IMPROVED TRANSMISSION LINE PROTECTION DURING CASCADING EVENTS

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SUMMARY

Relay operations during cascading events play an important role for the power system stability. Without knowing the whole system information, distance relay may make wrong decision from the view of system reliability since it operates only according to local measurements. This paper introduces an improved transmission line protection scheme during cascading events. It utilizes the interactive method of system-wide and local monitoring and analysis tools for on-line automated analysis of protective relay operation. The new system-wide analysis tools based on Vulnerability Index (VI), Margin Index (MI), and Equivalent Parallel Path Approximation (EPPA) allow the vulnerable transmission lines of the system and vulnerable conditions to be identified. Then new local on-line monitoring and control tools are capable of analyzing performance of relay operation and informing the centralized tool about the outcomes that will be invoked to mitigate incorrect or undesirable relay action. A case study is presented to demonstrate the improved transmission line protection scheme using the new tools.

KEYWORDS

Transmission Line Protection, Security Analysis, Topological Processing, Power Flow, Distance Relay, Cascading Event

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I. INTRODUCTION

Power systems are getting more stressed under new market rules introduced by deregulation. The reliability and security are the main issues of the current power systems. Although many factors will affect the power system operation, cascading outage, especially the large-scale cascading outage, is a key factor which may cause great economic loss and impact on people's life. Inadequate understanding of unfolding events, relaying problems, bad weather conditions, human errors, etc. may contribute to power system cascading outages [1]. Among those factors, relaying problems are the major part to cause for cascading outage. According to the survey results, relay problems contribute to 75% of large area disturbances and cascading blackouts [2, 3]. The Western Coast System Blackout in 1996 [4] and Northeastern System Blackout in 2003 [1] clearly demonstrated the influence of relay problems. It is extremely important to study the relay performance during cascading events.

Conventional solution to transmission line protection is to calculate the related relay settings based on a short circuit study, and then let the relays make their decisions based on local measurements without knowing or considering the entire system condition. In certain situations these decisions may not be appropriate from the view of the entire system reliability consideration, which could cause large area relay misoperations leading to system blackout. If the local information from substations cannot be sent to the control center, the system operator may not be able to make decision to issue corrective control, and hence may loose the precious possible chance to mitigate the cascading events. So better understanding of the interaction between the relay operation and reliability of the power system operation is needed, especially during cascading events. This may be achieved through better monitoring of the interaction between power system operation and relay operation, and performing corrective relaying action as a consequence.

This paper explores the means for on-line automated analysis of protective relay operations during cascading events and presents an improved method for transmission line protection. The purpose is to allow for automated corrective actions in the case of misoperations or unintended operations of transmission line protection. By using power system static security analysis based on Vulnerability Index (VI) and Margin Index (MI), the vulnerable transmission lines of the system and vulnerable conditions are identified. The possible overload problems when those vulnerable conditions occur are predicted by utilizing Equivalent Parallel Path Approximation (EPPA) based on the topology processing technique. The security of the relays corresponding to those vulnerable transmission lines will be increased. Possible relay operation correction may be executed. This improved transmission line protection method is based on the interactive system/local monitoring and analysis scheme.

II. ARCHITECTURE OF THE NEW PROTECTION SCHEME

Correct operation of protective relays is critical to assuring a secure and reliable operation of power systems. To our knowledge, no on-line analysis tools that will allow for automated monitoring of protective relay operations to be able to perform corrective actions in the case protection dependability and/or security are compromised are available today. The problem of the analysis reduces down to two steps: analysis of the faults and analysis of relay operations. Why the two steps seem to be quite straight forward, it is not as simple to develop on-line tools for the automated analysis. The complexity of implementation and deployment is associated with the type of data made available for the analysis, as well as the objective of the analysis.

The improved transmission line protection method requires coordinated system-wide and local monitoring and control tools that will improve both system security and local protection. The architecture of this interactive protection scheme is shown in Fig. 1. The approach for automated analysis and correction of protective relay operation uses a steady state approach utilizing the power flow method and topology processing method to identify vulnerable lines due to the stressed operation conditions. Power flow method is used in static contingency analysis to identify overload and low voltage problems due to transmission line outage. The security analysis tools based on Vulnerability Index and Margin Index are used to identify the vulnerable transmission lines of the system and vulnerable conditions.

