Journal of Southeast University (English Edition) Vol. 30, No. 1, pp. 32 - 38 Mar. 2014 ISSN 1003—7985

Research on large-scale cascading failure of power systems using synergistic effect

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Abstract: This paper discusses the primary causes from the point of synergistic effects to improve power system vulnerability in the power system planning and safety operation. Based on the vulnerability conception in the complex network theory, the vulnerability of the power system can be evaluated by the minimum load loss rate when considering power supply ability. Consequently, according to the synergistic effect theory, the critical line of the power system is defined by its influence on failure set vulnerability in N-k contingencies. The cascading failure modes are proposed based on the criterion whether the acceptable load curtailment level is below a preset value. Significant conclusions are revealed by results of IEEE 39 case analysis: weak points of power networks and heavy load condition are the main causes of large-scale cascading failures; damaging synergistic effects can result in partial failure developed into large-scale cascading failures; vulnerable lines of power systems can directly lead the partial failure to deteriorate into a large blackout, while less vulnerable lines can cause a large-scale cascading failure.

Key words: synergistic effect; cascading failure; power system vulnerability; critical line; load loss rate

doi: 10.3969/j. issn. 1003 - 7985. 2014. 01. 007

In recent years, large-scale cascading failures have become one of the focal problems to power systems[1-4]. Blackouts caused by the cascading failures occur as the domino effect, where partial failures gradually spread in the power network through interactions between each element, seriously influencing the capacity of the power supply[5-6], such as the 2003 blackout in USA and Canada and the 2006 blackout in Western Europe. However, not all the large-scale outages are caused by major cascading failure[7], taking the 2009 blackout in Brazil as an example. Accordingly, power system vulnerability is proposed to ensure a safe and reliable operation of power systems.

Received 2013-05-22.

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Foundation item: The National Natural Science Foundation of China (No. 51277028).

Citation: Li Yang, Su Huiling, Sun Yujun, et al. Research on large-scale cascading failure of power systems using synergistic effect[J]. Journal of Southeast University (English Edition), 2014, 30(1): 32 - 38. [doi: 10.3969/j. issn. 1003 - 7985. 2014. 01. 007]

The modern power network is regarded as one of the most complex artificial networks in the world[8-9]. Studies of vulnerability and cascading failures of the power system draw some research achievements from the complex network theory[10-11], such as the small-world property and the scaleless property. The small-world property makes information transfering between nodes possible, which can lead to the spread of partial failure. The scaleless property keeps connections between most nodes in the network even when randomly removing a small amount of them. However, the connectivity of the scaleless network is vulnerable if a small amount of nodes is deliberately removed from the network.

Furthermore, the modern power network is also a network for satisfying the balance of power transmission between supply and demand. Unbalance between the generation and the load triggers the transition of power flow in the network, where increasingly spreading of partial failure may lead to blackout by cascading failures[12]. While Refs. [13 - 14] concern the characteristics of power networks, they ignore the power system operation state. In addition, interactions among power system elements also play an important role in cascading failures, which can be regarded as the damaging synergistic effect of “1 + 1 > 2”.

Catastrophic accidents of the power system cannot merely be caused by a single reason. It is possibly due to the development of interaction of various factors, such as angle oscillation, overload, abnormal voltage and frequency collapse. However, power networks transfer the active power flow from the generation side to the load side but avoid the inactive power long-distance transmission.

In this paper, we propose vulnerability models of power systems utilizing the minimum load loss rate based on the vulnerability theory of the complex network. Then considering interactions among power system elements, we apply the synergistic effect theory to identify the critical lines of power system vulnerability in N-k contingencies. Cascading failures caused by overload is also studied. Based on the above process, this paper proposes the analysis method testified by IEEE 39. Ultimately, significant conclusions are presented.

1 Power System Vulnerability

In the complex network theory, the vulnerability V_i of node i is described as the network efficiency after removing node i from networks[15]. The vulnerability of the power system element can be expressed as[16]

$$V_i = \frac{P_{\text{shedding}i}}{\sum_{j \in \text{Load}} P_j} \tag{1}$$

where V_i represents the vulnerability of element i; $P_{\text{shedding}i}$ means the load loss when removing the element i from networks; P_j is the load of node j.

