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Creating Cascading Failure Scenarios in Interconnected Power Systems

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Abstract: The reported catastrophic failures of power systems from different geographical parts of the world often point to cascading outage events of system elements that eventually had led to system blackout. Although the initiating events of these cascading failures may, at times, be avoidable by vegetation management or proper protection settings, the occurrence of such an event as well as the eventual impact cannot always be predicted. There is much debate in the industry whether the operator has enough time to apply countermeasures to avoid blackouts. Besides, the process of determining effective countermeasures cannot be deemed accurate unless a system has been extensively studied for the occurrence of widespread blackouts. In this paper, methods to create different cascading failure scenarios are developed under credible contingency conditions. The methods are tested on the 118 bus test system and several cases are reported.

Keyword: Catastrophic failure, blackout, cascading outages, countermeasures, system vulnerability.

I. Introduction

On August 14th, shortly after a 650 MW power plant in Ohio failed, a 1200 MW capacity transmission line in the same state tripped, thus starting a series of cascading events that eventually led to the worst blackout in US history [1]. Uncontrolled system conditions had led to several power plants being tripped forcing power to flow through overloaded regional lines, which in turn, tripped to avoid damage.

Large scale blackouts are relatively rare. However, instances where blackouts have involved multiple areas point to certain features are insightful and educational. An analysis of recent blackout events [2]-[6], reveals an interesting theme:

June 1998 - A severe lightning storm in Minnesota initiated a series of events, causing a system disturbance that affected the entire Mid-Continent Area Power Pool Region and the northwestern Ontario Hydro system of Northeast Power Coordinating Council. Lightning struck a 345 kV line in Minnesota and system protection de-energized the line. Some underlying lower voltage lines became overloaded and were tripped by protective devices. Lightning caused the removal of a second 345 kV line and the remaining lower voltage transmission lines in the area were automatically removed from service. This successive removal of lines from service continued until the entire northern MAPP Region was separated from the Eastern Interconnection, forming three islands and resulting in the eventual blackout of the northwestern Ontario Hydro system.

March 1999 – A zone 3 relay tripped a 440 kV line in Sao Paulo, Brazil, resulting in cascading outages of several plants and high voltage ac and dc lines finally leading to a total blackout affecting 75 million people.

1997 – An ice storm in Quebec, Canada downed transmission lines and blacked out much of New England, USA.

July 1996 – A falling tree branch in Idaho led to a cascading failure of several power plants and transmission lines blacking out 18 western states in the US.

August 1996 - all major transmission lines between Oregon and California were dropped affecting 10 western states.

It is clear that transmission lines form a major link in the cascading failure phenomenon. Although, the reasons for line failure may be overloading, faulty protection setting, overgrown vegetation, or any other unpredictable system or weather condition, a line failure is often associated with growing system oscillations, voltage or transient instability.

A power system is resilient enough that it can easily recover from a single element outage or malfunctioning. Thus individual blackouts are generally triggered by random events ranging from multiple equipment failures and bad weather to vandalism. The blackouts then typically become widespread through a series of cascading events.

In order to understand the mechanisms of wide area blackouts brought about by cascading element failures in interconnected power systems, a study was undertaken with the primary goal of forcing the system under study to the brink of collapse. The overall objectives of this paper may be summarized as follows:

1. Determine the vulnerability of a system to a blackout. Although, there is no single indicator of system vulnerability. One may study the generation levels as compared to their individual capability curves, the line loading levels as compared to their overloading limit, MW and MVar reserves available, system loadability and stability margins under critical single and multiple contingencies, etc. These indicators may be used to develop a composite risk level that measures the vulnerability of the system. In general, the following minimum information is required to develop such a measure:

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a. System pre-condition – loading and generation levels, congestion points, voltage profile

b. Post-contingency condition

c. Availability of control actions

2. Determine the sequence of events that lead to a blackout. To create this sort of cascading events, one has to simulate a disturbance, then wait for the system to attempt to settle down, then simulate a second disturbance and a third, or fourth and so on to make the system fail to converge to a post-disturbance equilibrium.

Simulating cascading failures in large power systems is always a difficult task. An insight may be gained by carefully studying a medium-sized system that provides enough complexity to study a slew of possibilities, including the effect of interarea tie-line congestion, the presence of weak lines in high load areas, limited generating capacities in certain areas, etc.

II. The 118-Bus Test System

A. System diagram and operating conditions

The IEEE 118 bus test system, shown in Fig. 1 is used for testing the cascading outage schemes. Four principle areas are defined in the system as shown in the diagram.