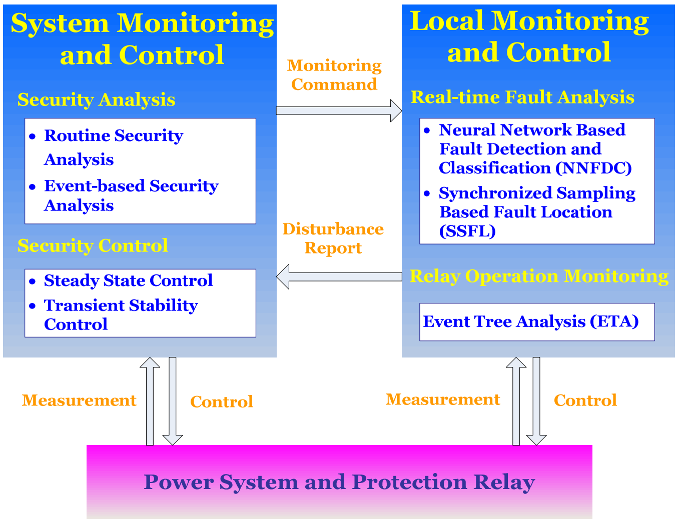

Fig. 1. Overall interactive scheme for protection

For those vulnerable transmission lines, the possible relay operations can be verified by performing dynamic analysis of relay behavior. Dynamic bus voltage phasors are calculated from the time-domain transient stability analysis. They are used to calculate the apparent impedance seen by distance relay and obtain the dynamic impedance trajectory [6]. If the apparent impedance falls into the relay protection zone longer than the setting time, the relay will operate based on its design character. This dynamic approach can identify vulnerable relay locations (lines) and vulnerable fault conditions.

In the mean time, by using Equivalent Parallel Path Approximation method, the possible overload transmission lines will be rapidly located under the condition of vulnerable lines being switched out. Once such a condition is identified, the system vulnerability tool invokes on-line monitoring tools located at the substations. The local tools are capable of analyzing performance of local relay operation and informing the centralized tool about the outcomes. They are also capable of performing a corrective action to mitigate incorrect or undesirable relay operation as needed.

III. THE MAIN APPROACH

A. *Power System Security Analysis*

Several large area blackouts illustrate that due to lack of real time and precise information about system events, the operators loose the chance to detect and mitigate the cascading outage. The reason is that sometime the power system will be in a much different state from what was predicted in the planning and other off-line studies. Many promising ideas for security analysis were proposed in the past [7-9]. Recently, a new approach based on Vulnerability Index as well as Margin Index is presented in [5, 10]. VI and MI provided precise vulnerability and margin information respectively for both the individual elements and the whole system performance. According to the different equipment groups in the power system, different equations and descriptions for generator level, bus level and transmission line level analysis are discussed. The more detailed description for the generation level and bus level analysis can be found in [5].

We can get the exact Vulnerability Index (VI) value for each branch under various system conditions, which could be used to evaluate the security and performance for individual system elements. The larger the VI , the more vulnerable the system or individual element..

The Margin Index (MI) of individual line distance relay is another very important parameter. It is well know that the smaller the normalized apparent impendence seen by the distance relay at no fault condition, the more likely the relay may misoperate since the apparent impendence may fall into the distance relay zone 3 or even zone 2. So the margin index and vulnerable index are closely related the value of the apparent impedance. The smaller the MI, the more vulnerable the distance relay decision.

The on-line monitoring tools located at the substations will be used to monitor those vulnerable distance relays.

B. Fast Overload Transmission Line Search Method

The apparent impedance seen by distance relay may fall into the relay protection zone longer than the setting time under overload conditions for transmission lines, which will cause relay misoperation. Paper [11] presents a novel Network Contribution Factor (NCF) method to relieve the overload and low voltage problems. Single-parameter/multi-parameter analysis and control can be achieved. NCF method is demonstrated to be fast and accurate by the full AC load flow analysis. However, the computation time for matrix inversion will increase dramatically with the increase of the power system size. Here we provide a new concept of Equivalent Parallel Path Approximation for search for the overload transmission lines rapidly.

