Research on blackout simulation model considering hidden failures and reclosing

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Abstract. In this paper, a blackout simulation model considering hidden failures and reclosing is proposed, which is more realistic than the previous model. The operation of reclosing devices, the synchronization control for reclosing in two-ended sources transmission lines and the interaction between reclosing and relay protection are simplified. Simulation results of IEEE39-bus test system are obtained to confirm the validity of the model. Compared with the blackout simulation model considering only the hidden failures of relay protection, it shows that the trip caused by the transient faults and hidden failures induced by transient faults can be corrected in this large-scale blackout simulation model. It also shows that with the increase of the probability of hidden failure, the failure rate of reclosing becomes an important factor affecting the system recovery.

1. Introduction
In recent years, there have been many large-scale blackouts at home and abroad. In order to analyze the mechanism of their generation and propagation, a large number of theories and models have been proposed by domestic and overseas scholars. Self-organized criticality theory has become an effective tool to investigate large-scale blackouts. Many blackout simulation models based on this theory have also been recognized by scholars, such as OPA model, Hidden Failure model, Cascade model, SOC-Power Failure model, etc.[1-4]. In the process of exploring the above mechanisms and models, the hidden failures of relay protection have become a hot issue that scholars pay more and more attention to. Reference [5] analyzed the causes of hidden failures in protection devices and applied risk theory to evaluate the impact of hidden failure probability on cascading trip during power outages. Reference [6] considered the hidden failures of relay protection and proposed a risk assessment model associated with a capacity of transmission lines. Reference [7] proposed a blackout simulation model considering the hidden failures of relay protection and studied the effect of hidden failures on the self-organized criticality of the power grid.

Reclosing is an automatic device used in power systems, which can quickly correct the malfunction of relay protection [8]. At present, scholars’ research on reclosing mainly focuses on how to reduce the failure rate of reclosing, such as the method of identifying accurately the permanent faults [9] and the control strategy of reclosing [10-11]. But how does reclosing hinder power outages? What is the relationship between reclosing and hidden failures during the blackout? These are important problems worth of study.

In order to solve the above problems, this paper proposes a more realistic blackout simulation model than the previous, which can be used to study hidden failures and reclosing during large-scale power
blackouts. Taking the IEEE39-bus system as the research object, this paper verifies the validity of the model and compares it with the model without considering reclosing.

2. Description of model factor

2.1 Model of hidden failure

At present, when quantitatively describing the impact of hidden failures on the protected lines, scholars usually use a variable to measure the probability of line outage. In this paper, the hidden failure probability model considered over-flow [5] is used and is shown in figure 1. $F$ is the active power flow, $F_L$ is the active power flow limit, $P_{H}$ is the probability of hidden failure, $P$ is the probability of line outage.

$$P = \begin{cases} P_{H} & F_i < F_L \\ \left(F_i - F_L\right) \times \frac{P - P_{H}}{1.4F_L - F_L} + P_{H} & F_L \leq F_i \leq 1.4F_L \\ P & F_i > 1.4F_L \end{cases}$$

(1)

Figure 1. Hidden failure probability model.

The probability of hidden failure is affected by external environment, worn circuit and human error. According to figure 1, the concrete expression of the probability of line outage due to hidden failures is as follows:

2.2 Simplification of reclosing

2.2.1 Operation of reclosing devices. By analyzing GB/T14285-2006 "Technical Regulations for Relay Protection and Safety Automatic Devices", it can be seen that the operation of reclosing devices is different when the different type of faults happen. However, the success of reclosing always depends on whether the fault is a transient fault. Therefore, the mechanism of reclosing can be simplified as follow: if the fault is a transient fault, reclosing will success and the system will resume normal operation; if the fault is a permanent fault, the relay circuit breaker will trip again.