In N-k($k>1$) contingencies, the vulnerability of the element is defined as

$$F = \{c_1, \ldots, c_k\} \qquad k > 1 \tag{2}$$

$$V_{c_i} = \frac{\sum V(F \mid c_i \in F, k)}{\text{num}(F \mid c_i \in F, k)} \qquad k > 1 \tag{3}$$

where F is the failure set in N-k contingencies; $c_1, \ldots, c_k$ are elements of the failure set F; V_{c_i} is the vulnerability of c_i in N-k contingencies; $V(F \mid c_i \in F, k)$ is the vulnerability of F including c_i; num is the number of F including c_i.

2 Synergistic Effects and Critical Line

2.1 Synergistic effects and its mathematical model

Synergistic effects, first proposed in the 1960s by Ansoff, are widely used in various fields, such as the medical and chemical, the social economic management system[17], etc. The synergy can be simply described as "1 + 1 > 2" or "2 + 2 = 5", which means that combinations between two or more independent resources or individuals will go beyond any of them alone to achieve a goal. In a system, if any of the subsystems or elements cannot cooperate with each other or even repel each other, it can be a disordered state. Therefore, the whole system cannot operate well or even develop into a collapse. On the contrary, if the subsystems or elements coordinate with each other normally, their power can condense into a good system, which will perform far exceeding the overall of their initial ability. In the following, we concentrate on the negative effect caused by synergistic effects.

Assume that the system is composed of multiple elements, where the failure set F contains k elements c. The failure set F can be divided into different subsets by a different method as follows:

$$D_i = \{S_1^i, \ldots, S_m^i\} \qquad i = 1, 2, \ldots, p \tag{4}$$

$$S_j^i \subset F,\ S_1^i \cap \ldots \cap S_m^i = \varnothing,\ S_1^i \cup \ldots \cup S_m^i = F \qquad j = 1, 2, \ldots, m \tag{5}$$

where D_i represents the i-th division of F; p represents the number of division D_i; $S_1^i, \ldots, S_m^i$ are the subsets under division D_i; m represents the number of subset S^i.

The synergistic effect exists if the negative effect satisfies

$$V(F) > \sum_{j=1}^{m} V(S_j^i) \qquad \forall\, i,\ i = 1, 2, \ldots, p \tag{6}$$

where $V(F)$ represents the negative effect of F on the system. So, the synergistic effect of F can be defined as

$$C_{\text{syn}}(F) = V(F) - \max_{D_i}\Big(\sum_{j=1}^{m} V(S_j^i)\Big) \tag{7}$$

where $C_{\text{syn}}(F)$ represents the synergistic effects of F.

We describe the synergistic effects of the fault set F as

$$f_{\text{syn}} = \frac{C_{\text{syn}}(F)}{V(F)} \tag{8}$$

where f_{syn} is the ratio of the synergistic effects of F.

2.2 Critical line in power system

The power system is a heterogeneous network, meaning that elements have obviously unequal characteristics. Moreover, the elements in the failure set might have various effects on the vulnerability of the failure set. The one with a large effect can be regarded as the more critical element.

Using the power system vulnerability and based on the synergistic effects, the criticality of the line in power systems in N-k contingencies can be defined as

$$C_{\text{size}=k}(c_i) = \frac{\sum C_{\text{syn}}(F \mid c_i \in F, k)}{\sum C_{\text{syn}}(F \mid k)} \tag{9}$$

where $C_{\text{size}=k}(c_i)$ is the criticality of line c_i in power systems; $C_{\text{syn}}(F \mid c_i \in F, k)$ is the synergistic effect in N-k contingencies where failure set F contains c_i; $C_{\text{syn}}(F \mid k)$ is the synergistic effect in N-k contingencies.

