

# Effects of Protection System Hidden Failures on Bulk Power System Reliability

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**Abstract** – Protection system hidden failures have been recognized as a contributing factor to power system cascading outages. However, in the current bulk power system reliability assessment practice, protection systems are generally assumed to be perfect, and the impact of protection system hidden failures are not taken into account. In this paper, a systematic methodology is proposed to evaluate the effects of protection system hidden failures on bulk power system reliability in the general bulk power system reliability assessment procedure. In the proposed methodology, a breaker-oriented bulk power system network model is developed to include detailed system substation configurations and protection system schemes. Any protection system constituents, such as transducers, relays, and circuit breakers, may suffer from hidden failures. Although hidden failures existing in transducers and relays can be detected considerably by advanced system real-time monitoring and analysis technologies, such technologies do not detect the trip abilities of circuit breakers. To conduct the analysis of hidden failures in circuit breaker trip mechanisms (CBTMs), the probabilistic model of the CBTM is built, based on which a hidden failure effects analysis method is developed to obtain contingencies resulting from CBTM hidden failures. Such contingencies as well as other contingencies resulting from independent outages and common-mode outages are subjected to a security-constrained adequacy evaluation approach to evaluate their influence on system reliability. The proposed methodology is demonstrated with a breaker-oriented 24-substation reliability test system, which is derived from the IEEE 24-bus reliability test system by integrating explicit substation and protection system models in the network model. Evaluation results show that protection system hidden failures downgrade the system reliability level because they lead to the outages of undamaged equipment following initial system disturbances.

**Index Terms** –Protection system hidden failure, circuit breaker-oriented substation model, bulk power system reliability assessment, circuit breaker trip mechanism, advanced real time power system monitoring and analysis, security-constrained adequacy evaluation.

## I. INTRODUCTION

**I**N both bulk power system planning and operation stages, an essential procedure is to conduct bulk power system reliability assessment [1]. The current practice in such reliability assessment mainly focuses on the analysis for N-1 contingencies and some credible N-2 cases. Component outage modes concerned in these contingencies generally

include independent and common-mode component outages. Most of contingencies that involve multiple component outages are considered as a result of several independent succeeding events in the system and usually not a major concern in the reliability assessment procedure. However, recent research [2-4] shows that protection system hidden failures may cause multiple component outages that are dependent upon each other, i.e., an initial component outage can lead to the cascading tripping of other intact components because of the protection system malfunction. Therefore, protection system hidden failures have been recognized as a contributing factor in spreading power system disturbances and even causing system blackouts. Since protection systems are generally assumed to be perfect when considering bulk power system reliability, the effects of protection system hidden failures are not taken into account in the current practice of bulk power system reliability assessment.

Hidden failures in protection systems are defined [5] as “a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event.” In other words, hidden failures remain hidden during the normal system operating condition, and when system disturbances occur, such as faults or overloads, hidden failures are exposed and cause unnecessary outages of intact equipment. The existence of hidden failures in protection systems makes the stressed system situation even worse and reduces the system reliability level.

Protection systems consist of many components, such as transducers (current and voltage transformers), relays, and circuit breakers, which contribute to the detection and removal of faults [6]. Hidden failures may exist in any of these constituents. Most of present research focuses on studying hidden failures in relays. For example, the mechanism and consequence of some possible hidden failure modes in various relays used for transmission system protections are analyzed in [7, 8]. On the other hand, the analysis of hidden failures in other protection system components, such as transducers and circuit breakers, has not received much attention.

Nowadays, the application of various intelligent electronic devices (IEDs) in power system substations, such as phasor measurement units and digital protection relays, has made it possible to implement advanced real time system monitoring and analysis technologies [9-11], based on which the hidden failures existing in transducers and relays can be detected considerably. However, such technologies can not examine the trip abilities of circuit breakers, even though the trip coil circuit may be monitored. Hidden failures in the circuit

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breaker trip mechanism (CBTM) can cause circuit breakers fail to open when they are required to do so. As a result, the analysis of the impact of CBTM hidden failures on bulk power system reliability is the major concern in this work, which includes the probabilistic modeling of the CBTM hidden failures and the hidden failure effects analysis to obtain contingencies resulting from the CBTM hidden failures.