2.2.2 Synchronization control for reclosing. In high-voltage power systems, reclosing of two-ended sources transmission lines need to consider the optimal reclosing time and synchronization of circuit breakers. When ignoring switching onto faulted lines in the asynchronous, whether the system resume normal operation depends on whether the circuit breaker closes successfully on the detecting voltage-free side [12]. In other words, it also depends on whether the fault is a transient fault.

2.2.3 Interaction between reclosing and relay protection. In order to improve the power supply reliability of the transmission lines, reclosing controls switch and circuit breaker to realize the front acceleration and rear acceleration protection of the whole power net. 220kV and above systems adopts post-acceleration protection, that is, the circuit breaker is first closed and then the fault type is identified.
3. Blackout simulation model
Imitating the fast dynamic process of the OPA model and the Hidden Failure model [13-14], a blackout simulation model considering hidden failures and reclosing is proposed. The procedure of simulation can be described as follow (figure 2).
Step1 Reading parameter of power grid.
Step2 Generating initial faults randomly.
Step3 Tripping and cutting off the faulted lines.
Step4 Calculating power flow and tripping according to the hidden failure probability model.
Step5 Judging whether reclosing is successfully. If yes, turn to step 6. If not, turn to step 8.
Step6 Judging whether the fault is a transient fault. If yes, return to step 2. If not, turn to step 7.
Step7 Tripping again of faulted lines.
Step8 Judging whether the power system generate lost load or islands. If yes, turn to step 9. If not, turn to step 2.
Step9 Calculating lost load and outputting the result.

![Model calculation flow chart](image)

**Figure 2.** Model calculation flow chart.
4. Blackout simulation model
In this paper, IEEE39-bus system is taken as an example (figure 3), whose reference voltage is 345kV.

![Figure 3. IEEE39-bus system.](image)

4.1 Parameter setting
According to reference [15], setting the probability of hidden failure $p_H$ is 0.0013. Statistics show that the success rate of reclosing depends mainly on the proportion of transient faults caused by external environment to the total faults. In this paper, let the ratio of transient faults to permanent faults in the initial faults caused by the external environment is 3:1. In addition, reclosing itself has a certain failure rate, such as equipment failure or misjudgment, which may lead to reclosing failure. Refer to [16], this paper sets the failure rate of reclosing is 0.0015.

4.2 Model verification
The research shows that there are self-organized criticality characteristics of power outage at home and abroad. According to the theory, the validity of the model can be verified by simulating the large-scale blackouts based on this model. Repeatedly run the model 200 times and the time series of the power outages are shown in figure 4. The corresponding loss load is counted in a scale-frequency double logarithmic graph with a base of 10, as shown in figure 5.

![Figure 4. Time series of the power outage.](image)
Least-square curve fitting method is used to fit 10 discrete points in the tail of figure 5. The fitted line and its correlation coefficient are obtained:

\[ \lg N = 7.4625 - 2.1069 \lg r \]  
\[ R = -0.9348 \]  

By checking the corresponding standard in the correlation coefficient test table, \( R_{0.01} \) is 0.765. Due to \( |r| > R_{0.01} \), it can be seen that the fitting equation is effective. Thus, the double logarithmic distribution of the scale-frequency of blackouts loss load using this model obeys the basic mathematical representation of self-organized criticality--power law distribution, which proves the feasibility of the model.

4.3 Comparison and analysis
Assuming that branch 17-18 has an initial fault, the impact of the fault on the system is analyzed as follows.
(1) Only considering the hidden failures of relay protection.
After cutting off branch 17-18, the power flow is shifted and redistributed. According to the hidden failure probability model, the load rate and outage probability of adjacent lines can be obtained, as shown in table 1.

| Branch | Load rate | Outage probability |
|--------|-----------|--------------------|
| 3-18   | 1.8508    | 1.0000             |
| 17-27  | 1.3404    | 0.8512             |
| 16-17  | 0.3499    | 0.0013             |

