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Identification of initial events of cascading failures using graph theory methods

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Abstract: In power systems, the unintentional outage of a grid element can lead to overload and outage of other equipment and, through a domino effect, all or a large part of a power system may collapse. The resulting events are called cascading, consecutive, or sequential failures. So far, various methods have been proposed to identify the initial events of cascading failures with different levels of accuracy and computational load. In this paper, an effective approach is employed which, by calculating the maximum flow of independent paths between generators and loads in the network graph, identifies the critical lines and transformers of the network so-called the initial events of cascade failures. To validate this method, the enumeration method is utilized. The proposed method is implemented in IEEE 118-bus test system and the results are indicative of its efficiency, accuracy and fastness compared to other methods.

Key words: Initial events, cascading failures, maximum flow, vulnerability index, enumeration method, contingency

1. Introduction

While expanding on a daily basis, electricity networks are becoming more and more critical systems for modern day life. With the growth in the economy and world population, electricity usage is escalating too. Heavy loads reduce the network capacity margins and with the increased stress on power lines, the occurrence of cascade failures becomes more likely. These faults and incidents reduce the network strength, probably leading to further outages and possible blackouts [1–3]. Blackouts due to cascade failures bring about enormous social, economic, and political consequences. Regarding social impacts, this phenomenon can hamper medical services as well as rail and road transportation etc. From an economic standpoint, the financial damage to the industry and banking sector caused by failures in Internet services, payment systems, and production facilities will be inevitable. From a political point of view, security problems may arise leading to unrest or even political threats to a nation [4]. Therefore, different methods have been proposed to identify the initial events of cascade failures in power systems. The prompt response of these methods is absolutely crucial as severe cascading incidents can inflict heavy tensions to the network. Moreover, voltage stability and transient stability phenomena have really fast transient durations and can immediately result in extended outages. Thus, the speed and accuracy of the initial event identification methods becomes even more significant. With timely identification of critical faults and performing corrective actions, such as load curtailment, generation isolation, and islanding actions, the network and its equipment can be reconfigured in a way to isolate affected sections and prevent the risk of cascade failures through increased security and reliability measures [5].

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Several research studies have been dedicated to the initial event identification of cascading failures. Some of these methods along with their capabilities and shortcomings are mentioned in Table 1.

Table 1. Summarized advantages and disadvantages of the initial event identification methods for cascading failures.

Row	Method name	Advantages	Disadvantages
1	Screening method [6, 7]	Through omitting the cascade failure dynamics, it predicts the outages and cascade failures faster than the dynamic methods.	The details of cascade failures are ignored.
2	Complex theory method [8–11]	A topological model which uses the physical configuration of network elements to determine line and transformer vulnerability based on graph theory and edge betweenness centrality.	Requires detailed electrical characteristics of many network elements including impedance or reactance and line capacity to yield credible results.
3	Enumeration method [12, 13]	High reliability and accuracy with consideration of every single scenario.	Very time-consuming and difficult to implement.
4	Cascade failure graph method [14]	Describes the cascade failure in a simple comprehensible way.	Difficult to implement on large-scale power networks.
5	Parallel corridor search method [15]	High computation speed in cascade failure identification.	Does not take into account line impedance or reactance.
6	Clustering method [16–18]	Analyzes high-loaded lines and transformers on network cutsets to identify and sort cascade failure initiation in offline and online modes.	Low scalability and very sensitive to initial parameter values. Moreover, the computations are highly time-consuming and can only partly identify the initiating events.
7	Classified neural network (CNN) method [19]	Used for accurate cascade event identification rooted in renewable resources such as wind power plants with lower errors compared to conventional neural network methods.	High computation time relative to decision tree algorithm.
8	Failure modes and effects analysis method [20]	As a risk assessment method, this method is able to identify high-risk events in smart grids including human or cyber/software errors as well as short circuit conditions.	The risk priority indices as calculated are very sensitive to any change in the network and any lack of data from the smart grid leads to errors in event identification and detection of hazardous conditions.
9	Cross-space cascade failure analysis method [21]	Using two indices, namely attack graph path of the cascade failure and the curtailed power mathematical model, it identifies and evaluates mutual attacks in cyber physical power system (CPPS) space.	Requires significant supervision mechanism as well as other machine learning considerations to properly and accurately evaluate the cascading failures.
10	Effective graph resistance (EGR) method [22]	Using two linear overload indices as well as the mathematical model of effective graph resistance, it identifies the critical lines with highest participation in cascading failures.	The mathematics of EGR is complex and difficult.

A detailed review of the mentioned approaches reveals that the main strategy common to all methods is the identification of the critical and vulnerable branches with no suggestions for any corrective actions after the initial events to save the system stability. The indices used in reference [22] suffer from computation complexity to identify the critical network lines. Our proposed approach, however, has a simple and routine computation procedure. In [20], failure modes and effects analysis (FMEA) is proposed but this method as a risk assessment technique requires different criteria and score tables of hazard intensity, hazard probability, and detection probability to identify failure cases, not to mention its demanding computation time. The proposed approach in this paper, however, is based on simple graph theory and the calculation of maximum flowing current in the graph which identifies the critical network elements within short time.

Table 2 summarizes the features of the proposed method as compared to reference [23].

Table 2. Comparison of the proposed method with that of [23].

Row	Description	Method of ref. [23]	Proposed method
1	Name of method	Maximum flow	Maximum flow
2	Algorithm	Ford–Fulkerson algorithm based on minimum cut (Min-Cut) theory	Ford–Fulkerson algorithm based on residual network theory
3	Network graph drawing	The network is depicted as a directional graph and the flows are assumed constant for all cases.	
4	Cascade failure model	Topological model for vulnerability analysis of the power system	
5	Priority list of important and critical lines	Based on maximum normalized flow	Based on maximum flow
6	Power flow type	DC	DC
7	Simulated power system	IEEE 39-bus	IEEE 118-bus
8	Simulation software	Graph visualization project (Graghviz) in MATLAB	Maxflow command code in MATLAB

Furthermore, in [23], only the critical line identification and prioritizations are performed with no validation of the method. In the proposed method, however, the results are validated using enumeration technique. Moreover, another unique feature of the current research is the detailed comparison of the proposed method in terms of proficiency and efficiency in initial event identification with other techniques proposed in the literature. Also as mentioned, the core maximum flow calculation algorithm is based on residual network considering stepwise load increase index. This is different from the technique in [23] where Min-Cut theory is used to determine the maximum flowing current on graph branches. The proposed method is also implemented on a realistic network to demonstrate its efficiency in identifying important and critical lines.

