Determination of Severe Loading Condition at Critical System Cascading Collapse Considering the Effect of Protection System Hidden Failure

N. A. Salim, M. M. Othman, I. Musirin, and M. S. Serwan

Abstract**—**Hidden failure in a protection system has been recognized as one of the main reasons which may cause to a power system instability leading to a system cascading collapse. This paper presents a computationally systematic approach used to obtain the estimated average probability of a system cascading collapse by considering the effect of probability hidden failure in a protection system. The estimated average probability of a system cascading collapse is then used to determine the severe loading condition contributing to the higher risk of critical system cascading collapse. This information is essential to the system utility since it will assist the operator to determine the highest point of increased system loading condition prior to the event of critical system cascading collapse.

Keywords**—**Critical system cascading collapse, protection system hidden failure, severe loading condition.

I. Introduction

POWER system is a complex interconnected system with the aim of supplying electric power to the consumer. In a large-scale networked systems, the electric power system has become increasingly automated in the past few decades as a result of technological advancement [1]. Due to this situation, an unintentional failure of one equipment due to the misoperation of a relay will produce significant destruction to the interconnected system. The disastrous disturbance is often triggered causing to a system cascading collapse while the grid is generally operating close to critical loading [2]. A number of severe blackouts that had happened around the world recently have resulted severe consequences to the national economy and social life [3]. The most current blackout had happened in India on the 30th and 31st July 2012, where over 620 million citizens all over the country were affected [4], which is equal to 9% of the world's overall population. The historical information on some other major blackouts afflicted by the system cascading collapse can be found in [5]-[7]. Since the effect of blackout could be catastrophic to the power system, therefore innovative approach is required in order to investigate the challenges in security planning to avert any turbulence which may occur to a large grid system.

There are various models used to study the impact of cascading collapse in a complex network system. The OPA model studied in [8-11] is a blackout model in power system that represents probabilistic cascading line outages and overloads. Its initial outage is generated by random selection of line outages and load variation. Meanwhile, CASCADE model explored in [12-14] is a probabilistic model of a system cascading collapse which depends on the system loading condition. Even though this model can analyze major blackouts, it assumes all transmission lines are identical. According to [15], more than 70% of power system major disturbances are caused by the hidden failure of a protection system. Many researchers [16-18] have studied its significant impact to a catastrophic power system condition.

Therefore, it is essential to investigate the consequence of cascading collapse as its impact to a power system is significant. In view of that, this paper put forward a computational useful technique of system cascading collapse considering the effect of protection system hidden failure. The study is performed in order to investigate the impact of different value of hidden failure probability to the average probability of cascading collapse and critical system loading condition. In this analysis, the determination of critical system loading condition is conducted according to the criticality of the system cascading collapse. The IEEE RTS-96 is used as a test system to confirm the effectiveness of the proposed technique considered in the assessment of system cascading collapse. Since the impact of system cascading collapse is catastrophic, therefore the assessment of cascading collapse should be done in the power system operation and planning in order to identify the critical loading condition which may cause critical system cascading collapse.

II. Determination of Severe Total Loading Condition Derived from the Critical Cascading Collapse

This section will discuss on the methods used to estimate the probability of cascading collapse considering different case studies of hidden failure probability which are $p_{HF} = 8\times10^{-7}$ [15], $p_{HF} = 1\times10^{-12}$ and $p_{HF} = 1\times10^{-2}$ [19]. The results of average probability of cascading collapse, $\mu(\hat{P}_{C_l})$ for each

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N. A. Salim is with the Faculty of Electrical Engineering, Universiti Teknologi MARA, 13500 Pulau Pinang, Malaysia. (e-mail: ashida_amani@yahoo.com)

M. M. Othman and I. Musirin are with the Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia. (e-mail: mamat505my@yahoo.com)

M. S. Serwan is with the Advanced Power Solution Sdn. Bhd., Worldwide Business Centre, Jalan Tinju 13/50, 40000 Shah Alam, Malaysia.

case study will be further analyzed in order to determine the severe total loading condition which may cause critical cascading collapse of a power system. The proposed algorithm starts with an initial tripping event of a transmission line. At the same time, the power flow solution is performed by considering 10% increased of the total system loading condition. After that, for each exposed lines connected next to the tripping line, determine the probability of incorrect tripping, p_{HF} [17]. Based on the excerption drawn from the NERC report, in the past 16 years that is from 1984 to 1999, there are 400 events of cascading collapse occurred, caused by the hidden failure of a line protective relay [20]. Even though the probability for one exposed line tripping event due to hidden failure is extremely small, yet, it cannot be ignored. This is due to its catastrophic effect on a power system condition.

Next, perform random tripping on the exposed lines with p_{HF} greater than the selected value of $p_{HF} = 8\times10^{-7}$. In this case study, $p_{HF} = 8\times10^{-7}$ is obtained based on the chronological information of transmission line tripping events considering the effect of hidden failure. This value will be used as a reference by comparing it with the other case studies which are at the lower end of $p_{HF} = 1\times10^{-12}$ and higher end of $p_{HF} = 1\times10^{-2}$. This study is performed to observe its impact to the probability of cascading collapse and severe total loading condition.