In this paper, a comprehensive approach for bulk power system reliability assessment, i.e., the security-constrained adequacy evaluation (SCAE) methodology, which is developed by authors in the past, is extended to evaluate the effects of protection system hidden failures on bulk power system reliability. The detailed SCAE approach can be found in references [12-14]. The proposed methodology is demonstrated with a breaker-oriented 24-substation reliability test system (RTS).

## II. METHODOLOGY

This section illustrates the proposed methodology that can take into account the effects of protection system hidden failures on bulk power system reliability in detail.

### A. Breaker-Oriented Substation

Since protection systems are assumed to be perfect in the current bulk power system reliability assessment procedure, system substations are generally simplified to buses, and different transmission lines simply converge at buses to connect generators or to serve loads. To consider hidden failures in protection systems, we develop the breaker-oriented substation model [15] in this study. Such model provides the substation configuration by converting each bus of the power system into a substation with specific bus arrangements (breaker and a half, ring, and so on). The selection of bus arrangements follows usual design procedures and practices. The substation models are then an integral part of the bulk power system network model and reflect the real life existence of substation configurations. Figure 1 shows an example breaker-oriented substation model with a breaker-and-a-half bus arrangement, which consists of six circuit breakers (CB1 to CB6) and four incoming/outgoing transmission lines (L1 to L4).

The breaker-oriented substation model adds a new level of detail in the network model, based on which the protection system schemes for various power system components can be introduced into the network model also. For instance, two examples of the protection system designs are shown in Figure 1. Protection systems 1 and 2 are to protect transmission line L1 and Bus B, respectively. Major components in these two protection systems include current transformers (CT1 to CT4), a voltage transformer (VT), relays (R1 and R2), and circuit breakers (CB1 to CB4) associated with trip coils (TC1 to TC4). The detailed substation and protection system models make it possible to study the impact of protection systems on power system performance. Specifically, in this work, the impact of protection system hidden failures on bulk power system reliability is investigated.

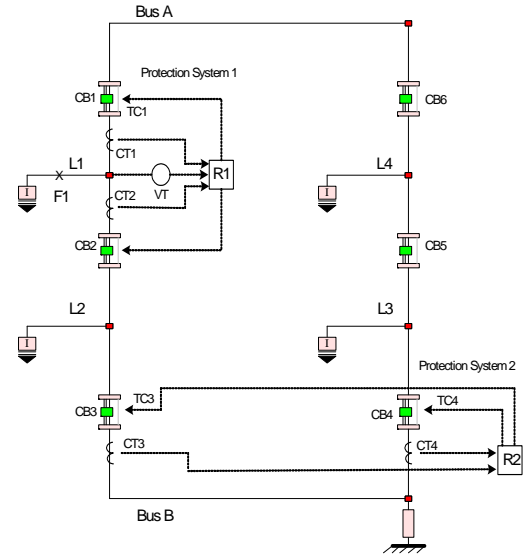


Figure 1. A breaker-and-a-half bus arrangement substation model

### B. Protection System Hidden Failures

Each of protection system components may suffer from hidden failures depending on its inherent mechanism. Some possible hidden failures of major protection system components are briefly analyzed below.

#### Current Transformer (CT)

After a fault occurs, fault currents may lead the current transformer core into saturation situation, in which the secondary current of the current transformer can not faithfully represent the primary current.

#### Voltage Transformer (VT)

For some voltage transformers, such as coupling capacitor voltage transformers (CCVTs), when a fault occurs and causes system voltage decreasing from the normal value to a low value, the output of the voltage transformer may be significantly different from the actual primary voltage during the transient procedure.