As demonstrated in [24], the maximum flow approach, as compared to other identification methods, has higher sensitivity to random intentional attacks. Through removing the identified critical lines, bigger outages are experienced within the network. In our paper, the comparison is based on the speed and accuracy of the methods and, as demonstrated, the proposed approach is proved to have higher computation speed and accuracy in identifying the initial events of cascading failures.

Thus, the novelties of the current research can be summarized as follows:

- Efficient practical algorithm to identify cascade failures
- Simple and straight forward identification of the most critical lines without any need for complex mathematical operations or elite operators

- Identification and prioritization of the initial events of cascade failures and both qualitative and quantitative comparison to other methods including complex theory and enumeration methods in terms of calculation speed and accuracy and efficient confinement of search space
- Suggestion of corrective actions in accordance with the accuracy and of the proposed method in identifying critical lines and transformers to prevent possible blackouts due to cascade failures
- Consideration of stepwise load growth in the proposed algorithm to expedite the identification of critical lines
- Implementation on a close-to-reality scale network to verify the efficiency of the proposed method compared to other algorithms
- Derivation of the optimal network expansion plan in the vulnerable sections based on the results of the proposed approach

The rest of this paper is organized as follows. In Section 2, different identification methods are presented, including the proposed method, for initial events of cascade failures. In Section 3, the identification methods are implemented on the test network and then the results are compared in terms of the defined metrics. Finally, Section 4 concludes the paper.

2. Methods of identifying the initial events of cascading failures

2.1. Enumeration method

The enumeration method is used to evaluate potential contingencies in the power system. As an exhaustive and time-consuming approach, enumeration is used to determine all $N-1$, $N-2$ and $N-3$ and eventually $N-k$ contingencies through carrying out $n!/k!(n-k)!$ simulations on the power system. Since all possible contingencies are evaluated by this method, it can be used as a validation and verification tool for other initial event identification methods.

2.2. Complex network theory-based method

In the complex network theory-based method, by examining the topology and structure of the power system, the vulnerability assessment of network equipment, including transmission lines and transformers, is performed. In this method, the IEEE 118-bus test system is modeled in MATLAB software environment by executing the command “maximum flow” and the network graph is constructed as a weight-oriented graph to analyze the network tolerance against disturbances.

In this method, using [11], the edge betweenness centrality $BC(e)$ of an edge $e \in E$ is defined as the sum of all pairs of vertices $u, w \in V$ of the fraction of the shortest paths between u and w passing through edge e, as given by:

$$BC(e) = \sum_{u,w \in V} \frac{Q_{uw}(e)}{Q_{uw}}, \qquad u \sharp w \tag{1}$$

where $Q_{uw}(e)$ is the shortest path between vertices u and w passing through the edge e (line or transformer) and Q_{uw} is the total count of shortest paths between u and w.

The vulnerability index (LVI_i) is defined according to [15] as follows:

$$LVI_i = BL_i \tag{2}$$

where BL_i is the shortest path between two nodes also known as the path with the smallest reactance. Therefore, the weight of line or transformer i is defined by its reactance. Consequently, by calculating the weighted distance i, the vulnerability index of line or transformer $i(LVI_i)$ is obtained.

2.3. The proposed method

The proposed method of maximum flow seeks to move as much amount of data or material as possible from one point in the network to another. Today, this method is highly utilized to transfer the maximum amount of data over the Internet. The first proficient algorithm for determining the maximum flow was innovated in 1962 by two well-known computer scientists, Ford and Fulkerson. Since then, a number of optimization methods have been proposed to speed up this algorithm [25]. In this paper, this algorithm is used in the proposed approach to calculate the maximum flow of branches located on the graph paths.

This method uses a concept called ”Preflow”. The Preflow is injected into the network as a default current since the total input current to the vertex (node) can be greater than the output current of the vertex (node). The preflow modifies the flow in the remaining graph paths saturating the paths to the sink. The algorithm terminates only when the preflow is maximized. The values obtained are the maximum flows in the network graph [25, 26]. The first purpose of this method is to send the maximum possible flow from the source (s) to the destination (t) in the network graph $G(V, E)$ by observing the following constraints:

$$\begin{aligned} & G(V,E), \quad s,t \in V \\ & f_{uv} \le c_{uv}, \quad \forall (u,v) \in E \\ & rf_{uv} = c_{uv} - f_{uv}, \quad \forall (u,v) \in E \\ & DF = \min\{rf_{uv}, \forall (u,v) \in E\}; \\ & \sum_{u:(u,v)\in E} f_{uv} = \sum_{u:(v,u)\in E} f_{vu}, \quad \forall v \in V \setminus s,t \end{aligned} \tag{3}$$

where f_{uv} is the flow between the source and the destination and must be at least equal to the edge capacity of c_{uv}. In the second constraint, rf_{uv} defines the residual capacity of the path between u, v. In the third constraint, the objective function of the algorithm (DF) is to minimize the residual capacity of the path between u, v. In other words, it is the maximum flow value that we can reach on one path. In the fourth constraint, for each vertex except the source and destination, the input flow to the vertex must be at least equal to the output flow from the vertex [24, 25].

The idea of analyzing the vulnerability of power systems using this method was first presented in [23]. As the complexity of the power system structure increases, there is an urgent need for an efficient and effective method to assess the vulnerability of the power system. To meet this challenge, a method for identifying the initial events of cascading failures is proposed in this paper. This method has four main steps. The first step is to model the power system as a graph with edges (line or transformer) and nodes (buses) using a command in MATLAB software called “graphmaxflow” [27]. In the second step, the multiple network graphs are converted into paired graphs encompassing the generator source and the load destination to reduce the computational load. In the third step, the maximum possible flow from the source to the destination is calculated by step by step increase of the load and observing the edge capacity limit. In the fourth step, the vital branches of the network graph are ranked based on their maximum flow.

The steps for calculating the maximum flow of branches are as follows:

$$z = [z_1, z_2, \ldots, z_m], \qquad z \in G(V, E) \tag{4}$$

$$f_{ij}^{\max} \in [f_{ij}^{z_1}, f_{ij}^{z_2}, \ldots, f_{ij}^{z_m}],\ f_{ij}^{z_m} \leq f_{ij}^{\max} \leq C_{ij}, \qquad \forall (i, j) \in E \tag{5}$$

where z is the set of paths of the network graph and m is the number of network graph paths between the source and sink nodes u and v. $f_{ij}^{z_m}$ is the flow passing between nodes i and j in the graph paths. Therefore, the maximum branch flow is displayed as $f_{ij}^{\max}$. C_{ij} is the capacity of the branches located on the graph paths.