3 Flow Analysis of Power System Cascading Failure

Partial failures in the power system can cause a shift in the power transmission path. In the case of exceeding the allowable constraint limits, the failure might lead a series of other elements to exit from operation. Consequently, the partial failure might spread into a large-scale one or even a blackout, which results in a direct load loss. Therefore, the large-scale cascading failure can be considered as follows:

1) The partial failure is the immediate trigger;

2) The spreading way is the power flow transferring;

3) The damage on the power system is multi-element outage;

4) The ending comes with the breakout of a large blackout or even a corrupted system;

We consider the overload in power systems under unbalance between power supply and demand. Faults in the transmission path might generate line outages with power flow transferring. If the system cannot respond timely of the outages that the load-shedding rate is beyond a set value, the most severe overload line can be out of operation, or even worse, a series of lines might be in outage, until the load-shedding rate is below the set value. The simulation process of cascading failures is shown in Fig. 1. The load-shedding rate is defined as

$$\alpha = \frac{P_{\text{shedding}}}{\sum_{i \in A(t)} P_i} \tag{10}$$

where P_{shedding} is the minimum load-shedding which should be cut for the safety of the network $A(t)$; $\sum_{i \in A(t)} P_i$ is the gross load of the network $A(t)$.

Here, considering N-k contingencies, failure sets with the damaging synergistic effects are considered to analyze the damaging synergy with different k. We compare the vulnerability of lines with its criticality to better understand the characteristics of the vulnerable lines, where the similarity zone method is used to clarify the difference between the vulnerability and the criticality. The method mainly contains three steps. First, sort the values of the vulnerability or criticality of lines with the biggest in front; secondly, divide the sequencing into a segment if the lines are neighbours; thirdly, zone the lines according to the similarity between values.

According to the vulnerability of lines with and without consideration of cascading failures in Fig. 1, there are five scenarios and they are defined as

$$\begin{aligned}
&\eta = \{\eta_1, \eta_2, \ldots, \eta_5\} \\
&\eta_1: V_i = V_i' = 0 \\
&\eta_2: V_i > V_i' > 0 \\
&\eta_3: V_i = V_i' > 0 \\
&\eta_4: 0 < V_i < V_i' \\
&\eta_5: V_i' = 1 \\
&\sum_{n=1}^{5} \eta_n = 1
\end{aligned}$$

where V_i is the vulnerability of line i without the consideration of Fig. 1; V_i' is the vulnerability of line i considering Fig. 1; and η is the probability distribution.

Based on the synergistic effects in section 2, η_1 and η_3 express that the vulnerability is unaltered with the consideration of cascading failure, indicating that no synergy exists in the power system. η_2 shows the improvement in vulnerability considering cascading failure, indicating that cooperative synergy exists in the power system. On the contrary, η_4 shows that the damaging synergy exists in the system. η_5 means that the system breaks down so that the network cannot supply any load.

4 Case Study

The case study uses the IEEE 39 system[18]. The equivalent branches of transformers are regarded as lines in networks. It is assumed that k equals 1, 2, 3 in the N-k contingencies and the ratio between the overall load and the maximum power generation of the system is expressed as γ with the initial value 0.85.

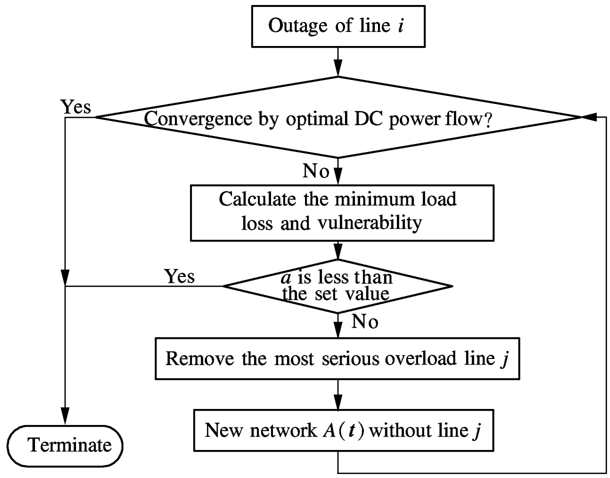

Fig. 1 Flowchart of cascading failure simulation in power system

To better understand the characteristics of the vulnerable lines, we arrange the data of the vulnerable, the critical and the synergy in a descending order and divide them into three categories: high, middle and low. The high values of vulnerability or criticality reveal that the lines are more vulnerable or critical. Besides, the high values of the synergy represent the stronger synergistic effect. In the following analysis, this paper focuses on the high and the low to reach conclusive results.

