Analysis of Power System Reliability Considering Protection Failures

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Abstract- **This paper describes evaluation of power system reliability including failures of protection system. A protection reliability model system is modified including two major protection failure modes is entrenched. The main cause of cascading outages is Protection system failure. The mechanism and scheme of protection system have been eveluated on their contribution to the cascading outages after a fault occurs. To implement the stochastic properties of component contingency and protection system failure Nonsequential simulation approach is used. The procedure is authenticated in the IEEE-9 bus system. BIP (Bus Isolation Probability), LOLP (Loss of Load Probability), and LOEE (Loss of Expected Energy) are calculated to exhibit the susceptibility of a power system under cascading outages.**

Index terms- **Power system, Reliability, Protection systems, Cascading.**

I.INTRODUCTION

Modern power systems have ambulated into the post establishing era, in which utility industry as well as ISO are involved. Consideration to the reliability study of power systems both in the utility companies and the ISO. Extensive progress has been made in power system reliability modeling and computational methods. In most reliability analysis, protection systems are broadly pretended to be perfectly reliable. Generally power system blackouts result from cascading failures. There are many blackout cases in history such as Northern grid blackout on2 January 2001; also Northern and North-eastern grid blackout on 30 and 31 July 2012; etc. India attested blackout on 2 January 2001 due to the collapse of the Northern grid, which afflicted approximately 230 million northern Indians depending on the second biggest interconnected network in the country.

Two relentless power blackouts afflicted most of northern and eastern India on 30 and 31 July 2012. The 30 July 2012 blackout impaired over 400 million people and was briefly the largest power outage in history by number of people affected, beating the January 2001 blackout in Northern India The blackout on 31 July is the largest power outage in history. The outage concerned more than 620 million people, about 9% of the world population, or half of India's population, spread across 22 states in Northern, Eastern, and Northeast India. An approximated 32 gigawatts of generating capacity was taken offline.

All these blackouts are associated to protection system hidden failures, which remain camatoset when everything is normal and are bared as a result of other system disturbances . There is progressive evidence that protection systems have illustrated in the origin and propagation of major power system disturbances. In the deregulated power systems where pecuniary consequences are involved, the ability to keep the cohesion of power supply becomes more compelling. Vast scale power system blackout is a rare event. Nonetheless, when it occurs, the impact on the system is destructive. Protection system breakdown plays a compelling role in the sequence of events that lead to power system blackouts. Nonetheless, not much effort has been spent on the study of the cascading events due to protection system breakdown. Therefore it is necessary to develop reliability study methodology regarding the protection system failures.

II. PROTECTION FAILURE MODES AND CASCADING OUTAGES

There are two main failure modes of protection system: “failure to operate” and “undesired tripping”. The former refers that when a fault occurs in a power system, the protection system refuses to operate to clear the fault. In practice, phenomenon of stuck breaker is included in this mode. The latter one means to either spontaneous operation in the absence of a fault or trip for faults outside the protection zone. A cascading outage refers to a series of tripping introduced into by one component failure in the system. When a fault occurs, the impact to the system such as over-current or voltage dropping may cause some protection devices to mis-operate. As we mentioned before, two types of protection system failures are the major cause of cascading outages. From the viewpoint of real life protection scenario, we can describe that "Failure to operate" will directly cause at least one bus isolation in the system. "Undesired tripping", nonetheless, makes the problem complicated due to various protection system hidden failures. Spectral tripping in the absence of a fault may be alleviated immediately by auto-recloser. This situation can be encountered and does not have any significant effect on the system reliability. Therefore, it is not within our study scope in this paper. Tripping for faults outside the protection zone is the main cause of the cascading outages.

III. MODEL AND ASSUMPTIONS

A. Model

There have been a number of models entrenched to facilitate the reliability evaluation including protection system failures. The model of current-carrying component paired with its correlated with protection system proposed by Singh and Patton is effective for general reliability analysis. Nonetheless, it doesn't differentiate protection failure modes. In this paper, therefore, the model is broaden to include the failure modes of protection system as shown in Fig. 1, where:

State 1: the current-carrying component and the protection system are both good.

State 2: the component is good but the protection is at risk for "undesired trip".

State 3: the component is good but the protection is exposed to "failure to operate".

State 4: the component is good and the protection system is being inspected.

Stage 5: the component is failed while the protection system is still under "undesired trip"

State 6: the component is failed but the protection system is good.

State 7: the component is failed while the protection system has experienced "failure to operate".