The steps for identifying the initial events of cascading failures by the maximum flow method are shown in the flowchart of Figure 1.

This flowchart consists of five main parts and eleven steps as follows:

- In part 1 (steps 1 through 3), the maximum flow method has been implemented based on Ford–Fulkerson algorithm and residual network model. The one-line diagram is drawn and the graph paths are derived. This part is executed by MATLAB coding and maxflow command [25].
- In part 2 (steps 4 and 5), using the algorithm, graph couples with one generator (source) and one unique load (sink or destination) are selected from among several graph paths. This reduces the computational time of the algorithm. Out of 3900 graph paths, 858 paths with generator source and load destination are selected. These paths are situated between 54 generation buses and 99 load buses.
- In part 3 (steps 6 to 8), using Matpower toolbox of MATLAB, DC power flow calculations are carried out for each selected path (Zm) of part 2. By increasing the load by a factor of k at each step, the maximum possible flow from source to the destination of the path is calculated and stored taking into account the capacity constraints. This part is repeated for each graph path with the respective generators and loads.
- In part 4 (steps 9 and 10), the maximum flow from the branches of each path is calculated and thus a sorted list of paths with maximum flows is obtained.
- In this method, the branch with the highest flow is vulnerable for outage and counted as an initial cause of cascade failures.
- In part 5 (step 5), the branches liable to be the initial events of cascade failures are validated by enumeration method and the most critical initiating events are determined.

3. Simulation results

In order to simulate and implement methods for detecting the initial events of cascading failures, the IEEE 118-bus test system is used. This system has 177 transmission lines, 9 transformers, 54 power plants, and 91 load buses. The installed capacity of power plants and the power consumption of the network are 4375 MW and 4242 MW, respectively, and the network losses are 132.9 MW [28, 29].

Scenarios involved in the process of forming cascade failures are modeled by the MATPOWER toolbox under MATLAB software environment and all network simulation studies are performed within the environment of this software [28]. The elements of the network are arranged in such a way that it has sufficient security against single-contingency disturbances. Hence, the network is said to have the so-called $N-1$ security condition.

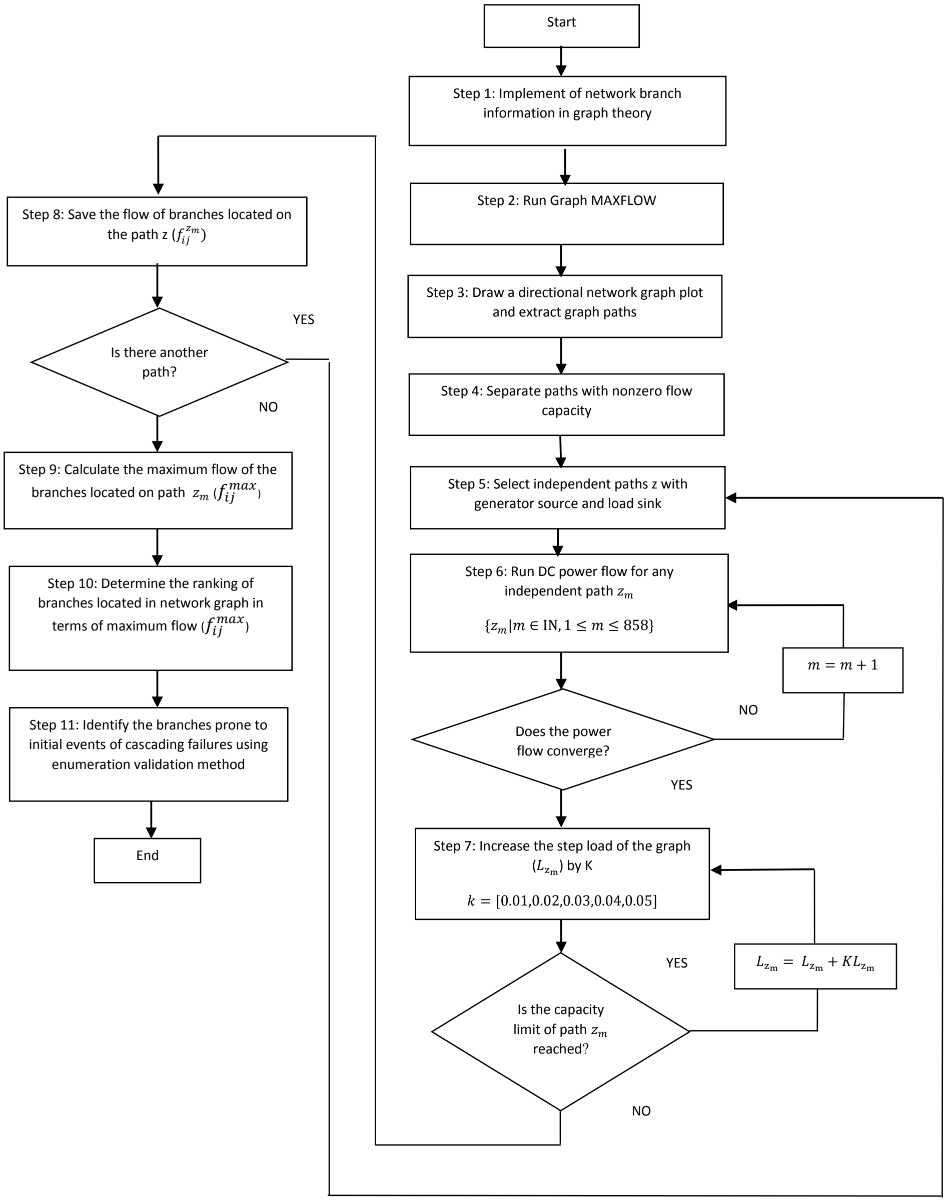

Figure 1. Flowchart of the maximum flow method.

In this section, the methods for identifying the initial events of cascading failures including the enumeration method, the complex network theory-based method, and the proposed method of maximum flow are simulated and implemented on the test system and the results are extracted. Moreover, the ability of these methods to identify severe and catastrophic events of cascade failure is measured and the events are ranked accordingly, and then the enumeration method is used for validation.