Concurrently, compute the conditional probability of tripping, P_{cj} [9] by using (1).

$$P_{cj} = \prod p_{H_j} \prod q_{H_j} \tag{1}$$

where

p_{H_j} is the probability of exposed transmission line encountering the random tripping event in state j.

q_{H_j} is the probability of the exposed transmission line not encountering the random tripping event in state j.

The current process is repeated until there is no exposed line to perform the random tripping event. Then, utilize (2) to determine the tripping events probability, P_{ci} by considering all of the conditional probability of tripping, P_{cj}.

$$P_{ci} = \prod_{j=1}^{NJ} P_{cj} \tag{2}$$

where

NJ is the total number of system state at initial tripping, i.

For the selected initial line tripping, the simulation is repeated for $K = 1000$ times in order to obtain the average probability of cascading collapse, $\hat{P}_{C_i}$ that can be calculated using (3).

$$\hat{P}_{C_i} = \frac{1}{K}\sum_{k=1}^{K} P_{C_{i,k}} \tag{3}$$

Then, calculate the estimated average probability of system cascading collapse, $\mu(\hat{P}_{C_l})$ that used to identify the criticality of system cascading collapse prior to a severe total loading condition by using (4).

$$\mu(\hat{P}_{C_l}) = \frac{1}{I}\sum_{i=1}^{I} \hat{P}_{C_{i,l}} \tag{4}$$

Arrange the $\mu(\hat{P}_{C_l})$ in an ascending order to determine the severity of total loading condition that might cause to a critical system cascading collapse. The severity of total loading condition is determined based on the changes of total loading condition that cause to a significant increase of $\mu(\hat{P}_{C_l})$.

III. Results and Discussion

The performance of the proposed technique of estimated average probability of system cascading collapse, $\mu(\hat{P}_{C_l})$ that takes into account the effects of hidden failure in a relay protection system is discussed in this section. Initially, the algorithm starts by selecting a transmission line to be the initial tripping event. The total loading condition is increased by 10% at the same time, sustaining a stable power factor in the system. The algorithm is repeated for 1000 times in order to acquire the precise $\hat{P}_{C_i}$. By referring to three different cases of hidden failure probability which are $p_{HF} = 8\times10^{-7}$, $p_{HF} = 1\times10^{-12}$ and $p_{HF} = 1\times10^{-2}$, further analysis was conducted on the results of $\mu(\hat{P}_{C_l})$ to obtain the severity of the total loading condition which may cause to a critical cascading collapse. The IEEE Reliability Test System 1996 (IEEE RTS-96) in [21] is used as a test system to verify the performance of the proposed technique.

The estimated average probability of system cascading collapse, $\mu(\hat{P}_{C_l})$ is obtained by increasing the total loading condition from 130% to 220%, by means of 10% increment for the IEEE-RTS96. In conjunction to that, Table I indicates the value of $\mu(\hat{P}_{C_l})$ that is obtained by increasing the total loading condition from 130% to 220% which implies for all the three case studies of the hidden failure probability, that is $p_{HF} = 8\times10^{-7}$, $p_{HF} = 1\times10^{-12}$ and $p_{HF} = 1\times10^{-2}$. It is noticeable that the value of $\mu(\hat{P}_{C_l})$ is quite small from 130% to 190% of the total loading condition. This is probably because of a stable system condition supported by a large number of generating units and transmission lines. Albeit the $\mu(\hat{P}_{C_l})$ is rather small, it cannot be disregarded due to its impact to the power system possibly will be devastating. For all the three case studies of $p_{HF} = 8\times10^{-7}$, $p_{HF} = 1\times10^{-12}$ and $p_{HF} = 1\times10^{-2}$, a rapid increase of $\mu(\hat{P}_{C_l})$ can be seen when the total loading condition is increased above 200%. It will carry on increasing drastically until it achieves to the maximum $\mu(\hat{P}_{C_l})$ due to the 220% of total loading condition. This information is imperative to identify at which total loading condition excites to the criticality of a system cascading collapse.

TABLE I
ESTIMATED AVERAGE PROBABILITY OF SYSTEM CASCADING COLLAPSE FOR IEEE-RTS96

Total Loading Condition (%)	Estimated Average Probability of System Cascading Collapse, $\mu\left(\hat{P}_{C_j}\right)$ (per unit)		
	p_{HF} = 1×10^{-12}	p_{HF} = 8×10^{-7}	p_{HF} = 1×10^{-2}
130	0.00019344	0.00019056	0.00000084
140	0.00025224	0.00025606	0.00000217
150	0.00008205	0.00008217	0.00000217
160	0.00010118	0.00010436	0.00002218
170	0.00003173	0.00003118	0.00000583
180	0.00001718	0.00001708	0.00000285
190	0.00005894	0.00005892	0.00000930
200	0.00271678	0.00271430	0.00069031
210	0.02335387	0.02333729	0.00923196
220	0.08822664	0.08820120	0.05050363