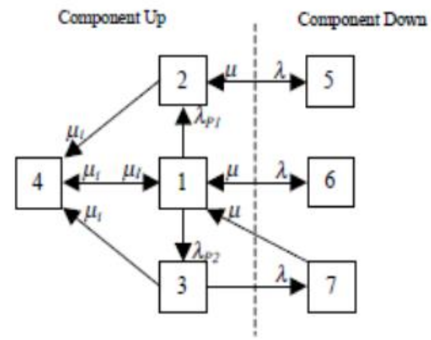

Fig. 1. State transition diagram of a component and its protection system.

B. Notation

μ_i inspection rate of protective system.

μ_I repair rate of protection system.

μrepair rate of component.

λ failure rate of component.

λ_{P1}failure rate of protection system to exposure to "undesired trip".

λ_{P2}failure rate of protection system to state of "failure to operate"

C. Assumptions

1. Failure to operate and undesired trip of the protection system failure do not overlap. That means whenever unrevealed protection failure exists, it will reside either in state 2 or state 3.
2. When component fails, the protection system does not fail.
3. All failures are mutually independent. Failures of the protection system are independent of the failures of the component.
4. Inspection of protection system does not lead to component failure.

Based on this model, we can get protection system failure probability with regard to its inspection. The derived data can be used in our following study.

IV. METHODOLOGY

A. Basic Methodology

As shown in Fig.2, suppose a fault occurs in L-1, normally protection system for this line will operate to clear the fault. L-2 and L-3, sharing the same bus with the faulted L-1, are exposed lines that are at risk to trip also.

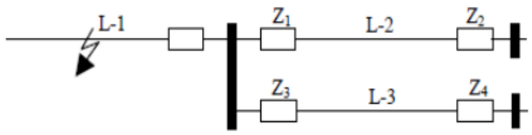

Fig. 2. Sequence of cascading outage

If L-2 trips for its protection system failure, then up to thisstep the probability of cascading outage can be calculated by:

P(cas)=Pf(L-1) * Pf (Z1UZ2)* (1-Pf (Z3UZ4)) (1)

where

P(cas) probability of cascading outage.

Pf(L-1) probability of L-1 failure.

Pf(Z1UZ2) probability of the union of protection system Z1 and Z2 failure

Pf(Z3UZ4) probability of the union of protection system Z3 and Z4 failure

B. Protection System Failure Properties

In this paper, we introduce some simplification for the probability properties. For distance protection scheme, property is shown in Fig. 3.

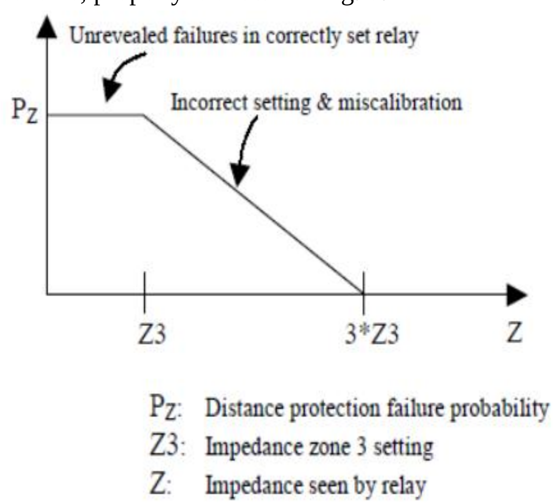

Fig. 3. Distance protection failure probability of exposed line

Similarly, we give over-current protection failure probability property as shown in Fig. 4. Fig. 3 and Fig. 4 show that the probability of exposed line tripping incorrectly is not simply a fixed value as derived from Markov model in Fig.1. On the contrary, it is also dependent on the fault and operating conditions.

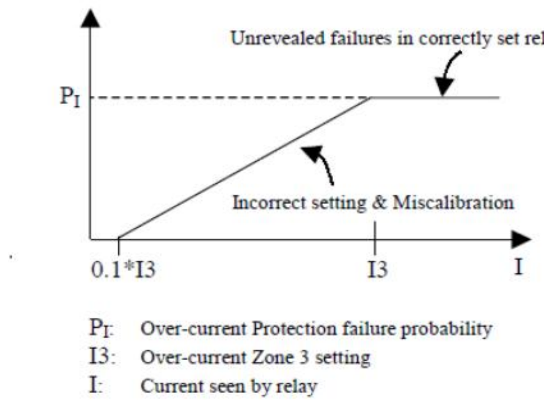

Fig. 4. Over-current protection failure probability of exposed line

C. Assumptions in Calculations

In calculations, we are only concerned about the distance protection zone 3 and over-current zone 3. We choose zone 3 impedance setting as 250% of the line impedance; zone 3 over-current setting as 10% of the rated secondary current of CT (Current Transformer). Besides the above description, additional assumptions are

made as follow:

1. Generator and transformer are treated as one unit whose failure rate is the sum of their individual failure rates.
2. For the initial fault, only first order contingency is considered.