4.1 Vulnerability of failure sets and synergistic effects

The results in Fig. 2 show that the more vulnerable the failure sets, the lower the synergistic effects and vice versa. It indicates that the most vulnerable failure sets can directly lead to large-scale blackout, while a partial failure alone will not. However, as the strong synergistic effect exists, partial failures will gradually spread into a large-scale cascading failure or even a blackout.

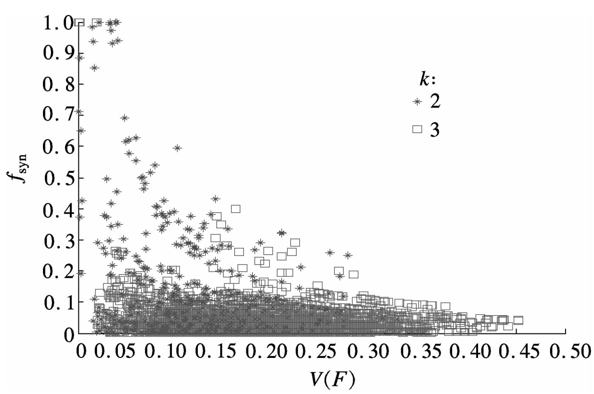

Fig. 2 Vulnerability and synergy of failure set F in N-k contingency

Besides, the maximum vulnerability in the situation of $k=3$ is greater than that of $k=2$. On the contrary, the synergy of the N-3 contingency is weaker than that of the N-2 contingency. It indicates that faults under N-3 contingency are not caused by all the elements in the failure sets but some subsets. Under N-2 contingency, the failure sets have a stronger synergistic effect but lower vulnerability, since the vulnerable lines are fully considered in N-1 failure.

Tab. 1 shows partial results of more vulnerable failure sets in a descending order. In the N-2/3 contingency, with the vulnerability of F reducing, its corresponding synergistic effect fluctuates irregularly. For example, the failure set {39, 46} has the highest vulnerability in N-2 contingency but a lower synergistic effect ratio. However, failure set {27, 46} is less vulnerable than failure set {39, 46} and has a higher synergistic effect. Thus, we can see that more vulnerable failure sets generally have a lower synergistic effect.

Meanwhile, the vulnerable line 46 coexists in the failure set of $k=1$, $k=2$ and $k=3$. More vulnerable failure set {39, 46} in N-2 contingency is the subset of failure set {33, 39, 46} in N-3 contingency. Thus, it can be concluded that the vulnerable lines in N-1 contingency are generally included in the vulnerable failure sets in N-k contingencies($k>1$).

Tab. 1 Vulnerability ranking of failure set F and its synergistic effect ratio in N-k contingency

Serial number	$k=1$		$k=2$			$k=3$		
	Line label	$V(F)$	Line label	$V(F)$	$f_{syn}/\%$	Line label	$V(F)$	$f_{syn}/\%$
1	46	0.162 3	{39, 46}	0.328 1	0.046 6	{33, 39, 46}	0.452 3	0.038 2
2	39	0.150 6	{37, 46}	0.312 4	0.049 6	{20, 39, 46}	0.451 9	0.043 1
3	37	0.134 6	{27, 39}	0.276 9	0.249 1	{14, 39, 46}	0.441 5	0.020 8
4	14	0.104 2	{14, 46}	0.272 8	0.023 2	{13, 39, 46}	0.436 7	0.042 8
5	20	0.099 9	{33, 39}	0.272 7	0.119 7	{33, 37, 46}	0.436 6	0.039 6
6	33	0.089 5	{20, 46}	0.272 7	0.038 6	{20, 37, 46}	0.436 2	0.044 7
7	34	0.088 7	{20, 39}	0.270 1	0.072 7	{19, 39, 46}	0.435 4	0.039 8
8	19	0.085 8	{27, 46}	0.269 1	0.183 8	{23, 39, 46}	0.428 5	0.045 6
9	13	0.085 5	{33, 46}	0.269 1	0.064 2	{14, 37, 46}	0.425 8	0.021 7
10	35	0.085 2	{35, 46}	0.264 7	0.065 3	{34, 39, 46}	0.424 9	0.019 0

4.2 Vulnerability and criticality of lines

Tab. 2 shows the partition of the vulnerability of the lines in N-k contingencies, while Tab. 3 shows the partition of the criticality. Results in the square brackets represent that the lines are neighbor lines. The zone index is ranked in a descending order according to the vulnerability or the criticality.