3.1. Enumeration method

The IEEE 118-bus system is a relatively large network. Therefore, $N-1$ contingency is considered safe and secure while $N-3$ contingency is unlikely for this network. Using the enumeration method, 17205 $N-2$

contingencies are extracted for branches (lines and transformers). In this network, the basis of identifying a branch overload due to $N-2$ contingencies is a loading level of 100% or higher. Therefore, an $N-2$ contingency which causes overload and outage of the next branch is considered the initial event of cascading failure scenario. In this network, the total capacity of the branches can be equally increased up to 9900 MVA. By performing DC power flow and gradual increase of branch capacity in MATLAB software environment, $N-2$ contingencies with the potential to cause initial events can be extracted by assuming branch capacity of up to 600 MVA. By further increasing the branch capacity, the probability of cascading failure scenarios with the initial occurrence of $N-2$ contingencies decreases to zero.

Based on the results obtained from the enumeration method, the initial $N-2$ contingencies of the cascading failure scenarios are ranked based on the number of participation of these contingencies in initial events of cascading failures. The diagrams of the initial events of $N-2$ contingencies in the first 20 ranks of the cascading failure scenarios of the test system, with branch capacities of 300 and 500MVA, are shown in Figures 2 and 3. The five initial events include double contingencies (8-5 and 16-17), (8-5 and 26-25), (8-5 and 30-17), (8-5 and 26-30), and (25-27 and 26-30) shown in Figure 2, which are involved in the overload of 6 branches. However, with a branch capacity of 500 MVA, the 12 initial events related to double contingencies contribute to the overload of only one branch, as shown in Figure 3. In the test system with 186 branches and a capacity of 300 MVA, 177 branches participate in the occurrence of the initial events of cascading failures. However, with a branch capacity of 500 MV, only 9 branches are involved in the initial events of cascading failures. The presentation of these diagrams shows that with the increase of branch capacities in the test system and assuming a liberalized power transmission, the number of initial $N-2$ contingencies and the participation of the branches in the occurrence of cascading failure scenarios are greatly reduced.

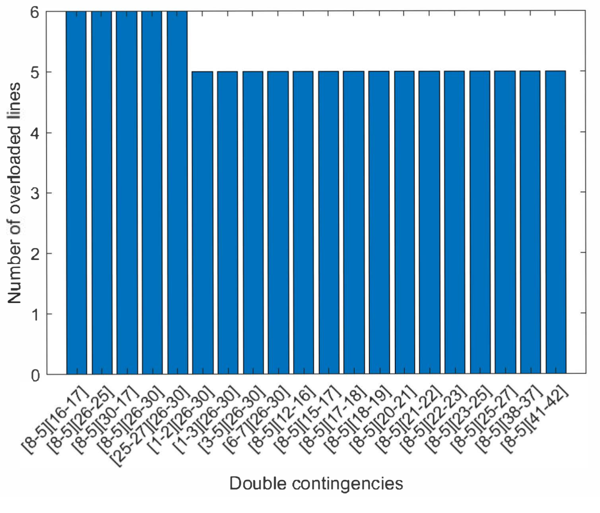

Figure 2. Top 20 ranks of initial double contingencies in 118-bus IEEE test system with a branch capacity of 300 MVA.

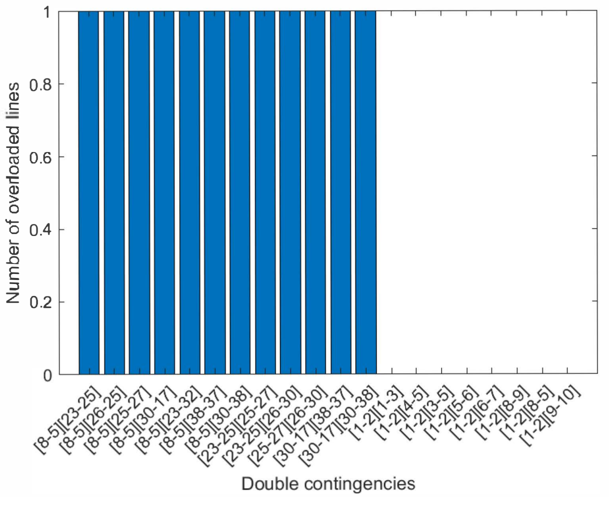

Figure 3. Top 20 ranks of initial double contingencies in 118-bus IEEE test system with branch capacity of 500 MVA.

3.2. Complex network theory-based method

In this method, the IEEE 118-bus test system is modeled in MATLAB software environment by executing the command “maximum flow” and the network graph is constructed as a weight-oriented graph to analyze the network tolerance against disturbances.

Using graph theory in MATLAB software, 3900 paths within the test system graph are extracted based on the capacity characteristic. The edge betweenness centrality index is calculated using Eq. (1) in these paths which is equivalent to the vulnerability index of the line or transformer $i(LVI_i)$ in Eq. (2). In addition, the higher the edge betweenness centrality index of the line or transformer i located on the paths, the higher the importance of the relevant branch implying that its outage can be an initial event of cascading failures.

In this method, the vulnerability index is calculated for 186 branches of the test system and the ranking list is formed based on the highest vulnerability index. Figure 4 show the first 30 rankings of the complex network theory-based method ranking list for the IEEE 118-bus test system. In Figure 4, line 42-49, with the participation of 1443 graph paths and a vulnerability index of 1443, is identified at the first place of critical initial events by this method. The list of the top 30 ranks of initial events of cascading failures obtained by enumeration validation method for three levels of branch capacity, i.e. 300, 450, and 475 MVA are shown in Table 3. According to this table, for the three applied branch capacities, the complex network theory-based method can identify 5, 11, and 13 initial events of cascading failures, respectively.

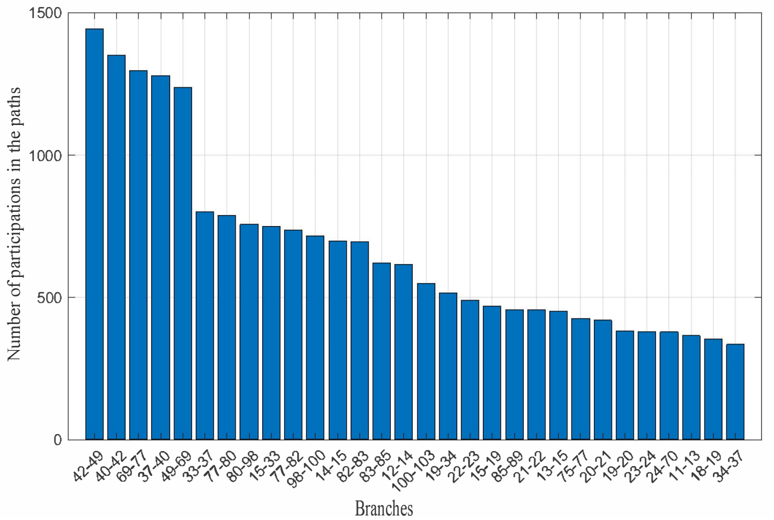

Figure 4. Top 30 places of the ranking list by complex network theory-based method for IEEE 118-bus test system.