#### Relay

When the system operating condition changes, if the setting of an influenced relay does not change accordingly, the relay may fail to detect the system status correctly under system disturbances and operate inappropriately as a result of the outdated setting in the relay.

#### Circuit Breaker

Any failures in the trip mechanism of a circuit breaker, such as the open circuit of trip coils and the failure to separate circuit breaker plates because of welding or obstacles in plate motion paths, will lead the circuit breaker fail to trip when it is required to open the circuit.

### C. Impact of Advanced System Monitoring and Analysis Technologies

Nowadays, besides conventional RTUs, a variety of intelligent electronic devices (IEDs) become available in power system substations, including phasor measurement units, digital protection relays, and so on. Compared to the limitation, inaccuracy, and delay in traditional SCADA data, more redundant, accurate, and real time system measurements can be obtained from these IEDs. Based on IED data, substation level system information extraction functions, such as substation level state estimation and alarm processing, can significantly advance the capability of the system real time monitoring and analysis.

The advanced system real time monitoring and analysis functions brought by the application of IEDs can detect protection system hidden failures existing in transducers and relays considerably. In particular, the real time validation and verification can be performed for transducer outputs and relay settings. If any hidden failures exist in CTs or VTs that cause their outputs fail to reflect actual primary system statuses, the substation level state estimation based on IED measurements can identify bad data in a fast and reliable way. In addition, based on the real time synchronized measurements of system states obtained from the phasor measurement units, the real time system model can be built and relay settings can be verified on line to avoid misoperations caused by relay outdated settings. However, such advanced monitoring and analysis techniques can not detect the trip abilities of circuit breakers ability. Hidden failures in the circuit breaker trip mechanisms will remain uncovered until circuit breakers fail to open during system disturbances. Hence, in this work, the consideration of protection system hidden failures concentrates on hidden failures in the circuit breaker trip mechanism.

### D. Probabilistic Modeling of Hidden Failures in the Circuit Breaker Trip Mechanism (CBTM)

This section presents the probabilistic modeling of hidden failures in the CBTM. For the example substation model shown in Figure 1, which has six circuit breakers, the independent and common mode hidden failure models of the corresponding CBTMs are described below.

#### Independent Hidden Failures of CBTMs

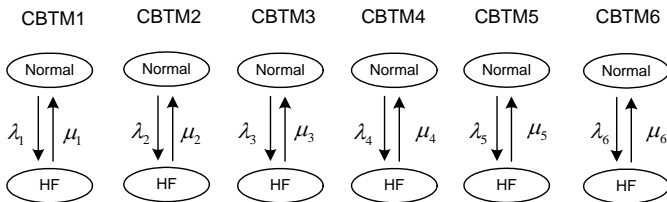


Figure 2. Two-state Markov models of CBTMs

Each CBTM can cycle between normal and hidden failure statuses. This process can be modeled as a two-state Markov process with constant transition rates. We assume that the occurrences of such hidden failures are independent with their own failure and repair rates. Two-state Markov models for the six CBTMs (CBTM1 to CBTM6) are shown in Figure 2, in

which  $\lambda_x$  and  $\mu_x$  represent failure and repair rates of each CBTM, respectively.

The differential equations that govern transitions for each CBTM between the normal and hidden failure statuses are:

$$\frac{d\mathbf{p}_x(t)}{dt} = \mathbf{p}_x(t)\mathbf{A}_x, \quad (1)$$

where  $\mathbf{p}_x(t)$  is the row vector that contains normal and hidden failure status probabilities (i.e.,  $p_x(t)$  and  $q_x(t)$ ) of each CBTM  $X$ ,

$$\mathbf{p}_x(t) = [p_x(t), q_x(t)]. \quad (2)$$

Also, the probabilities of normal and hidden failure statuses for each CBTM satisfy the following condition:

$$p_x(t) + q_x(t) = 1, \quad (3)$$

where  $0 \leq p_x(t) \leq 1$  and  $0 \leq q_x(t) \leq 1$ .