We consider the power system as a linear network system for approximation. When one line is tripped in the system network, for example L_{ij}, we can take it into account by adding one admittance between the node i and node j, which equal to the negative value of the branch admittance [12]. According to the Superposition Theorem, if a linear system is driven by more than one independent power source, the total response is the sum of the individual responses. So the network status after one line is tripped will be equal to the sum of the initial network and compensated network.

With the full AC power flow, the system initial status can be known. We focus on how to get the compensated status for the system. From DC power flow, under the approximation conditions ($r_{ij} \ll x_{ij}, \sin(\theta_i - \theta_j) \approx \theta_i - \theta_j, V_i \approx V_j \approx 1.0$), the approximation power flow for node i and j is:

$$P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \tag{1}$$

Its DC network model can be easily obtained:

$$I_{ij} = \frac{V_i - V_j}{r_{ij}} \tag{2}$$

So if we could get the current distribution with the equivalent current source in node i and j for the DC network, we will know the power flow distribution. It is very easy to get the exact current value for each transmission line according to circuit theory. But its meaning is not significant under the DC power flow for its approximation. Our purpose is to find the maximum current branches, which should be the same branches carried the maximum distributed power flow. Here we present Equivalent Parallel Path Approximation method to find the possible group lines which have the maximum power flow.

For the DC network under single current source, the Loop Analysis method could offer the analytical solutions if the independent loops can be identified. If the network is n-node b-branch system, the number of independent loops will be $[b - (n - 1)]$. Obviously, the total number of loops which contain the current source is greater or equal to $[b - (n - 1)]$. Those loops are defined as equivalent paths, which carry some amount of current from node j to node i. In other words, the whole non-source network can be decomposed into a group of parallel branches connected with node i and j, which is shown in Fig. 2.

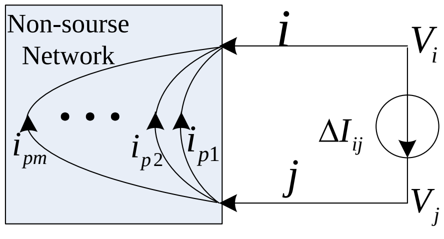

Fig. 2. Equivalent Parallel Path Decomposition

For each Loop Analysis equation, the self-resistance is much larger than the mutual-resistance. We will omit the mutual-resistance for approximation. If we want to find the maximum value current path, we only need to locate the path with the minimum loop resistance. As a conclusion, we will locate the possible overload on a transmission line under the conditions of one line being tripped by finding the path with minimum total reactance.

Once the influence on each transmission line caused by one line outage is decided, the possible overloaded lines could be identified by utilizing topological processing and equivalent parallel path approximation. This approach is much faster since it has no matrix computation, which will benefit the online application.

IV. CASE STUDY

We will take an example of the standard IEEE 39-bus New England System, as shown in Fig.3, to demonstrate the proposed approach. The detailed data for full AC power flow running can be found at [13]. The steady state results, including bus voltage, transmission line flows and generator outputs, will be obtained.

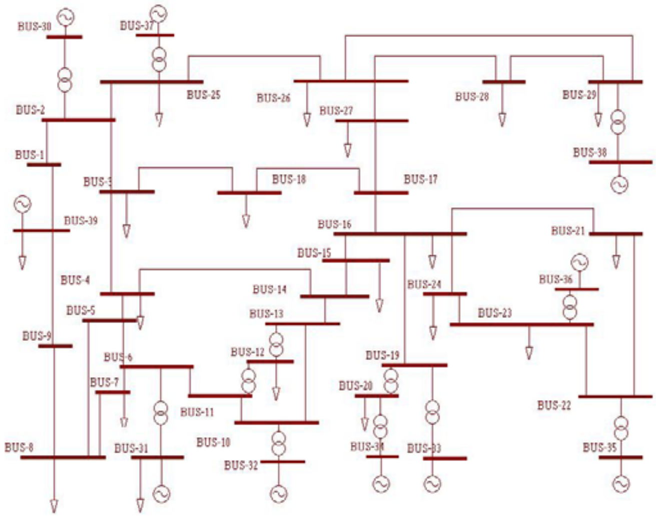

Fig. 3. IEEE 39-bus New England System

We assigned all weights as 1, voltage variance as 0.075 p.u., PQ bus voltage magnitude limits as 1.0 p.u., transmission line transfer limits as 10.0 p.u., and line bus voltage angle difference limits as 40 degrees. The vulnerability index and margin index values for transmission lines are calculated, which is shown in Table I. Different loading conditions are considered, including base load, 1.1 times the base load, and 1.2 times the base load.