From Tab. 2, we can see that more vulnerable lines in power systems are in the minority. Considering the partition which ranks the first three serial numbers, the proportion is 6.5% in N-1/2 contingency, and the proportion is 8.7% in N-3 contingency. Otherwise, more vulnerable lines in the situation of $k=1$ have the same features in the situation of $k=2/3$, such as line 46 in number 1, line 39 in number 2 and line 37 in number 3.

Referring to the power network configuration, lines 46, 39, 37, 14, 33 and 34 are all transformer equivalent branches connected directly to generators. Among them, line 46 connects with generator bus 38, which supplies 91.3% active power to load buses 29, 28, 26 and 27; line 39 connects to generator bus 38, which mainly supplies active power for nearby load buses 23, 24 and a small part for bus 16; line 37 connects to generator bus 35, which mainly supplies active power for nearby load buses 21, 23 and 16. These lines are more vulnerable in the power system since failures on these lines will engender immediate effects on load. Whereas line 5 connects with generator bus 30, of which the power supply capacity is limited to scatter the distribution of load buses 1, 3,

Tab. 2 Lines partition according to the vulnerability in N-k contingencies

Serial number	Line label		
	$k=1$	$k=2$	$k=3$
1	46	46	46
2	39	39	39
3	37	37	[35, 37]
4	14, [9, 13, 18, 19, 20, 23]	14, 20, 33, 34, 35, 41	33, 14, 34
5	33, 34, 35	[9, 19, 23], [10, 12, 13]	[9, 19, 20, 23], 41, [10, 12, 13]
6	41, [10, 12]	27	45, 3, 18, 38, [42, 44], 11, 25, [1, 4, 5]
7	[25, 27, 28], 3, 45, 11, 38, 42	45, 18, 38, 3, [42, 44], [25, 28], 32, 11	[26, 28, 30]
8	32, [4, 5], 44, 8, 15, [26, 30], [40, 43]	[1, 4, 5]	43, [6, 7, 8], 15, 2, 40, 27, 16, 24, 31, [21, 22], 17, 36, 29, 32
9	[21, 22], [1, 2, 16, 17], [6, 7], 24, 29, 31, 36	[26, 30], 43, 8, 15, 40	
10		2, [21, 22], [6, 7], 24, 31, 36, [16, 17], 29	

9, 39. So line 5 is less vulnerable. The lines connected to the important generators can be the most vulnerable lines in power systems. Therefore, distribution features of the load and the generation are the main factors influencing the vulnerability. Here, the criteria of the importance of power generations or loads are measured by the capacity of available power supply or the load demand.

Combining Tab. 3 with Tab. 2, more vulnerable lines are less critical, such as lines 6 and 39, while less vulnerable lines are more critical, such as lines 1 and 2 in $k=2$ contingency and lines 4, 5 and 41 in $k=3$ contingency. More vulnerable lines can cause immediate damage to load without the synergy, while more critical lines have stronger synergistic effects which will cause load loss.

Tab. 3 Lines partition according to the critical value in N-k contingencies

Serial number	Line label $k=2$	Line label $k=3$
1	[1, 2]	33
2	[27, 28, 32, 33, 35]	[4, 5, 41]
3	41, 44, 5, 37, 39, 13, 20, [19, 23], [40, 43, 45, 46], 38	[28, 35, 37]
4	26, [10, 12, 14], 9, 36, 42, 30, [3, 4], 29, 18, [11, 15, 16, 17], 34, 31, [24, 25], [6, 8]	39
5	[21, 22], 7	13, [19, 20, 23], [1, 2, 3]
6		[10, 14]
7		26
8		[43, 44, 45, 46], [9, 24], 18
9		34
10		[6, 8], [7, 30], 40, [25, 27], 12, [31, 42], 32, 38, [11, 15, 16, 17]
11		36, [21, 22], 29

4.3 Simulation of large-scale cascading failure

We assume that the allowable load-shedding rate is 0.1, and the ratio γ between the overall load and the sum of the maximum power generation belongs to [0.30, 1.00] with an interval of 0.5. The load of each node changes with γ.