(2) Considering the hidden failures and reclosing.
When the initial fault is a permanent fault, reclosing will not successful. The outage of the lines is the same as in case (1).
When the initial fault is a transient fault, the fault source will disappear after the branch 17-18 is cut off once. All the circuit breaker can be switched on and the system can reach stability again. At this time, whether the relevant electric transmission lines resume power supply in time depends on whether reclosing devices have working ability, that is, reclosing’s failure rate.
Compared case (1) and case (2), it can be known that when faults happen, hidden failure of relay protection in power system plays the role of expanding the outage range and reclosing can avoid cascading trip through correcting the transient faults. That is, reclosing can reduce effectively the probability of large-scale blackouts in the power grid. Establishing a blackout simulation model based on the case 1 and running it 200 times, a time series diagram of the blackouts can be obtained, as shown in figure 6.

Figure 6. Time series diagram of power outage based on model built in case (1).

In the case of 200 power outages, the simulation model considering reclosing (figure 4) takes more than 1200 days, which is about four times as long as the model without considering reclosing (figure 6). The ratio is basically consistent with the setting of the success rate of reclosing. It can be further analyzed that reclosing plays an important role in delaying blackouts. If ignoring reclosing in the simulation and early warning of blackouts, the stability of the system will be underestimated and the accuracy of the assessment will be affected.

According to the above mentioned analysis, the success rate of reclosing is mainly determined by the proportion of the transient faults caused by the external environment, which is a factor with less controllability. The probability of hidden failure of relay protection depends on the reliability of relay protection equipment in the power system, which is a factor with greater controllability. In order to further study the interaction between hidden failures and reclosing during the blackouts, the ratio of the transient faults to the permanent faults 3:1 is maintained and the probability of hidden failure of relay protection is changed. The value of the hidden failure probability is shown in table 2.

| Situation | $P_H$ | Situation | $P_H$ | Situation | $P_H$ |
|-----------|-------|-----------|-------|-----------|-------|
| 1         | 0.0003| 3         | 0.0023| 5         | 0.0043|
| 2         | 0.0013| 4         | 0.0033| 6         | 0.0053|

The histogram in figure 7 shows the time required for 1000 power outages in systems which considering reclosing or not under different hidden failure probabilities. The broken line indicates the ratio of the time required by the two models.
It can be seen from figure 7, as the hidden failure probability increases, the time required for both models decreases and the time ratio also decreases. That is, the effect of reclosing on reducing the risk of power system blackouts is gradually weakened. When there are more hidden failures in relay protection equipment, there will be more broken lines need to be re-closed. The factors of reclosing failure caused by self-fault is magnified and the failure rate of reclosing plays an increasingly important role in system recovery. Therefore, in the case where the external environment cannot be changed, in order to ensure the stability of the system, it is necessary to improve the operating conditions of reclosing to reduce the failure rate of reclosing.

5. Conclusion
Considering that reclosing can quickly correct instantaneous faults, a blackout simulation model considering hidden failures and reclosing is proposed in this paper by reasonable simplifying reclosing. Taking IEEE39-bus system as an example, the validity of the model is proved by using the self-organizing criticality theory of blackouts. Based on the proposed model, the role of reclosing during the blackout and the relationship between reclosing and hidden failures are analyzed.

1. In the process of power outage, reasonable consideration of the role of reclosing is in line with the actual operation of the system. By correcting transient faults in the system, reclosing can eliminate most of the power outages caused by transient faults and reduce the frequency and scale of blackouts. Therefore, it is necessary to consider the role of reclosing in the blackout simulation modeling and accurate risk assessment.

2. Reclosing can correct trips caused by instantaneous faults and further correct false trips caused by hidden failure of relay protection induced by instantaneous faults, so as to avoid the expansion of the scope of the fault caused by hidden failure of relay protection. The success rate of reclosing mainly depends on whether the fault is a transient fault. However, when too many hidden failures happen in the system, the failure rate of the reclosing will gradually become an important factor affecting the success of the reclosing.

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