From Table I, we can see that the transmission line is more vulnerable with the load increasing. This is consistent with practical experience.

The margin index for transmission line distance relay is calculated. The vulnerable lines will be ranked by margin indices. Table II gives the top four most vulnerable lines under different loading conditions. Similarly, relay is more vulnerable with the load increasing.

TABLE I

VULNERABILITY INDEX VALUES OF TRANSMISSION LINES AT DIFFERENT LOADING CONDITONS

	Pl	Ql	Qc	line_ ang	relay	line_off
Base load	2.856	0.132	0.021	0.182	0.192	0
1.1 load	3.457	0.180	0.012	0.225	0.233	0
1.2 load	4.116	0.244	0.008	0.273	0.282	0

TABLE II
MARGIN INDEX VALUES OF TOP 4 LINES AT DIFFERENT LOADING CONDITONS

Line No	base load	1.1 base load	1.2 base load
37(B6-31)	4.204	3.491	2.866
38(B10-32)	4.798	4.123	3.521
42(B23-36)	4.782	4.055	3.444
45(B29-38)	5.711	4.977	4.341

According to the trajectory of impedance seen by the relay at bus 26 (B26) of L33 (B29-26), which is shown in Fig. 4, the relay will misoperate. From t=1.0s to t=1.016s, which is during the second fault, distance relay sees zone 2 fault; from t=1.626s to t=2.002s, the distance relay still can see zone 3 fault. If the relay setting time is shorter than the time that the apparent impedance stays inside the zone 2 or zone 3 circle, the distance relay will trip L 33 according to its algorithm. The system may lose stability due to relay misoperation.

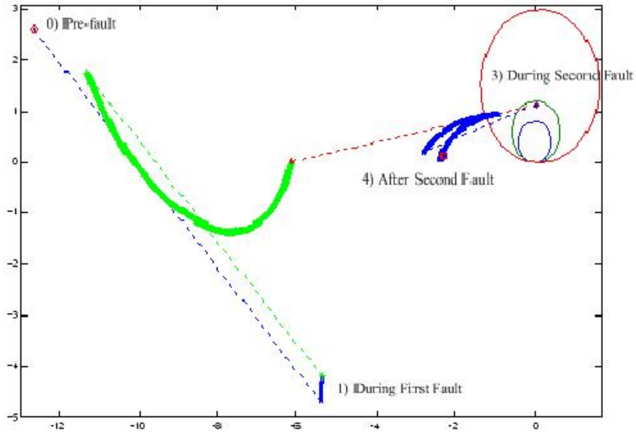

Fig. 4. Apparent impedance seen by the distance relay at B26 of L33

However, when L34 (B29-28) is tripped, the Equivalent Parallel Path Approximation method can rapidly find the maximum power flow transferred from L 34 to other lines. The path with minimum total reactance is (B29-B26-B28). The protection relays for those transmission lines have the possibility of misoperation. The relay dynamic analysis also validated this result.

V. CONCLUSION

This paper presents an improved transmission line protection scheme based on the interactive system-wide and local monitoring and analysis tools during cascading events. The means for on-line automated analysis of protective relay operations is discussed. The static security analysis tools based on Vulnerability Index and Margin Index identify the vulnerable transmission lines of the system and vulnerable conditions. Equivalent Parallel Path Approximation based on topology processing technique locates the possible overloaded transmission lines. With such vulnerability and security information, local on-line monitoring and control tools are invoked for analyzing performance of local relay operation and informing the centralized tool about the outcomes. Corrective action to mitigate incorrect or undesirable relay action will be issued if necessary.

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