In addition,  $\mathbf{A}_x$  is the transition intensity matrix for CBTM  $X$ , i.e.,

$$\mathbf{A}_x = \begin{bmatrix} -\lambda_x & \lambda_x \\ \mu_x & -\mu_x \end{bmatrix}. \quad (4)$$

The initial condition represents a CBTM with the probability of normal status set to one and the probability of hidden failure status set to zero.

$$\mathbf{p}_x(0) = [1 \ 0].$$

The solution to the above differential equations gives the probabilities of normal and hidden failure statuses of each CBTM  $X$ :

$$\begin{aligned} p_x(t) &= \frac{\mu_x}{\lambda_x + \mu_x} + \frac{\lambda_x}{\lambda_x + \mu_x} \exp(-(\lambda_x + \mu_x)t), \\ q_x(t) &= 1 - p_x(t) = \frac{\lambda_x}{\lambda_x + \mu_x} - \frac{\lambda_x}{\lambda_x + \mu_x} \exp(-(\lambda_x + \mu_x)t). \end{aligned} \quad (5)$$

If only long-term status probabilities are of interest, the normal and hidden failure status probabilities of each CBTM are expressed as following:

$$p_x(\infty) = \frac{\mu_x}{\lambda_x + \mu_x}, \quad q_x(\infty) = \frac{\lambda_x}{\lambda_x + \mu_x}. \quad (6)$$

For the substation shown in Figure 1, each combination of the operational statuses of six CBTMs constitutes a substation state. The different combinations of CBTM statuses generate a total of 64 ( $2^6$ ) substation states in its state space. Part of this state space (states 1 to 16) is shown in Table 1.

Table 1 Partial State Enumeration for the Example Substation (States 1-16)

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
CBTM1		X						X	X	X	X	X				
CBTM2			X					X					X	X	X	X
CBTM3				X					X				X			
CBTM4					X					X				X		
CBTM5						X					X				X	
CBTM6							X					X				X

X indicates a hidden failure status of the CBTM

Because we assume that hidden failures of CBTMs are independent, the probability of each substation state can be obtained by multiplying the probability of each CBTM status. For example, for substation state 3 in Table 1, in which CBTM2 is in the hidden failure status, all others are in the normal status, the probability for this substation state is calculated as follows:

$$p_{s3}(t) = p_{CBTM1}(t)q_{CBTM2}(t)\prod_{i=3}^6 p_{CBTMi}(t) \quad (7)$$

The sum of the substation state probabilities is forced to 1 simply because the total 64 states are mutually exclusive and their union forms the certain event, i.e. ,

$$\sum_{k=1}^{64} p_{sk}(t) = 1 \quad (8)$$

#### Common Mode Hidden Failures of CBTMs

The independent hidden failure model of CBTMs prevents considering common mode failures that involve simultaneous hidden failures of two or more CBTMs as the result of a single outage event. For example, a loss of the power resource, which supplies power to two or more trip coils, can cause multiple circuit breakers the enter hidden failure status simultaneously. When considering common mode hidden failures of CBTMs in the substation shown in Figure 1, differential equations that govern the transitions among substation states, initial conditions, and sum of probabilities are given below:

$$\begin{aligned} \frac{d\mathbf{p}_s(t)}{dt} &= \mathbf{p}_s(t) \cdot \mathbf{A}_s \\ \mathbf{p}_s(0) &= [1 \ 0 \ 0 \ \dots \ 0] \\ \sum_{k=1}^{64} p_{sk}(t) &= 1, \end{aligned} \quad (9)$$

Where  $\mathbf{p}_s(t)$  is the row vector of substation state probability, and  $\mathbf{A}_s$  is the substation transition intensity matrix. Off-diagonal terms (i, j) of matrix  $\mathbf{A}_s$  have the failure/repair rate from state  $i$  to state  $j$ , and diagonal terms are the negative sum of failure and repair rates of all transitions from the current state to an adjacent state (transition rates found in the same row). The sum of all elements in each row of the transition matrix is zero. The initial state is assumed to be at the state 1 in Table 1, in which every component works in the normal

status. The solution to the differential equations gives the probability of each substation states at any instant of time.