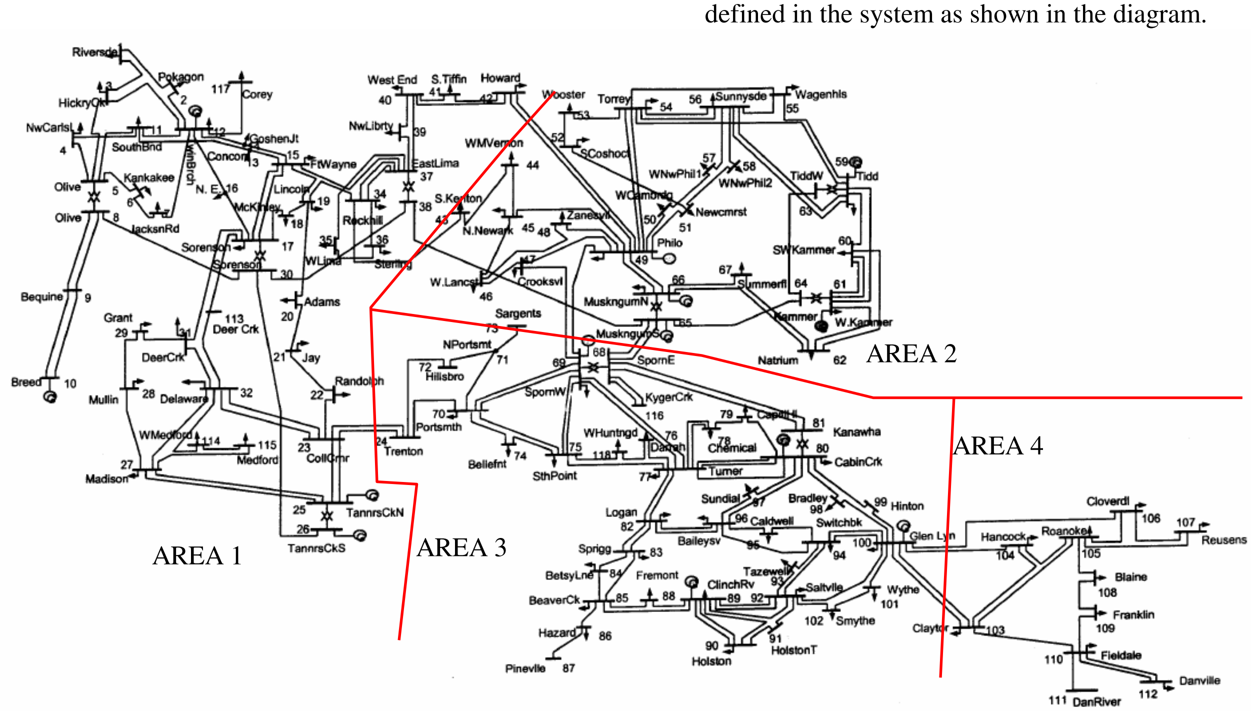

Fig. 1. The 118-bus test system.

As a first step, it was desirable to identify the following topological conditions as well as some operating conditions of the system:

- Location of large generators and generation reserves
- Location of large loads
- Loading levels and capacity on tie-lines
- Loading levels on major transmission corridors
- Pre-disturbance voltage profile of system
- Location of high capacity transformers that connect to the higher voltage levels.
- Location of distributed generations
- Major flowgates

Table 1 shows the interconnections flowgates in the system. It is obvious that the transfer capability between areas 1 and 3 is the least among all area interchanges. Therefore any system condition that creates a stress on these tie lines may be cause for concern.

It may also be noted that Area 4 has inadequate generation to serve its native load and imports heavily from Area 3. Area 4 is only interconnected to Area 3. Thus, export limitation from Area 3 to Area 4 may be a cause for concern.

Table 1 Interconnection Flowgates in the 118-Bus Test System

Area Connection		Line Connection		Capacity
From Area	To Area	From Bus	To Bus	MVA
		49	42	272
1	2	65	38	258
		34	43	42
1	3	72	24	27
		70	24	31
		69	70	164
2	3	69	75	168
		69	77	94
		81	68	131
		100	106	92
3	4	100	104	86
		100	103	182

III. Creating Cascading Collapse Cases

The power system is tested for overloads due to various contingencies. Only line outages are considered as contingencies. Generator outages or other dynamic problems are not considered. Since lines have limited capacity to carry power, they can easily get overloaded if the power flow on the tripped lines is redistributed through them. This can cause further deterioration of the overall health of the system if those overloaded lines are also tripped.

Single line contingency screening was carried out initially. Less than a quarter of the tested contingencies caused a serious overloading problem. The extent of overloading was used as a criterion for deciding further outages in the system. This process highlighted the specific path followed by a failure. In most of the cases, there were a number of lines which got overloaded. Sometimes it may happen in a real system, that the highest loaded line may survive and a different line may trip due to different protection settings. This possibility was considered in some cases, whenever there were a large number of overloads. In most cases, the selection of the specific line to be outaged merely effects the number of steps in which the system progresses towards collapse.

Out of all the possible single line contingencies, 37 contingencies were identified as a set of potentially dangerous contingencies. However, many of them result in a failure because they cause islanding of certain buses. Out of the 37 contingencies, we identified only 12 contingencies for further study. The results of this analysis are presented in the following sections. It can be observed that some of these contingencies caused wide-spread overloads, some scenarios only created overloads that were limited to just one particular area in the system while some resulted in overloading of interarea tie-lines. Some of these short listed outages and their impact are discussed in the next section.

A. *Outage of line 4-5*

Outage of the line seems to be a comparatively wider problem encompassing the northwestern part of Area-1. Line 4-5 connects a generator and a load at bus 4 to bus 5. Outage of this line causes overloading of line 5-11, which in turn causes overloads in lines 5-6, 6-7 and 7-12 as shown in Fig. 2.