3.3. Maximum flow method

According to the explanations in Section 2, the proposed method is modeled using Ford–Fulkerson algorithm in MATLAB software by executing the command "graphmaxflow" on the graph of IEEE 118-bus test system with 3900 paths as drawn in Figure 5.

The purpose of this method is to send the maximum possible flow from the source to the destination by observing the constraints mentioned in Eq. (3). Therefore, with the implementation of the algorithm, 858 out of 3900 paths with generator source and load destinations are selected. These paths are between 54 generation buses and 99 load buses. Using the Matt Power toolbox in the MATLAB software environment, DC power flow is performed for each of these paths. In order to calculate the maximum flow of the branches located on the paths, the load growth is applied in steps of 0.01 and 0.05 while observing the path capacity limit. These paths are the shortest paths between the generator and the load and each path has the lowest impedance. In the ranking list of this method, lines and transformers located on the paths with the maximum flow can have the potential to cause cascading failures. Therefore, they can be considered the initiating events.

Table 3. Comparison of top 30 events in the ranking list of enumeration and complex network theory-based methods for cascading failures of IEEE 118-bus test system.

Branch capacity	300 MVA			450 MVA				475 MVA			
Enumeration validation method			Complex network theory method	Enumeration validation method			Complex network theory method	Enumeration validation method			Complex network theory method
Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank
1	8-5	25		1	8-5	30		1	8-5	27	
2	26-30	6		2	1-2	1		2	23-25	3	
3	16-17	1		3	1-3	1		3	30-17	2	
4	26-25	1		4	4-5	1		4	26-25	2	
5	30-17	1		5	3-5	1		5	25-27	2	
6	25-27	1		6	5-6	1		6	11-13	1	28
7	1-2	1		7	6-7	1		7	12-14	1	15
8	1-3	1		8	4-11	1		8	13-15	1	22
9	3-5	1		9	5-11	1		9	14-15	1	12
10	6-7	1		10	11-12	1		10	19-20	1	25
11	12-16	1		11	2-12	1		11	15-19	1	19
12	15-17	1		12	3-12	1		12	20-21	1	24
13	17-18	1		13	7-12	1		13	21-22	1	21
14	18-19	1	29	14	11-13	1	28	14	22-23	1	18
15	20-21	1	24	15	12-14	1	15	15	27-28	1	
16	21-22	1	21	16	13-15	1	22	16	28-29	1	
17	22-23	1	18	17	14-15	1	12	17	23-32	1	
18	23-25	1		18	12-16	1		18	31-32	1	
19	25-27	1		19	16-17	1		19	15-33	1	9
20	38-37	1		20	17-18	1		20	19-34	1	17
21	41-42	1		21	18-19	1	29	21	33-37	1	6
22	43-44	1		22	19-20	1	25	22	34-37	1	30
23	44-45	1		23	15-19	1	19	23	38-37	1	
24	45-46	1		24	20-21	1	24	24	30-38	1	
25	42-49(1)	1	1	25	21-22	1	21	25?	65-68	1	
26	42-49(2)	1		26	22-23	1	18	26	69-70	1	

Table 3. (Continued).

Branch capacity	300 MVA			450 MVA				475 MVA			
Enumeration validation method			Complex network theory method	Enumeration validation method			Complex network theory method	Enumeration validation method			Complex network theory method
Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank
27	45-49	1		27	23-24	1	26	27	17-113	1	
28	63-59	1		28	23-25	1		28	32-113	1	
29	63-64	1		29	26-25	1		29	26-30	1	
30	49-66	1		30	25-27	1		30			