Fig. 1 shows the estimated average probability of cascading collapse $\mu(\hat{P}_{C_l})$ as a function of the hidden failure probability for IEEE-RTS96. From the three different case studies of hidden failure probability, $p_{HF} = 8\times10^{-7}$ which is obtained from the historical data is set as a benchmark to compare the results of $\mu(\hat{P}_{C_l})$ for the other two cases $p_{HF,}$ which is $p_{HF} = 1\times10^{-12}$ and $p_{HF} = 1\times10^{-2}$. From the obtained results of $\mu(\hat{P}_{C_l})$, it is clearly shown that the $\mu(\hat{P}_{C_l})$ for $p_{HF} = 1\times10^{-12}$ presents almost similar results as $p_{HF} = 8\times10^{-7}$. On the other hand, $p_{HF} = 1\times10^{-2}$ produces lower value of the $\mu(\hat{P}_{C_l})$. This indicates that it is important to choose the correct value of p_{HF} in order to achieve an exact estimated average probability of system cascading collapse, $\mu(\hat{P}_{C_l})$. From the results, the determination of accurate value of hidden failure probability, p_{HF} is significantly important in view of the fact that this will have an effect on the results of the estimated average probability of cascading collapse, $\mu(\hat{P}_{C_l})$ and the criticality of system cascading collapse prior to a severe total loading condition.

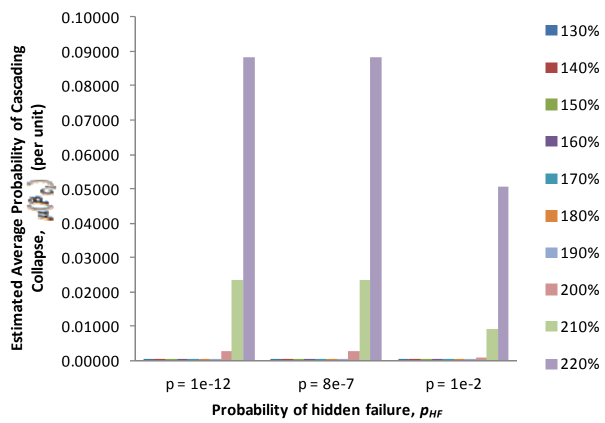

Fig. 1 Estimated average probability of cascading collapse $\mu(\hat{P}_{C_l})$ as a function of the hidden failure probability for IEEE-RTS96

IV. CONCLUSION

The growing amount of system catastrophic occurred currently has discovered that there is an imperative need for innovative techniques of critical cascading collapse required by the system planning and operation. The critical system cascading collapse typically can take place immediately by an initial tripping event of a transmission line. This paper has discussed on the assessment of estimated average probability of cascading collapse considering different probability of incorrect tripping due to the hidden failure in a protection system. In this study, three different case studies of hidden failure probability are applied in order to obtain the estimated average probability of cascading collapse. The results have revealed that the estimated average probability of cascading collapse increases as the probability of hidden failure is selected at lower value. Alternatively, a higher value of the probability of hidden failure will reduce the value of estimated average probability of cascading collapse. For that reason, it is very important to use accurate probability of hidden failure as it has a considerable effect on the result of estimated average probability of cascading collapse. The power system operation and planning should conduct the assessment of critical cascading events due to hidden failure from time to time in order to prevent the power system from any type of disastrous events. The estimated average probability of cascading collapse was also investigated to determine the severity of total loading condition. Therefore, it is crucial for the utility and power system planner to recognize severe total loading conditions that would cause critical impact of system cascading collapse.

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Nur Ashida Salim received her MEng (Power System & Electrical Energy) from Universiti Malaya in 2006 and Bachelor in Electrical Engineering (Hons.) from Universiti Teknologi MARA in 2003. She is a lecturer at Universiti Teknologi MARA Pulau Pinang and currently pursuing her PhD in Universiti Teknologi MARA, Shah Alam. Her research interests are power system reliability, power system planning and artificial intelligence.

Muhammad Murtadha Othman received his Ph.D. in Electrical, Electronic and Systems Engineering in 2006 from Universiti Kebangsaan Malaysia and MSc degree from Universiti Putra Malaysia in 2000. He currently lectures at Universiti Teknologi MARA, Malaysia. His research interests are artificial intelligence, power system reliability, power system stability, transfer capability assessment and energy efficiency.

Ismail Musirin received his PhD in Electrical Engineering, Universiti Teknologi MARA, Malaysia in 2005 and MSc in Pulsed Power Technology, University of Strathclyde, Glasgow United Kingdom, 1992. He currently lectures at Universiti Teknologi MARA, Malaysia. His research interests are Application of Artificial Intelligence in Power System Optimization, Green and Renewable Energy, Loss Minimization and Reactive Power Control.

Mohd Salleh Serwan received his Bachelor of Science in Mechanical Engineering from University of Southwestern Louisiana, US. He has 30 years working experience as an engineer. He used to work with National Electricity Board, Malaysia and Tenaga Nasional Berhad, Malaysia. Currently, he’s attached to Advanced Power Solution Sdn. Bhd., Malaysia as a software development and software support.