Bus 7 has a small load and bus 12 has a moderately sized generator. Taking out line 7-12, causes major overloads in lines 3-5 and line 16-17. This is because the generator at bus 10 delivers power through line 3-5 and lines 8-30, 30-17 and 17-16.

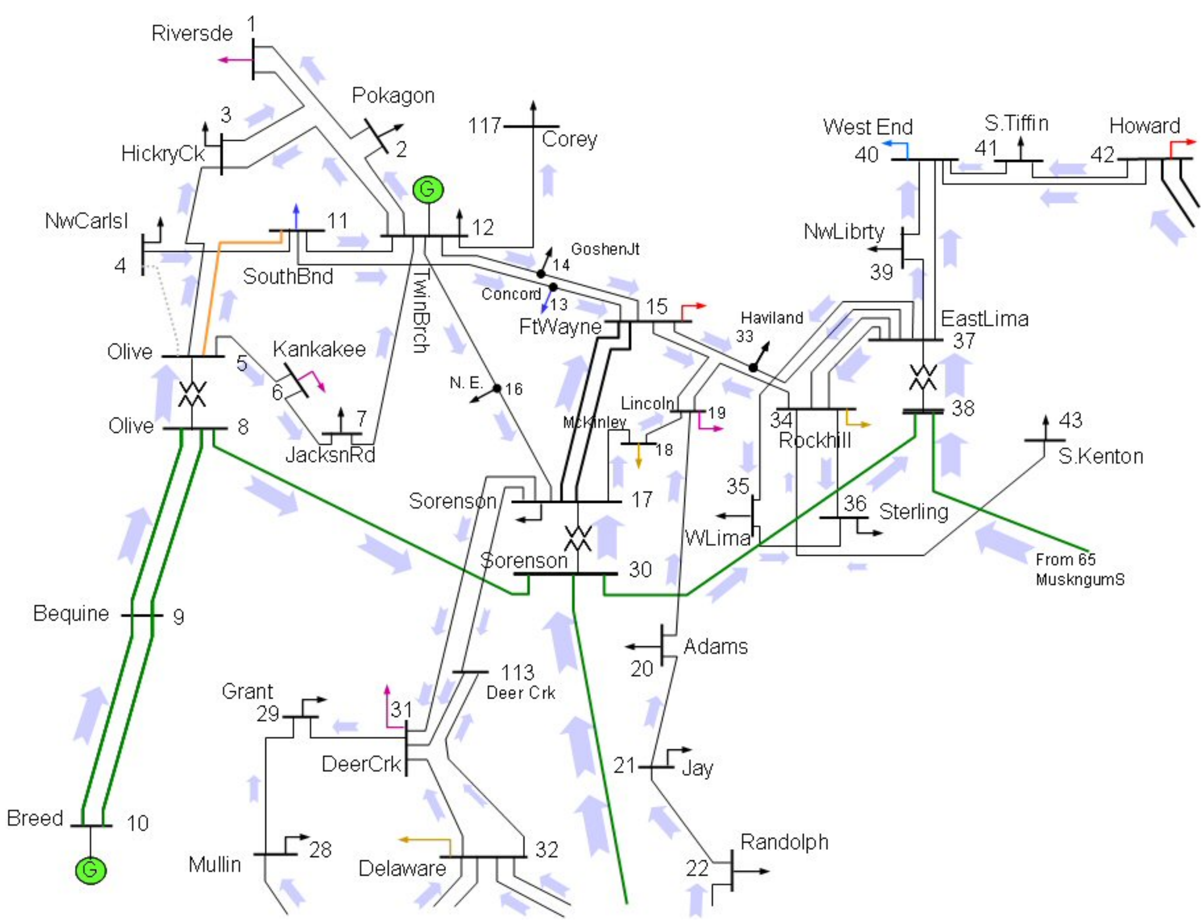

Fig. 2. Initial effect of the outage of line 4-5 in the 118-bus test system.

Line 3-5 is again one of the lines that connect the buses in northwest part of Area-1 to the transformer at 5-8. Taking line 3-5 out causes a large number of major overloads. Now the troubled region extends towards the centre of Area-1. Lines 8-30 and 16-17, which get overloaded in the process, are crucial. They both connect the northwestern part of Area-1 and the crucial transformer at bus 17.

Taking out line 16-17 further overloads the same lines are previously overloaded. Also, line 17-15 is now used to route power to the northern region and hence gets overloaded. This worsens the condition in the entire area. Line 14-15 gets enormously overloaded (681 %). Overloads also spread over entire Area-1. Lines 15-33, 33-37 and 15-19 bring power from the eastern region of Area-1 which is connected to Area-2. Lines 21-22, 22-23 deliver power from south to north.

Finally, taking out line 14-15 causes the system to fail. This scenario essentially limits the power delivered by transformer 5-8 to the north-western part of Area-1. Due to the initiating failure, the power flow is routed via line 8-30 and transformer 30-17. In the process the lines which carry power from transformer 30-17 get overloaded. Further outage of these lines signals trouble.