V. RELIABILITY INDICES

According to the assumptions made, any system condition with two and more components outage is caused by protection system failure.

In this paper, we calculate

1) BIP (Bus Isolation Probability).

$$BIP = \sum_{i} I_i/N \qquad (2)$$

Where i is the element of set of bus isolation.

Ii is the number of system state *i.*

N is the total number of simulations.

Bus isolation is a major disturbance to the power system.

BIP shows the weakness of system in which one component outage might result in bus isolation.

In simulation, “bus isolation” is the criterion to stop for a series of outages. This means that as the series of outages progress, it is stopped as soon as a bus is isolated.

2) LOLP (Loss of Load Probability).

$$LOLP = \sum_{i} \frac{L_i}{N} \quad (3)$$

Where *i* is the element of set of load curtailment.
Li is the number of system state *i*.
N is the total number of simulation.

Normally power system can withstand one component outage without adequacy and security violation. Based on our assumption, here the LOLP represents the loss of load resulting from protection system failure. Since we are concerned here with loss of load, the series of outages is stopped as soon as a loss of load occurs.

3) LOEE (Loss of Expected Energy).

$$LOEE = \sum_{i} \frac{C_i}{N} \quad (4)$$

Where *i* is the element of set of completion of cascading outages.
Ci is the load curtailment of system state *i*.
N is the total number of simulation.

This index with unit of "MW" can numerically show the impact to the system by cascading outage. In simulation, no artificial stop criterion for a series of outages is used for calculating this index. The series of outage will keep extending until no more new outage occurs.

VI. CALCULATION OF RELIABILITY

A. Formulation of OPF

In the process of calculating LOLP and LOEE, OPF (optimal power flow) is used to determine the occurrence and the amount of load curtailment of the system. OPF formulation is shown as below:

Objective:

$$min \sum_{i=I}^{n} (Load\ Curtailment)_i \quad (5)$$

Where $(Load\ Curtailment)_i = P_{di} - P_{li}$

ST:

$$P_{gi} - P_{li} - \sum_{j=1}^{n} U_i U_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) = 0$$

$$Q_{gi} - Q_{li} - \sum_{j=1}^{n} U_i U_j (G_{ij} \cos\delta_{ij} - B_{ij} \sin\delta_{ij}) = 0$$

i=1,…,n

$$P_{gi\,min} \le P_{gi} \le P_{gi\,max}$$

$$Q_{gi\,min} \le Q_{gi} \le Q_{gi\,max}$$

i=1,…,ng

$$0 \le P_{li} \le P_{di}$$

$$0 \le Q_{li} \le Q_{di}$$

i=1,…,nd

$$U_{i\,min} \le U_i \le U_{i\,max}$$

i=1,…,n

$$P_{ij}^2 + Q_{ij}^2 \le S_{ij\,max}^2$$

ij∈[1,…,nb]

where

n, *ng* , *nd*, *nb* are the number of node, generator node, load node and branch;
Pgi, *Qgi* are the real and reactive output of the generator;
Pgimin, Pgimax are the min/max real power of the generator;
Qgimin, Qgimax are the min/max active power of the generator;
Pli, *Qli* are the load after rescheduling of generation;
Pdi, *Qdi* are the actual demand;
Ui is the voltage magnitude;
Uimin, Uimax are the voltage magnitude limits;
Pij, Qij are the line flow;
Sijmax is the line flow limit.

B. Flowchart

Non-sequential Monte Carlo simulation approach is applied to calculate all reliability indices. The sequence of simulation steps is shown in Fig. 5 and Fig. 6.