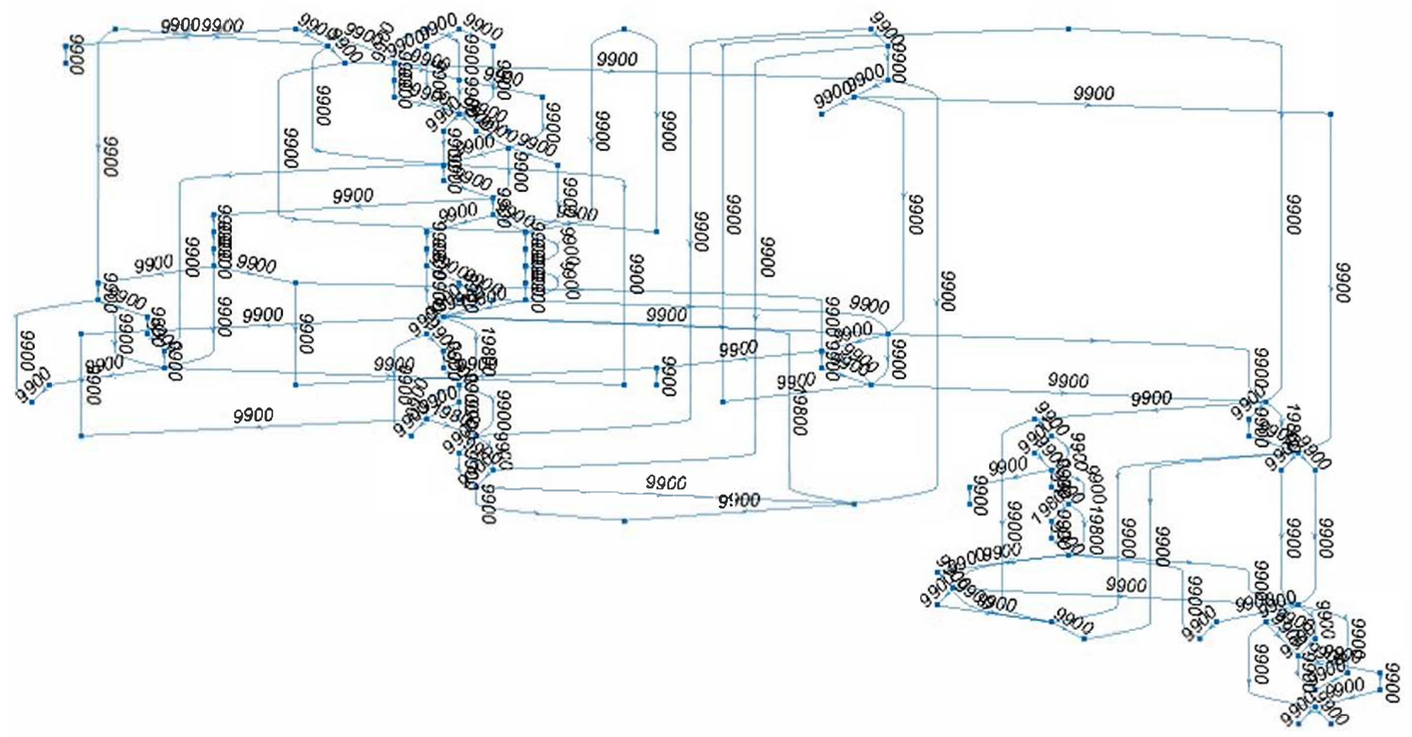

Figure 5. Schematic of the studied IEEE 118-bus test system.

Table 4 shows the top 30 of the maximum flow method ranking list for IEEE 118-bus test system. In this table, line 85-86 with the highest calculated flow is identified as the first rank by this method.

Table 5 shows the top 30 initial events of cascading failures obtained by enumeration validation method for three levels of branch capacity equal to 300, 450, and 475 MVA. According to Table 5, the maximum flow method, through applying a load increase of 1%, can identify 3, 7, and 6 initial events of cascading failures at the three applied branch capacity levels, respectively. This method can also identify the most vulnerable initial event of cascading failure (Transformer 8-5) at 11th rank. This transformer is one of the most critical branches between generation and consumption buses and, in comparison to other branches, it has the highest participation in the occurrence of initial events of cascading failure scenarios.

A realistic example of the performance of the proposed algorithm is given as below:
Using the proposed algorithm in steps 4 and 5, 858 paths with generator sources and load destinations are selected. Using DC power flow and 1% load increase at each step, assuming branch capacity of 300 MVA for the 118-bus network, the flows in the graph paths are calculated and stored based on steps 6 to 8. According to equations (4) and (5) and steps 9 and 10 of the algorithm, the maximum flows of the branches (lines and transformers) are computed and the maximum flow-based ranking list is obtained. The first 30 branches are given in Table 4. In this network, branch 85-86 with power flow of 300 MVA is ranked first while branch 53-54 with a power flow of 298.9 MVA is ranked the last critical branch. In the final step of the algorithm, using the enumeration method, the initial events are verified. Based on the verifications by enumeration method, branches 5-8, 1-3, and 12-16, which are ranked 11^{th}, 25^{th}, and 29^{th}, respectively, are designated in Table 6 as the initiating events of cascade failures.

Table 4. Top 30 ranks obtained by maximum flow method for IEEE 118-bus test system.

Branch capacity		300 MVA	450 MVA	475 MVA	Branch capacity		300 MVA	450 MVA	475 MVA
Rank	Branch name	Max Flow	Max Flow	Max Flow	Rank	Branch name	Max Flow	Max Flow	Max Flow
1	85-86	300	450	475	16	68-81	299.2	448.7	473.7
2	12-117	300	450	475	17	12-14	299.2	448.7	473.7
3	76-118	299.5	449.2	474.2	18	48-49	299.1	448.7	473.6
4	65-68	299.4	449.1	474.1	19	80-98	299.1	448.7	473.6
5	77-78	299.4	449.1	474	20	29-31	299.1	448.7	473.6
6	82-83	299.3	449	474	21	75-118	299.1	448.6	473.6
7	11-13	299.3	449	473.9	22	40-41	299.1	448.6	473.6
8	49-50	299.3	448.9	473.9	23	74-75	299.1	448.6	473.5
9	4-5	299.2	448.8	473.8	24	78-79	299.1	448.5	473.5
10	105-108	299.2	448.8	473.8	25	12-16	299	448.5	473.5
11	8-5	299.2	448.8	473.8	26	108-109	299	448.5	473.4
12	70-71	299.2	448.8	473.8	27	34-37	299	448.4	473.4
13	8-30	299.2	448.8	473.7	28	60-61	298.9	448.3	473.3
14	34-43	299.2	448.8	473.7	29	1-3	298.9	448.2	473.2
15	19-20	299.2	448.7	473.7	30	53-54	298.9	448.2	473.2

Table 5. Comparison of the top 30 initial events identified by enumeration and maximum flow methods in IEEE 118-bus test system.

Branch capacity	300 MVA			450 MVA				475 MVA			
Enumeration validation method			Max flow method	Enumeration validation method			Max flow method	Enumeration validation method			Max flow method
Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank
1	8-5	25	11	1	8-5	30	11	1	8-5	27	11
2	26-30	6		2	1-2	1		2	23-25	3	
3	16-17	1		3	1-3	1	29	3	30-17	2	
4	26-25	1		4	4-5	1	9	4	26-25	2	
5	30-17	1		5	3-5	1		5	25-27	2	
6	25-27	1		6	5-6	1		6	11-13	1	7
7	1-2	1		7	6-7	1		7	12-14	1	17
8	1-3	1	29	8	4-11	1		8	13-15	1	
9	3-5	1		9	5-11	1		9	14-15	1	
10	6-7	1		10	11-12	1		10	19-20	1	15
11	12-16	1	25	11	2-12	1		11	15-19	1	
12	15-17	1		12	3-12	1		12	20-21	1	
13	17-18	1		13	7-12	1		13	21-22	1	
14	18-19	1		14	11-13	1	7	14	22-23	1	
15	20-21	1		15	12-14	1	17	15	27-28	1	
16	21-22	1		16	13-15	1		16	28-29	1	
17	22-23	1		17	14-15	1		17	23-32	1	
18	23-25	1		18	12-16	1	25	18	31-32	1	
19	25-27	1		19	16-17	1		19	15-33	1	
20	38-37	1		20	17-18	1		20	19-34	1	
21	41-42	1		21	18-19	1		21	33-37	1	
22	43-44	1		22	19-20	1	15	22	34-37	1	27
23	44-45	1		23	15-19	1		23	38-37	1	
24	45-46	1		24	20-21	1		24	30-38	1	
25	42-49(1)	1		25	21-22	1		25	65-68	1	4
26	42-49(2)	1		26	22-23	1		26	69-70	1	
27	45-49	1		27	23-24	1		27	17-113	1	
28	63-59	1		28	23-25	1		28	32-113	1	

Table 5. (Continued).