B. Outage of line 38-65

Line 38-65 is one of the important tie-lines between Area-1 and Area-2. Quite understandably, it is also one of higher capacity lines in the system. Outage of this line forces power through other area interconnections. This line connects a very large generator at bus 65 to the transformer at bus 38. Area-1 is a net importer of power and line 38-65 delivers a considerable amount of power to Area-1. In absence of this line, other area interconnections share the burden. Inter-connection between Area-1 and Area-3 is made up of two lines (24-70 and 24-72). Both these lines get overloaded as seen in Fig. 3. In the northern part, lines connecting buses 40, 41, 42, 39 are affected. Also line 34-43 and 43-44 which are responsible for inter-area power transfer impacted. The only noteworthy flow reversal is in line 23-24. Real power now flows from bus 24 to bus 23.

Outage of a second line – that between buses 23 and 24, limits the power that can be transferred from Area-3 to Area-1. Thus effectively two tie lines are lost which could supply power to Area-1. This puts the burden on Area-2 to supply to Area-1 through tie line 34-43. Line 43-44 delivers power to this link. This line is highly overloaded. Also, lines 39-40 and 37-40 act as the northernmost tie line. This line mainly draws power from lines 40-41, 40-42 and 41-42. All these lines are affected after this outage. Not many reversals in direction of power flow are observed. This is because even in a healthy state, Area-1 draws power from other areas.

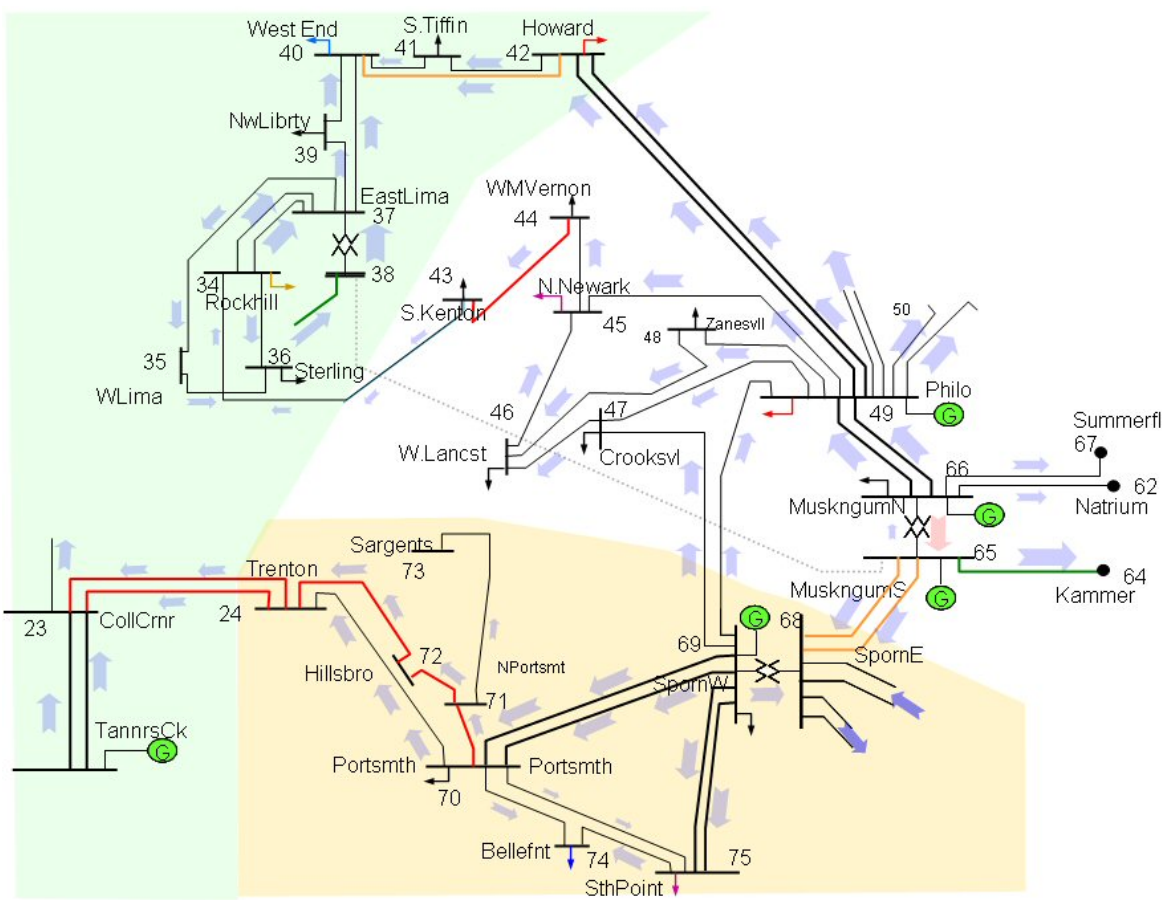

Fig. 3. Initial effect of the outage of line 38-65 in the 118-bus test system.

If line 43-44 is tripped, then there is only one corridor for power transfer between Area-1 and Area-2. Area-3 is already cut off from Area-1. Thus, only the north most inter-connection gets burdened with the responsibility to cater to some loads in Area-1. Area-1 has heavy loads close to this inter-connection. Now power is drawn from central and eastern part of Area-2. In the process lines 40-41, 40-42, 41-42, 39-40, etc. get overloaded. Line 40-41 is the highest overloaded line. Also very strong lines like 42-49 also get overloaded while supplying power to this inter-connection. Power is ultimately drawn for the swing bus. This shows the wide-spread effect of the contingency.