#### E. CBTM Hidden Failure Effects Analysis

Hidden failures in CBTMs can cause the trip of intact equipment following system disturbances, which reduces the system reliability level. In this section, an approach of CBTM hidden failure effects analysis for each system substation is proposed to obtain possible hidden failure outages following any initial faults. The proposed hidden failure effects analysis procedure is illustrated by the example substation shown in Figure 1.

We assume that the substation is operating under state 3 as enumerated in Table 1, in which the trip mechanism of circuit breaker 2 (CBTM2) has a hidden failure that can cause circuit breaker 2 (CB2) fail to open and all other circuit breakers are in the normal operating status. If an initial fault F1 occurs to transmission line L1 as shown in Figure 1, circuit breakers 1 and 2 should open to isolate the faulty circuit L1 accordingly. Since CB2 fail to open due to its hidden failure, circuit breaker 3 (CB3) that is adjacent to CB2 will open and then cause the outage of intact transmission line L2 following the initial fault on transmission line L1. The conditional probability of the hidden failure outage of transmission line L2, given the incidence of the initial fault on L1, is the product of the occurrence probability of the example substation is in state 3 and the probabilities of all other substations in their specific states, which is represented as following:

$$P_{cd\_s3}(t) = p_{s3}(t) \prod_{i=1}^N p_{ik}(t) \quad ,$$

where

$p_{s3}(t)$  : the probability of the example substation is in state 3

$p_{ik}(t)$  : the probability of the substation  $i$  is in state  $k$

$N$  : the total number of the rest substations in the system

Such effects analysis procedure can be repeated for all other possible initial faults. The results, including initial faulty circuits, associated hidden failure outages, and corresponding conditional probabilities are listed in Table 2. We can see that the initial faults on L1 or L2 will cause the outages of intact equipment in the substation under state 3, while the initial faults on other components do not cause any hidden failure outages. For the example substation, there are total of 64 states, a cut-off probability can be predefined to reduce states in the state space that are subject to hidden failure effects analysis. The states with probabilities less than cut-off probability will not be considered due to their small incidence. Furthermore, the hidden failure effects analysis procedure can be performed for every substation state and all substations in the system.

Table 2 Effects Analysis for Substation State 3

Initial Fault	Hidden Failure Outage	Conditional Probability
Fault on Bus A	N/A	N/A
Fault on L1	L2	$P_{cd\_s3}(t)$
Fault on L2	L1	$P_{cd\_s3}(t)$

Fault on Bus B	N/A	N/A
Fault on L3	N/A	N/A
Fault on L4	N/A	N/A

### F. Security-Constrained Adequacy Evaluation for Bulk Power System Reliability

The security-constrained adequacy evaluation (SCAE) approach is a comprehensive approach for bulk power system reliability assessment, which was developed by authors recently to evaluate system contingencies resulting from independent outages and common-mode outages. To assess bulk power system reliability including the effects of protection system hidden failures, the SCAE approach is extended to evaluate contingencies resulting from protection system hidden failures. Specifically, the hidden failure effects analysis is first performed on each power system substation to obtain possible contingencies resulting from hidden failure outages as well as their conditional probabilities given the occurrence of initial system disturbances, and then contingencies resulting from hidden failure outages along with other system contingencies resulting from independent and common-mode outages are subject to the SCAE approach to obtain their influence on system reliability. In this section, we only provide a briefly description about the SCAE approach, the detailed information can be found in [12-14].