Fig. 3 shows the probability distribution of η_k with γ variations. η_4 and η_5 decline from $\gamma=1.00$ to $\gamma=0.90$, and keep smooth without fluctuation when $\gamma<0.90$, where $\eta_4=0.02$ and $\eta_5=0$. It means that if the power system is in the state of the heavy load, the latent damaging synergy can make the system more vulnerable or even collapse, such as $\eta_5=0.04$ with $\gamma=0.95$ and $\eta_5=0.20$ with $\gamma=1.00$. In the scenario of $\gamma<0.90$, line 46 contributes more to the synergy. Line 46 is the essential connection to the generator 38, load 28 and neighbour load 26. Failures on the line can cause the neighbouring lines to overload. Moreover, line 46 is the weak point in the power network, which has no relevance to the system load conditions. So, even if the system load is not so heavy, the weak lines in the power network can trigger damage synergy, while some other lines might have no synergy.

In the scenario of $\gamma\geqslant 0.90$, the probability of η_1 is 0, while η_3 increases with the decrease of γ. In the scenario of $\gamma<0.90$, η_1 increases while η_3 decreases with the increase of γ. It suggests that the lines are more vulnerable when the power system is under heavy load conditions, and less vulnerable vice versa. In the scenario of $\gamma\geqslant 0.80$, $\eta_2>0$; and in the scenario of $\gamma<0.80$, $\eta_2=0$. It indicates that under heavy load conditions, cascading failure can cause configuration change in power networks, and meanwhile the change in the redundance of the power

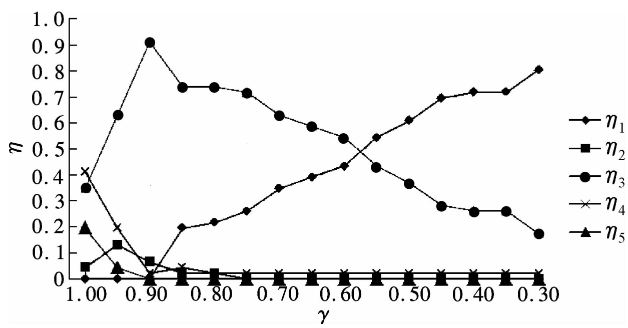

Fig. 3 Probability distribution of $\eta(k)$ with different γ

network will not aggravate damage but might result in some improvement; on the contrary, under light load conditions, no synergy exists in the system, since the margin of the redundance is large enough to deal with the conditions.

Based on the above analysis, we can conclude that the synergistic effects in power systems are affected by the load conditions, which can be considered as no synergy under light load conditions but the damaging or the cooperative synergy under heavy load conditions. What's more, the probability of the damaging synergy in the power system under heavy load conditions is larger than that of the cooperative synergy.

We focus on the scenario of $\gamma>0.80$. The number of outage lines caused by cascading failures is defined as the length of the cascading failure sequence, which is shown in Fig. 4. In the scenario of $\gamma>0.90$, the length is a fluctuant curve, while in the scenario of $\gamma\leqslant 0.90$, the probability of cascading failure is lower where the curves are nearly a straight line. However, line 46 has little change in the length of cascading failure. Combined with the above analysis, line 46 is the weak point in the power system so that the outage of the line will cause the cascading failure. Therefore, the cascading failure is not only affected by the load conditions but also by the weak point of the system.

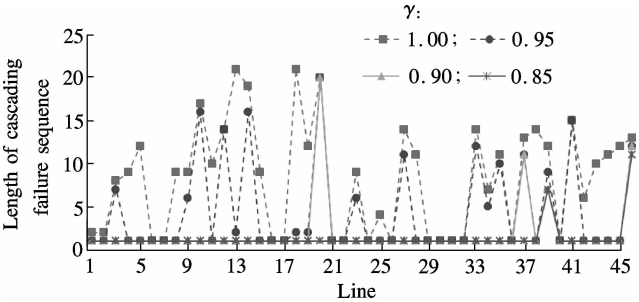

Fig. 4 Length of the cascading failure sequence with $\gamma > 0.80$

From the above analysis, the more the vulnerable lines, the more the immediate load loss. However, more critical lines can cause serious effects on power supply by the damaging synergy. The sequence of the probability of cascading failure is shown in Tabs. 4 and 5, ranking the first 30% and the last 30% of all the lines, respectively. Combined with Tab. 2, the probability of cascading failure of the more vulnerable lines is lower, such as lines 46, 39 and 37, which are shown in Tab. 5. The less vulnerable lines have a higher probability of cascading failure, such as lines 24, 7 and 31. Therefore, it can be concluded that vulnerable lines can cause immediate load loss or even a large blackout while less vulnerable ones can cause a cascading failure or even spreading into a large-scale outage.