Outage of line 40-41 worsens the situation in Area-2. The system is held together by just the north most inter-connection. It is on the verge of being divided into two halves. Lines 40-41 and 41-42 are equivalent to a single parallel line to line 40-42. So, outage of line 40-41 causes overloading of line 40-42. The extent of overloading on previously overloaded lines increases further. Notable lines are 42-49, 47-69 and 49-69. Line 42-49 is a strong double line and still it gets overloaded. Also, the transformer at 65-66 gets overloaded. This shows the severity of power flows.

Outage of line 40-42 completely cuts off Area-1 from the rest of the system. Technically this can classify as islanding, but it actually creates two big islands. This scenario shows the nature of interaction between area inter-connections.

C. Outage of line 64-65

Line 64-65 connects a transformer at 65-66 to another transformer at 61-64. It is a crucial line in Area-2. In steady-state condition, this line carries power from bus 65 to bus 64. The pre-outage line flow is very heavy. The reason behind such a large power flow is that a large load exists at bus 59 (277MW, 113 MVar). This load is being supplied by this west to east power transfer.

Line 64-65 takes power from the large generators at bus 65 and bus 66 and delivers it to the eastern part of Area-2. This area has major loads at buses 59, 60 and 61. Outage of line 64-65 causes overloads on line 62-66 and line 62-67 as seen in Fig. 4. These are two alternative paths for taking power to the eastern region of Area-2. Power is also seen to flow to the North and then to the East and finally looping back to the South so as to serve these major loads. Thus immediate overloading occurs on lines 62-66 and 62-67. No significant changes in direction of power flow are noticed.

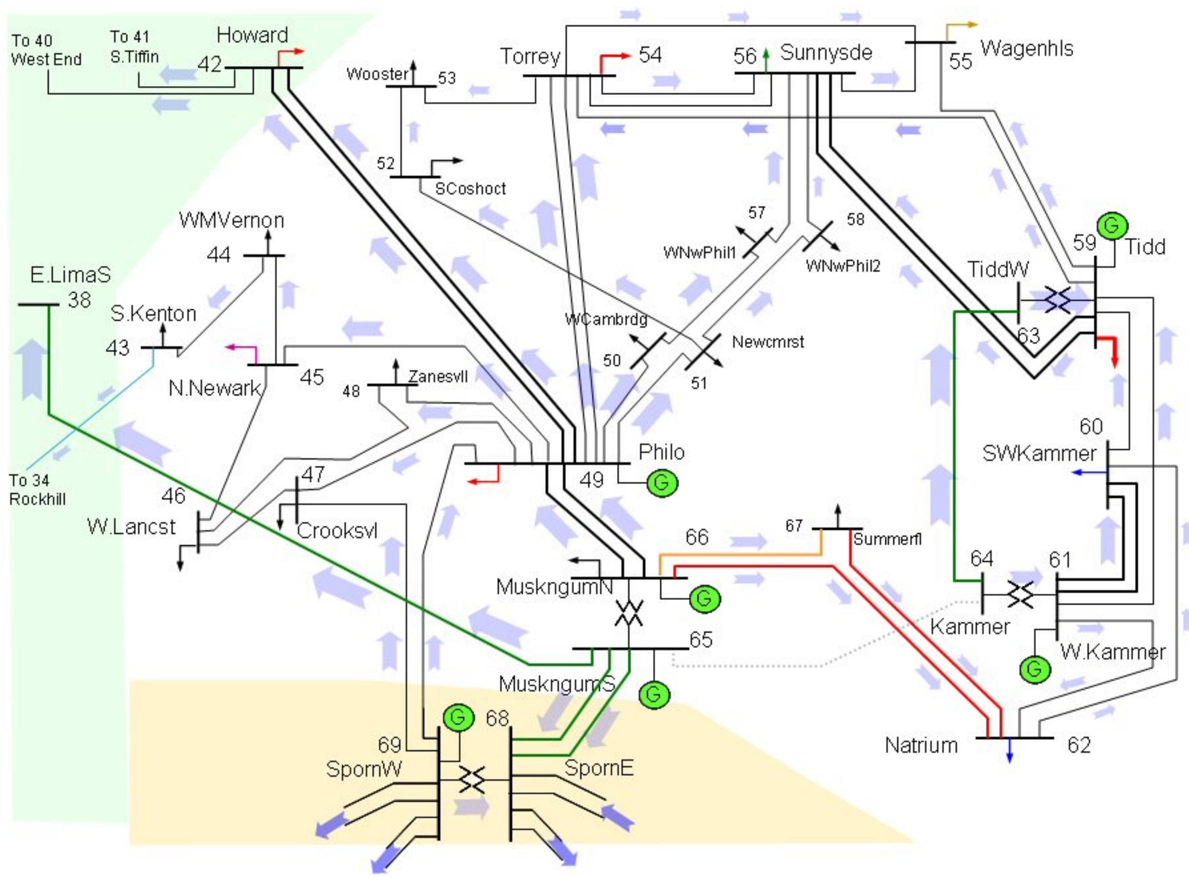

Fig. 4. Initial effect of the outage of line 64-65 in the 118-bus test system.