The SCAE approach is implemented using analytical techniques and encompasses three main steps: (1) critical contingency selection and ranking, (2) contingency effects analysis, and (3) reliability index computation. To improve the accuracy and efficiency of steps 1 and 2, an advanced power flow model, i.e., the single phase quadratized power flow (SPQPF) model [16], is utilized as a basis in the SCAE approach. The SPQPF model is set up based on applying Kirchhoff's current law at each bus, with the intention that most of power flow equations are linear in a large-scale system. Also, system state variables (bus voltage phasors) are expressed in Cartesian coordinates to avoid trigonometric terms. Moreover, all power flow equations are quadratized, for which the Newton's method is ideally suitable to solve. Such formulation of SPQPF model provides superior performance in two aspects compared to the traditional power flow model: (1) faster convergence and (2) ability to model complex load characteristic in the quadratized form.

The objective of critical contingency selection and ranking is to identify the most critical contingencies that may lead to system unreliability from the entire system state (contingency) space in an approximate but fast way. An advanced performance index based contingency ranking method, i.e., the system state linearization method, and an improved wind-chime contingency enumeration scheme [17] were developed to conduct critical contingency selection and ranking. Such developed techniques can reduce misranking considerably compared to the traditional performance index linearization method used in the contingency selection and ranking.

After critical contingency selection and ranking, contingency effects analysis is performed to evaluate critical

contingencies against certain system failure criterion, such as the loss of system load, to examine if these contingencies violate the criterion and therefore represent the system failure. Contingency effects analysis is the most essential but computationally demanding procedure in the reliability assessment. It is important to simulate contingencies in a realistic manner to capture the system response including all major operational practices. The simulation of contingencies must also be efficient so that the overall computational effort of reliability assessment is reasonable. The effects analysis based on traditional power flow technology many times breaks down (non-convergence), especially when multi-level contingences are considered and the system is severely stressed.

In the SCAE methodology, a non-divergent optimal quadratized power flow (NDOQPF) algorithm [12] is proposed for contingency effects analysis, which can simulate contingencies efficiently in a realistic manner. In the NDOQPF algorithm, major system operational practices are taken into account, and a constrained optimization problem incorporating security constraints is formulated to solve for post-contingency solution. The non-divergence of power flow is achieved by introducing fictitious bus injections that are driven to zero as the solution progresses. It guarantees convergence if a solution exists; if a solution does not exist, it provides a suboptimal solution that may include load shedding. The NDOQPF algorithm is capable of efficiently solving the RTO/ISO operational model in the deregulated environment as well. Such RTO/ISO operational procedure is formulated as an optimization problem with the objective function being the bid cost function and congestion constraints.

The SCAE framework also includes reliability index computations. Reliability indices are computed on the basis of identifying the set of system contingencies that satisfy a specific failure criterion and using the transition rates from any contingency inside the set to a contingency outside the set. Three different classes of reliability indices, i.e., probability, frequency, and duration indices of the system failure, can be computed [14].

### III. CASE STUDY

The proposed methodology for evaluating the impact of protection system hidden failures on bulk power system reliability is demonstrated with a breaker-oriented 24-substation reliability test system as shown in Figure 3. This breaker-oriented system model is mostly derived from the original IEEE 24-bus reliability test system (RTS) developed by the IEEE Reliability subcommittee and publicized in 1979 [18]. The original IEEE 24-bus RTS is a bus-oriented system, and the approach that has been used to develop the breaker-oriented model is to replace each node (bus) of the original system with a substation that has specific bus arrangement (ring, breaker and a half, and so on). As a result, the bus arrangement at each node and the location of each circuit breaker become the explicit part of the system network model.