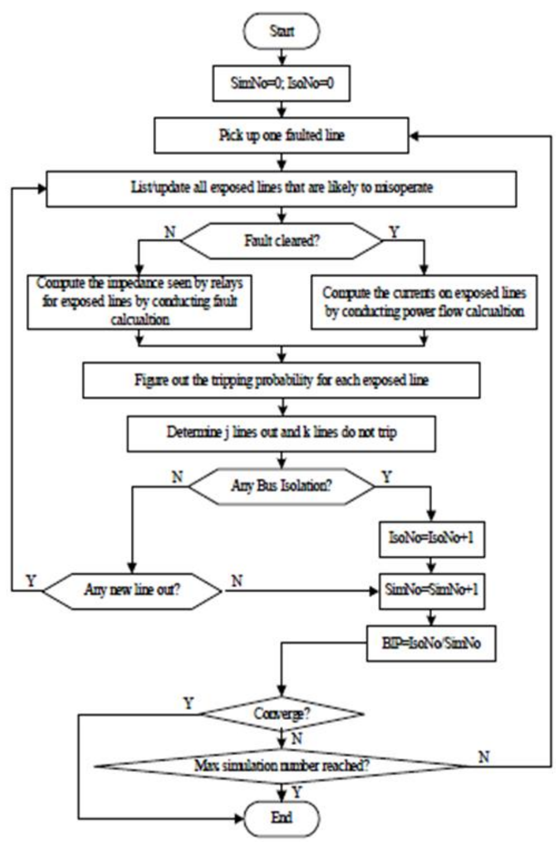

Fig. Flowchart for calculating bus isolation probability

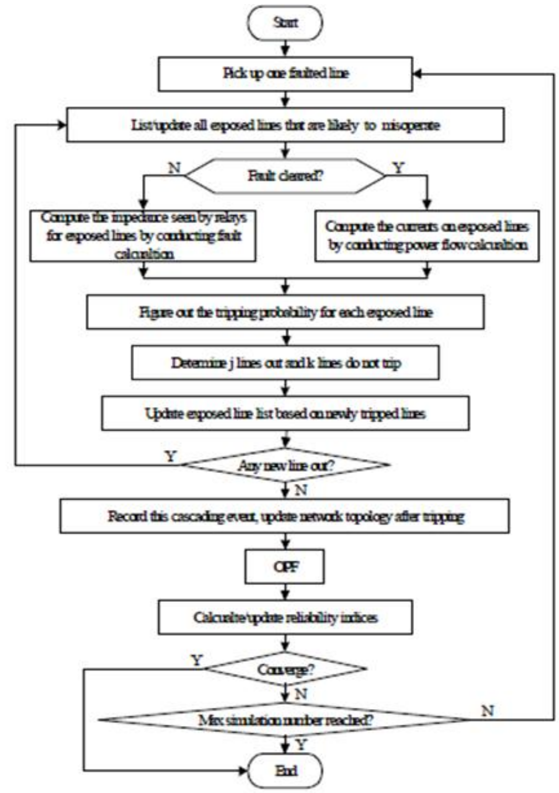

Fig. Flowchart for calculating LOLP and LOEE

C. Test System

We use WSCC-9 bus system as the test system (shown in Fig. 7). Because it is not complex, it clearly provides insight into cascading outages.

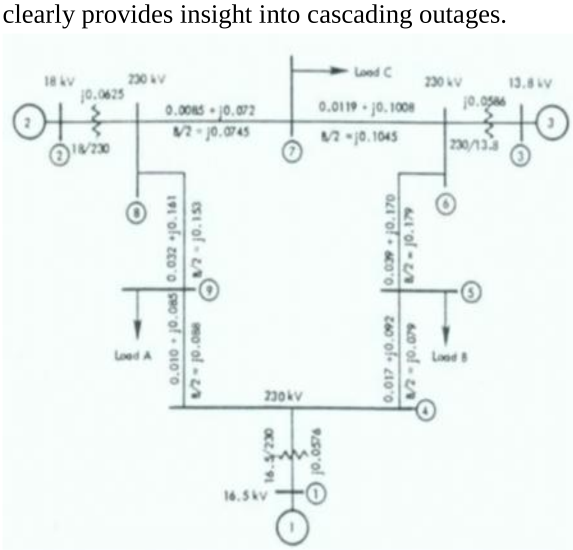

Fig.7. IEEE-9 bus system

VII. CONCLUSION

In this paper, a more specific model of component aligned with protection system is established to include two types of protection failures. Based on this model, a simulation approach is refined to simulate system behavior under cascading outages. Besides common reliability indices such as LOLP, one new index LOEE is introduced to depict the asperity of the impact by cascading outages. Diverse power systems may have different reliability indices due to their different network topologies, installation capacities, and protection devices/scenarios

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