A second outage - that of line 62-67, then eliminates one of the two remaining paths for delivering power directly from the western to the eastern region of Area-2. This outage shifts the flow on line 62-66. It also causes a flow from South to North in Area-2. This power further flows towards the East and loops back to the South. As a result, lines 50-57, 54-56, 56-57, etc. get overloaded. This outage also overloads the transformer at 65-66.

Now, an outage of line 63-66 eliminates any possibility of West-East power transfer in Area-2. In order to serve the heavy loads at buses 59, 60, 55, 56, etc., power now flows from South to North in Area-2. For example - the power now flows from 66 to 49 to 50/51 to 57/58 to 56 to 55 to 59. As a result the lines which run South-North get overloaded. Even some of the lines such as 47-49 which run West-East contribute to this flow and get overloaded in the process. Almost all the lines which are connected to bus 49 get overloaded. This is so, because bus 49 is the junction from where power can flow to North and then to East. Line 49-54 is overloaded in spite of being a strong double line. Line 54-59 shows a reversal in the direction of real power flow. It now supplies power from bus 54 to bus 59. Earlier, bus 59 was drawing power from the transformer at 64-61. Line 56-58 which carries power from South to North is the most heavily loaded line.

Outage of line 56-58 limits the South-North flow to an extent. This causes overloads in lines carrying power from the western region of Area-2 to the eastern region. Line 54-56 is one of them. Other lines which carry power from South to North are further overloaded. Lines which were previously overloaded are now at dangerously high overload levels. Also, the transformer at 65-66 is overloaded. Both these buses have major generations. Line 54-56 is the highest overloaded line.

As a next step, outage of line 54-56 limits the West-East power flow that ultimately flows towards bus 59, 60, 55 and 56, which have heavy loads. Line 54-55 is the only line which can accomplish this West-East flow. Also, most of the power is drawn from lines which run South-North. In the process, all lines running North from bus 49 get overloaded. The extent of overloading in the South-North lines reaches dangerous levels.

Outage of a further line, that between buses 54 and 55 leaves only one option for the power transfer: 49 to 51 to 57 to 56 to 59. This path gets highly overloaded. Line 56-57 is the weakest line amongst these lines. Naturally this line is the highest overloaded line. All the previously overloaded lines experience a more severe overload.

If line 56-57 is now tripped, then the system reaches a blackout state.

D. *Outage of line 89-92*

Line 89-92 is a very strong connection between a major generator at bus 89 and a large load at bus 92. Outage of this line does not have a wide-spread effect on the network in Area-3 since a second circuit exists to the load at bus 92. This second circuit does get overloaded. The North-South connection 82-83 also gets overloaded as seen in Fig. 5.