Tab. 4 Cascading failure probability of the first 30% of all lines

Serial number	$\gamma = 1.00$		$\gamma = 0.95$	
	Line label	Cascading failure probability/%	Line label	Cascading failure probability/%
1	24	8.07	24	7.84
2	7	7.81	21	6.86
3	31	7.55	7	6.37
4	17	7.03	31	6.37
5	6	6.25	17	5.39
6	21	5.21	6	4.90
7	32	4.95	8	2.94
8	40	3.13	29	2.94
9	8	2.34	11	2.45
10	42	2.34	15	2.45
11	9	2.08	16	2.45
12	15	2.08	25	2.45

5 Discussion

The power system is a dynamic nonlinear system. The catastrophic accident of the power network can be caused by various factors, such as angle oscillation, overload, abnormal voltage and frequency collapse. Ref. [7] shows

Tab. 5 Cascading failure probability of the last 30% of all lines

Serial number	$\gamma = 1.00$		$\gamma = 0.95$	
	Line label	Cascading failure probability/%	Line label	Cascading failure probability/%
1	39	1.04	18	0.98
2	4	0.78	20	0.98
3	5	0.78	23	0.98
4	13	0.78	38	0.98
5	18	0.52	45	0.98
6	45	0.52	33	0.49
7	33	0.26	34	0.49
8	34	0.26	35	0.49
9	35	0.26	37	0.49
10	37	0.26	39	0.49
11	41	0.26	41	0.49
12	46	0.26	46	0.49

that two failure lines in the power system can probably cause the system to become unstable, and furthermore some failure sets can lead to a disaster. Therefore, based on the synergistic effect theory, this paper explores that the critical lines which contribute to the vulnerability by filtering the sets with a negative effect.

In addition, Refs. [12, 19] studied cascading failures from the connectivity of power networks. It concludes that high betweenness lines are the more vulnerable lines once suffering intentional attacks, and also the long-range connection can propagate the partial failures. However, cascading failures can not only alter the power networks but also change the initial redundance of power systems, which directly influence the safety and reliability of system operation. Based on the results of the vulnerability and the criticality of lines, this paper shows that the load condition is also a significant factor as well as the power network in cascading failures.

6 Conclusion

This paper studies the mechanism of the cascading failure in power systems from the point of synergistic effects. From the simulation results, it can be seen that cascading failure in power systems is relevant with the weak points of the power networks and the system load conditions. The weak lines can cause cascading failure whether the system load is heavy or light, while other lines can cause cascading failures only under the heavy load condition. Besides, the probability of cascading failures is related to the vulnerability of the lines. The vulnerable lines can lead to an immediate large blackout while the less vulnerable lines can cause cascading failure to a blackout under heavy load conditions.

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基于协同效应的电力系统大规模连锁故障研究

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摘要:为改善电力系统脆弱性并服务于电网规划和系统安全运行,从系统协同效应的角度探讨连锁故障的发生机理.基于复杂网络脆弱性理论,考虑电力系统的供电能力,采用最小失负荷率建立电力系统脆弱性模型.然后基于协同效应理论,考虑 N-k 故障情况,建立电力系统线路关键性模型,以分析影响脆弱性的关键线路.通过设置允许切负荷水平值,建立电力系统过负荷情况下的连锁故障模型.采用 IEEE39 算例分析验证了所提方法的有效性.分析结果表明:电网结构的薄弱点及重负荷是诱发大规模连锁故障的主要原因;高脆弱线路能够直接导致大停电事故,而低脆弱线路能够导致大规模连锁故障的发生.

关键词:协同效应;连锁故障;电力系统脆弱性;关键线路;失负荷率
中图分类号:TM71