As an example, bus 180 of the original IEEE 24-bus RTS, which connects to one unit, three transmission lines, and one system load, is replaced with the substation 180 of a mixed breaker-and-a-half and double-breaker scheme as illustrated in Figure 4. The overall conversion procedure from the original bus-oriented system to the breaker-oriented system amounts to replacing each bus of the original IEEE 24-bus RTS with a substation. To make the system model interesting and more realistic, we have selected a variety of bus arrangements, such as breaker-and-a-half, double-breaker, ring bus, and so on. Therefore, the proposed breaker-oriented reliability test system includes substations of various breaker arrangements with different reliability levels. A summary of the substation topology is provided in Table 3.

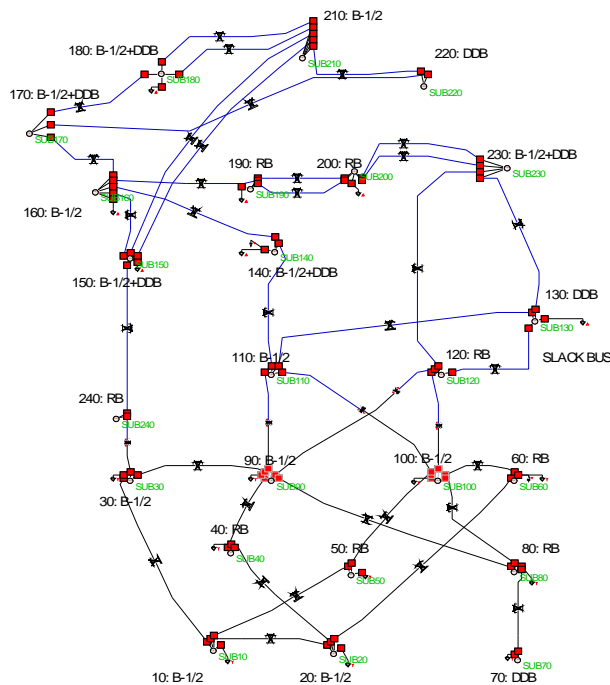


Figure 3. Breaker-oriented three phase 24-substation reliability test system

Based on the breaker-oriented system model, the effects analysis of CBTM hidden failures is performed for each substation. We consider two different levels of CBTM hidden failure probabilities to illustrate the impact of different CBTM hidden failure probability levels on bulk power system reliability. Note only independent hidden failure outages are concerned in the CBTM hidden failure effects analysis. Considering substation 180 under these assumptions, contingencies resulting from hidden failure outages are listed in Table 4. The obtained results include the initial faulty circuit and the corresponding hidden failure outage.

After contingencies resulting from CBTM hidden failures for all substations are obtained and consolidated, the security-constrained adequacy evaluation approach is applied to evaluate contingencies resulting from independent, common-mode, and hidden failure outages. In this procedure, the system peak load level is applied, and system remedial actions

include generating unit real and reactive power adjustment, shunt reactor bank switch, and load shedding. If any of such contingencies result in the system loss of load, which is defined as system failure, such contingencies have nonzero contribution to system unreliability. The evaluation results show that six contingencies that result from independent outages, two contingencies that result from the common-mode outages, and seventy-nine contingencies that result from hidden failure outages lead to system unreliability. These contingencies are provided in Table 5, in which only part of contingencies resulting from hidden failure outages are listed. It can be seen that most of such contingencies that result in system failures are contingencies resulting from hidden failure outages because of intact system component outages following the initial system faults making the stressed system situation worse.

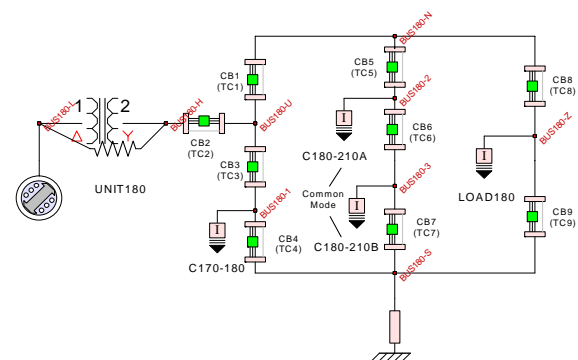


Figure 4. Breaker-oriented model of substation 180

Table 3 Summary of Substation Topologies

Bus Arrangement	Substation No.
Double-breaker (DDB)	70,130, 220
Breaker-and-a-half (B-1/2)	10,20,30,90,100,110,160,210
Mixed double-breaker and breaker-and-a-half (B-1/2+DDB)	140,150,170,180,230
Ring-bus (RB)	40,50,60,80,120,190,200,240