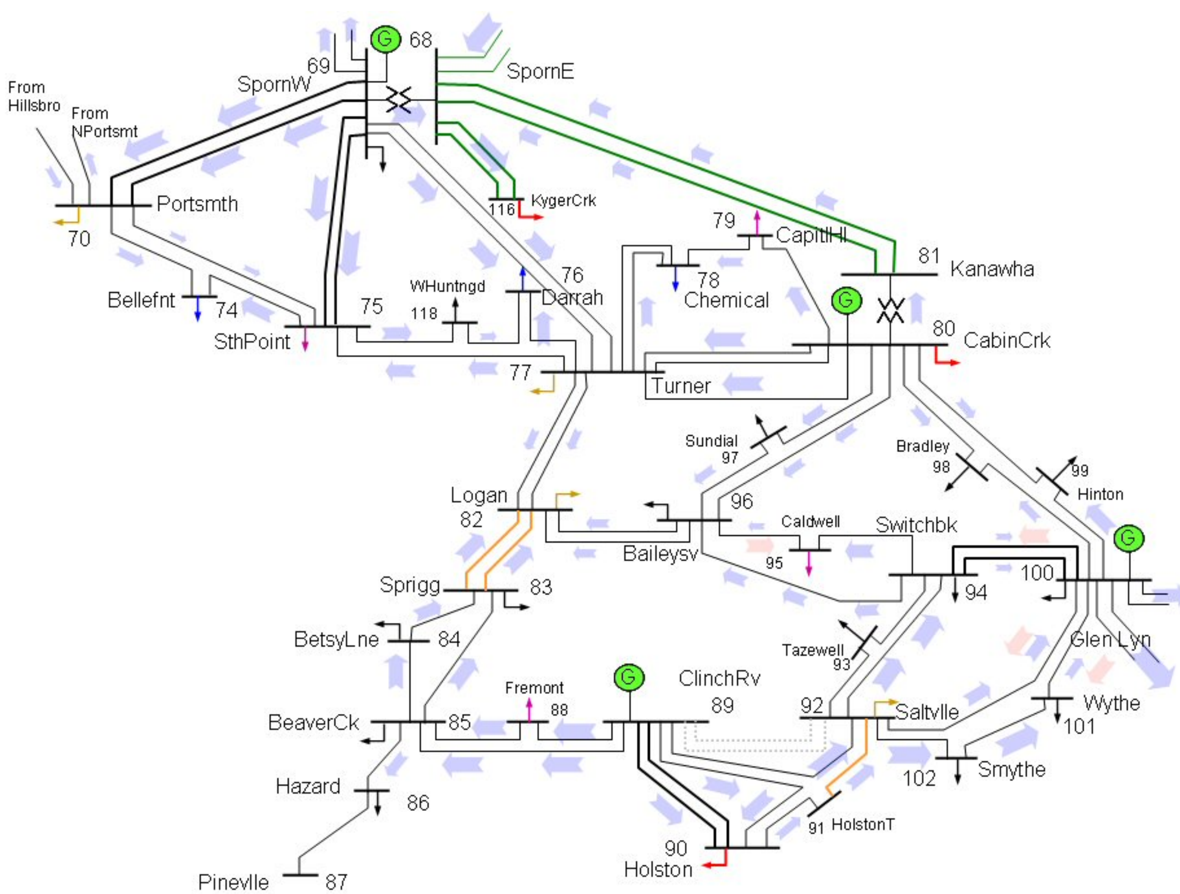

Fig. 5. Initial effect of the outage of line 89-92 in the 118-bus test system.

Line 82-83 is located in the southern part of Area-3. Outage of this line further overloads line 91-92 which serves a large load at bus 92.

Outage of line 91-92 put the burden on other lines that can bring in power to this region. Lines 94-100 and 100-101 serve this purpose and are therefore overloaded.

If line 100-101 is outaged, then the overloading occurs over a wider region in Area 3. Line 94-100 is now more severely overloaded.

Outage of line 94-100 causes a wide-spread problem in this region of Area-3. Line 95-96 is the highest overloaded line. Most of the lines are not severely overloaded at this point.

Outage of line 95-96 increases the extent of overloading in the previously overloaded lines. As a result, line 94-96, which acts like a parallel path to line 94-96 is dangerously overloaded. Outage of this line causes a blackout.

E. Outage of transformer 37-38

The transformer 37-38 is located in the eastern part of Area-1. The outage events caused by this contingency seem to be limited to this particular region. But overloading occurs over a wider area. This transformer receives power from Area-2 and delivers it to Area-1. This makes its location critical. Outage of this transformer hampers the ability of the system to serve the heavy loads in Area–1. This outage ultimately affects a wide portion of the system.

The outage of transformer 37-38 overloads line 15-33 which serves heavy load at buses 15 and 33. There is a cluster of heavy loads at buses 18, 19, 33, 34, 35, 36 and 39. All these loads are geographically close. Thus outage of the transformer at 37-38 overloads these lines. Line 15-33 carries power mostly from the generators in Area-1. This outage also overloads lines 40-42 and 43-44 in Area - 2. which bring in power to Area -1 as shown in Fig. 6. Also, a reversal of real power flow is observed in line 19-34. Power now flows from bus 19 to bus 34.

Outage of line 15-33 causes overloading over a wider region. Line 19-34 serves the same purpose as line 15-33. Hence, it takes the brunt of losing line 15-33. Line 19-34 now brings as much power from Area-1 generators as possible. Naturally, line 19-34 is the highest overloaded line after this outage. Heavy power transfer ensues between buses 19 and 34. Two lines in Area-2 which are close to Area-1 get dangerously overloaded. Line 39-40 is an area tie line which gets overloaded.

Outage of line 19-34 has a tremendous impact on almost all lines in the northwestern and most of the western part of Area-2. Due to limited transmission capacity, Area-1 generators can no longer supply the heavy loads at buses 18, 19, 33, 34, 35, 36, etc. As a result, more power is fetched from Area-2 and the inter-area tie lines get overloaded.