Branch capacity	300 MVA			450 MVA				475 MVA			
Enumeration validation method			Max flow method	Enumeration validation method			Max flow method	Enumeration validation method			Max flow method
Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank	Rank	Branch name	Number of participants in the initial event	Rank
29	63-64	1		29	26-25	1		29	26-30	1	
30	49-66	1		30	25-27	1		30			

Table 6. Quantitative and qualitative comparison of methods in ranking and identifying the initial events of cascading failures.

Row	Comparison area	Enumeration method	Complex network theory method	Max flow method with load increase of five percent	Max flow method with load increase of one percent
1	Advantages	High reliability and accuracy, no case is ignored.	Faster computational speed compared to max flow method	Simple theory and a faster calculation speed than the enumeration method	Higher accuracy due to higher number of load growth steps
2	Disadvantages	Due to the exhaustive number of power flow calculations, it is time consuming.	Lower accuracy compared to max flow method	Longer calculation time compared to complex network theory method	Longer calculation time due to higher number of load growth steps
3	Accuracy in identifying initial events	Identifies all initiatial events	Identifies two events in the first 11 ranks	Identifies two events in the first 11 ranks	Identifies three events in the first 11 ranks
4	Number of initiating events in the first 6 ranks of the method's ranking list	Identifies all initiating events	Identifies only one event	Identifies two events	Identifies three events
5	Calculation time (seconds)	3543	34	445	1555
6	Search space to identify the most vulnerable initial event (Transformer 8-5) in the first 30 ranks	First row of the ranking list	Not identified	28th row of the ranking list.	11th row of the ranking list

3.4. Quantitative and qualitative comparison of methods in terms of speed, accuracy of calculations, and the range of search space

Considering the effect of computational speed, efficient search space limitation and accuracy of the results on preventing cascade failure, a comparison is drawn between the capabilities and shortcomings of the proposed maximum flow method against enumeration and complex network theory-based methods. Table 6 and Figures 6 and 7 demonstrate this comparison between methods in identifying initial events of cascading failures based on mentioned criteria for IEEE 118-bus test system. According to this comparison, using the proposed method compared to other methods has the following advantages:

- It is successful in identifying the top 3 events from the first 6 ranks of the ranking list. Hence, this method has acceptable accuracy compared to the complex network theory-based method. In other words, instead of searching for 17,205 cases to find the $N-2$ contingencies as the initial event in the enumeration method, these can be found in the first 6 iterations.
- The proposed method is successful in reducing the search space in identifying the most vulnerable initial event (Transformer 8-5) as it is capable of identifying this event in the first 11 iterations of the ranking list. However, this event is not detected in the complex network theory-based method.
- Maximum flow and enumeration methods both use DC power flow in their calculations, but the maximum flow method has a simple theory in graphs and fast computation speed such that, within 445 seconds, it extracts the initial event ranking list. However, despite being the most accurate method by not eliminating any initial events, the enumeration method requires a very long computation time.

It is noteworthy that the time required to extract the results of each method is measured using a computer with an Intel Core i5 processor, 2.5 GHz, 6 GB RAM and the codes are run in MATLAB software environment.

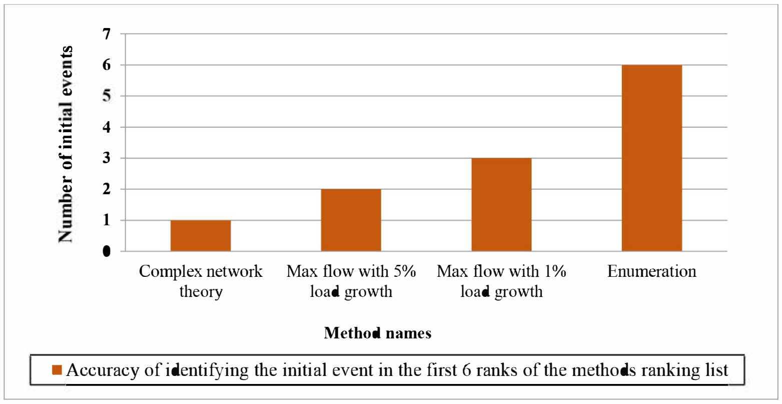

Figure 6. Accuracy comparison diagram of the maximum flow method against other methods in identifying initial events of cascading failures.

3.5. Comparison of methods in terms of the effect of remedial action scheme on reducing the occurrence of initial events of cascading failures.

According to the results of Table 5, the maximum flow method in the best case has been able to identify Transformer 8-5 as the most critical element within the first 30 places of the ranking list. This equipment, with the highest number of participations in initial events, is the first rank identified by the enumeration validation

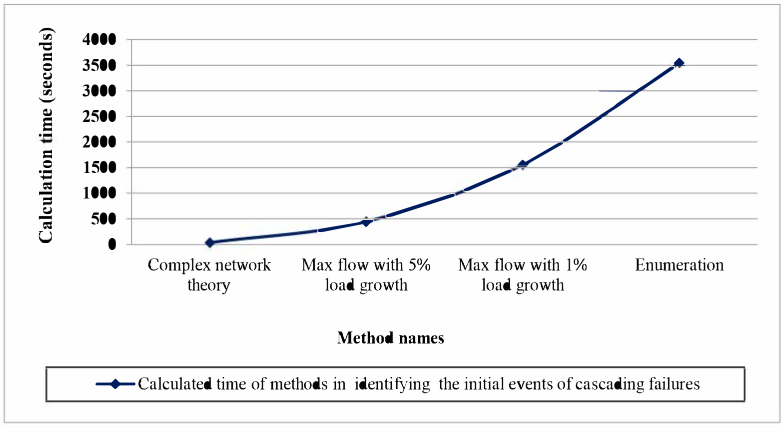

Figure 7. Speed comparison diagram of the maximum flow method against other methods in identifying initial events of cascading failures.

method. According to Table 3, however, the complex network theory-based method is at best able to identify the transmission line 20-21 with a rank of 12.

According to Figures 8 and 9, by adding a new transformer with the same capacity parallel to transformer 8-5 and reconducting a DC power flow study with different branch capacities, it is inferred that this remedial action has a relatively large impact of about 94% to 100% reduction in the occurrence of double contingencies leading to initial events. This action also reduces the participation of branches in the occurrence of the initial events of cascading failures. If the transmission line 20-21 is doubled, a very small effect of about 3% to 4% in reducing the occurrence of double contingencies with the potential of initial events is witnessed. Moreover, a small reduction is observed in the participation of branches in the occurrence of the initial events of cascading failures.