Table 4 Summary of effects analysis for Substation 180

Initial Faulty Circuit	Hidden Failure Outage
Fault on BUS180-U	C170-180
Fault on C170-180 or BUS180-1	UNIT180
Fault on C180-210A or BUS180-2	C180-210B
Fault on C180-210B or BUS180-3	C180-210A
Fault on BUS180-N	UNIT180
	C180-210A
	LOAD180
Fault on BUS180-S	C170-180
	C180-210B
	LOAD180
Fault on UNIT180	N/A
Fault on LOAD180 or BUS180-Z	N/A
Common Mode outage of C180-210A and C180-210B	N/A

The reliability indices of probability, frequency, and duration of such system loss-of-load event are calculated for both situations with and without the consideration of contingencies resulting from hidden failure outages. In the

situation that contingencies resulting from hidden failure outages are included, reliability indices are calculated for three cases that have different CBTM hidden failure probabilities. All these Results are shown in Table 6, which show that hidden failures in protection systems can downgrade the system reliability level and such influence increases with the increase of the CBTM failure probability.

Table 5 SCAE of First Level Contingencies for 24-Substation System (C: Circuit G: Generator)

Contingency Type	Contingency No.	Outage Component
Independent outages	1	C60-100
	2	C150-240
	3	C30-240
	4	C160-170
	5	C20-60
	6	C120-230
Common-mode outages	7	C70-80, G70-1,2,3
	8	C150-210A, C150-210B
Hidden failure outages	9	C30-90, C30-240
	10	C20-40, C40-90
	11	C50-100, C10-50
	12	C60-100, C20-60
	13	C80-100, C80-90
	14	C60-100, C50-100
	15	C110-140, C140-160
	16	C160-190, C160-170
	17	G180, C170-180
	18	C30-240, C150-240

Table 6 Comparison of reliability indices with and without hidden failure contingencies

Reliability Index	w/o contingency from HF	with contingencies from HF	
		Case 1	Case 2
Probability	1.113e-3	1.188e-3	1.685e-3
Frequency(/yr)	0.4425	0.4586	0.6034
Duration(hrs/yr)	22.03	22.68	24.68

Note: Hidden failure probabilities of CBTMs are at the level of  $10e-3$  in case 1 and  $10e-2$  in case 2.

#### IV. CONCLUSIONS

This work investigates the effects of protection system hidden failures on bulk power system reliability. Explicit breaker-oriented substation models are integrated in the network model to consider the influence of protection systems. Advanced system monitoring and analysis technologies can detect hidden failures in transducers and relays in protection systems considerably, as a result, hidden failures in circuit breaker trip mechanism that cause the circuit breaker fail to trip is the major concern in this work. Intact power system component outages due to such hidden failures are obtained for each substation under all possible initial system disturbances through hidden failure effects analysis. Contingencies resulting from independent, common-mode, and hidden failure outages are subject to the security-constrained adequacy evaluation to assess bulk power system reliability. The proposed power system reliability evaluation framework is demonstrated with a breaker-oriented 24-substation reliability test system. Evaluation results show that hidden failures in protection systems can downgrade the system reliability level as a result of the outages of intact

equipment following the initial system disturbances making the stressed system situation even worse. Therefore, it is important to include the impact of protection system hidden failures on system reliability in the reliability assessment procedure to obtain more realistic system reliability information.

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