption that communication delays follows a normal distribution and bit error follows a Poisson distribution, probabilistic models of false trips and refuse-operation faults are proposed. In these models, the probabilistic relationships between communication issues and protection malfunctions are established. With the proposed models, typical data and parameters are adopted to demonstrate the effects of communication delays and bit errors on differential protection. The simulation results show that more severe communication problems result in a larger probability of malfunction of differential protection.

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Author Contributions

Yingjun Wu, Manli Li, and Yi Tang contributed in developing the ideas of this research, Yingjun Wu, Manli Li, Yi Tang, and Ming Ni performed this research, all the authors involved in preparing this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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