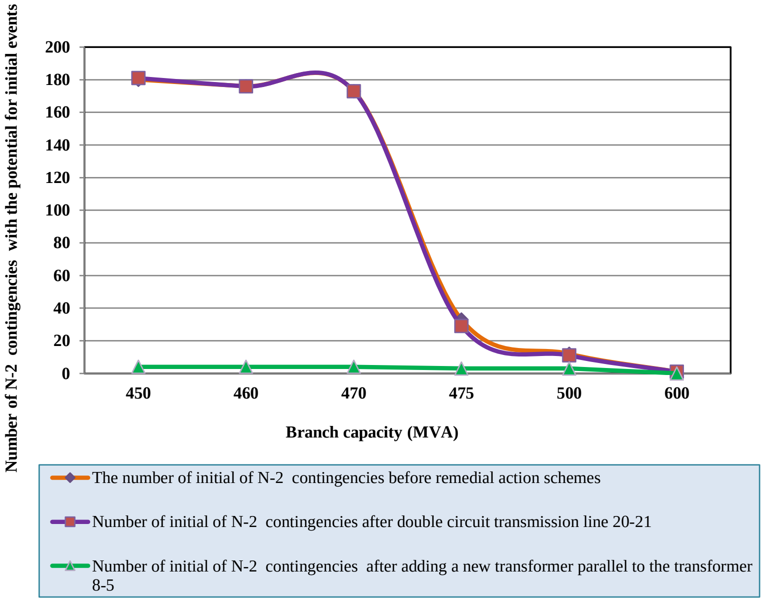

Figure 8. Comparison of the effect of remedial action schemes on reducing the occurrence of double contingencies with the potential of being initial events of cascading failures.

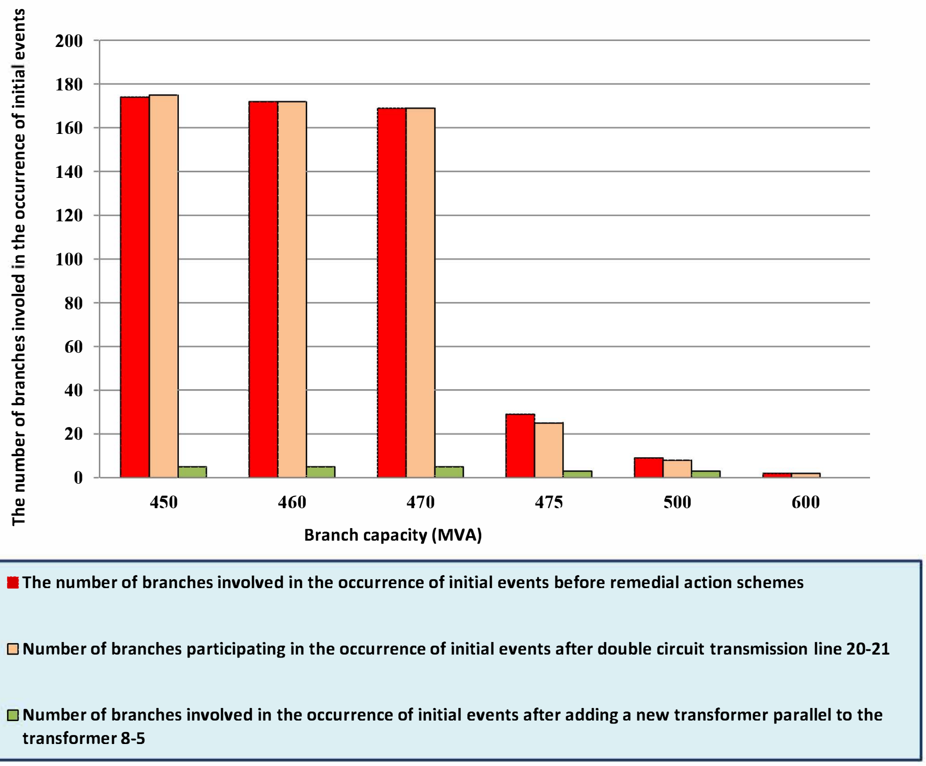

Figure 9. Comparison diagram of the effect of remedial action schemes on reducing the participation of branches in the occurrence of initial events of cascading failures.

Therefore, by quickly identifying the vulnerable transformer 8-5 and taking remedial action, an important step can be taken to reduce the occurrence of the initial events of cascading failures in the IEEE 118-bus test system. Therefore, the proposed maximum flow method, compared to the complex network theory-based method, has been able to accurately identify this important and vital equipment as the initial event in the first place of the ranking list.

4. Conclusion

Considering the increasing load and also the wide range of hazards and incidents being faced by the power system, there is a need to increase investment in transmission network development to reduce equipment failure rate and increase their reliability. Therefore, effective analysis of power system vulnerability with fast and accurate identification of the initial events of cascading failures is inevitable. This paper presented a new method for identifying the initial events of cascading failures in the power system with relatively high speed and accuracy which can be used by regional power companies to prevent widespread blackouts, reduce grid recovery time, and restore the power system to normal condition. This method was implemented on IEEE 118-bus test system and its results were compared against other methods in terms of accuracy, reduction of search space and the speed of calculations. Numerical results indicate the following conclusions:

- The proposed method, by identifying the initial events of cascading failures while the network is offline and using it during normal operation, can help avoid the occurrence of cascading failures.
- Implementation of the maximum flow method compared to other methods shows that besides calculation

speed, the accuracy of calculation is highly significant in identifying initial events to prevent sudden cascading failures and reduce the risk of network vulnerability.

- In order to better evaluate and analyze the accuracy and reduce the computation time of the proposed method compared to other methods, a large test system similar to a real network was used in this paper. The evaluation reveals that the proposed method has a higher accuracy in identifying a dangerous initial event than the complex network theory-based method and has a higher computational speed than the enumeration method.
- From the results of remedial action schemes in the test system, it is found that the maximum flow method, as compared to the complex network theory-based method, is more effective in identifying dangerous initiating events leading to a significant reduction in the occurrence of cascading failures.

In future works, the results of this method can be used to examine appropriate repair operations and network development in vulnerable sectors to reduce global blackouts. In addition, to improve the accuracy of the methods in extracting the initial events of cascading failures, combined algorithms, such as random chemistry algorithm, can be used for fast analysis of high-order N-K $(3 < n \leq 5)$ contingencies.

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