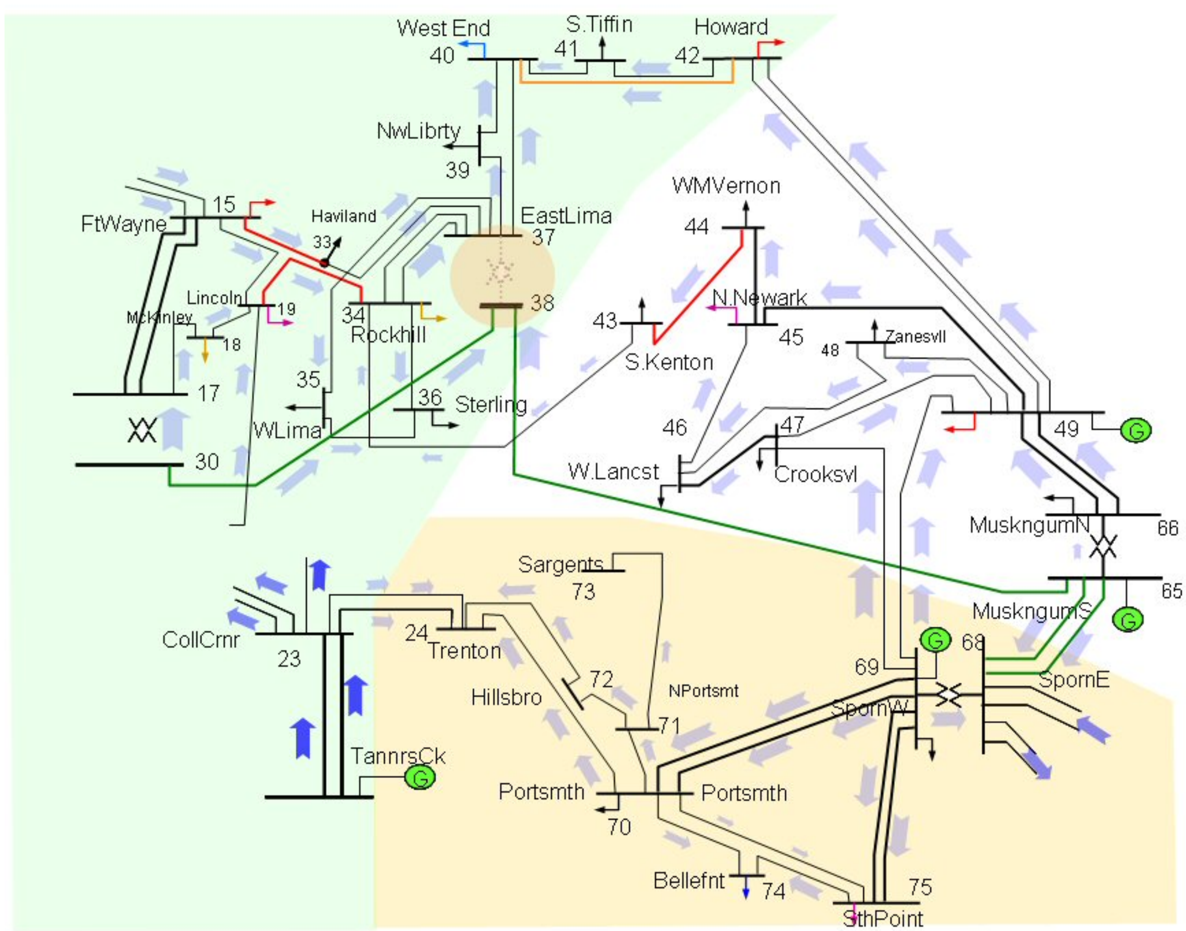

Fig. 6. Initial effect of the outage of transformer 37-38 in the 118-bus test system.

The extent of overloading is dangerously high. Line 37-40 is one of the area interconnections. It also shows reversal of power flow after this outage. The same is the case for line 39-40. Line 34-43 is the only inter-area connection between Area-1 and Area-2 that is not connected to the outaged transformer 38-37. Because of this, line 34-43 gets overloaded. Line 43-44 is the line adjacent to this interarea connection between area-1 and area-2. Being a comparatively weak line, it gets heavily overloaded. Overloads are observed even in the central part of Area-2. This implies that the region of impact is considerably large. At this stage we actually have an overloading of a transformer 65-66 which is very close to the swing bus. This creates a critical situation. Most of the flows in Area-2 are from the East to the West.

Outage of line 43-44 restricts the power transfer through the area interconnection 34-43. This stresses other inter-connections and increases the severity of overloading of the previously overloaded lines. Now the heavy loads in Area-1 are supplied through the northern interconnection between Area-1 and Area-2. Line 40-41 is the heaviest loaded line and it is responsible for the interarea power transfer in the northern region. One interesting observation is the overloading of one of the area interconnections between Area-2 and Area3, due to the transformer outage in Area-1. This shows how the initial failure has spread throughout.

Removal of line 40-41 also causes a similar effect of increasing the severity of the overloading. Naturally, line 40-42 bears the brunt and gets overloaded to a dangerously high level. This outage also affects lines in the far eastern region of the system. Line 64-65 is a crucial line for supplying loads in that region. It gets overloaded in the process. One more dangerous consequence is the overloading of transformer at 68-69. This is a crucial transformer, because it is connected to a large generator in the system. Finally, outage of line 40-42 leads to a blackout.

IV. Conclusions

Even though the security criteria are met for N-0 and N-1 conditions, a power system could be threatened by an impending blackout if certain conditions are forced on the system. Such conditions are created by cascading failures, some of which cannot be predicted either because they are random events or because of the current lack of intent on the planner's part or the lack of computational power to look into every single event possibility under every single possible condition. One cannot blame the planner for lack of intent to analyze all different possibilities because, not all scenarios are probable. As for the current lack of computational capability, like a chess game, the power system can provide security scenarios that are combinatorially intractable, and therefore, such a task has never been undertaken.

The work reported in this paper has investigated only the effect cascading failure conditions on the possibility of blackout. The events simulated were deemed to be probable from the perspective of the level of overloading. Although a line with the highest level of overloading may be picked to be the most likely line to fail under an emergency, it does not always happen this way as seen in many of the reported blackouts. Because of the preponderance of zone 3 backup relays and that of hidden failures, it is not unusual to see an underlying line close to the point of the initial disturbance to start the final cascading events that eventually lead to a blackout.

V. Acknowledgment

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VI. References

[1] U.S.-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," North American Electric Reliability Council, www.nerc.com, April 5, 2004.

[2] G. Andersson, P. Donalek., R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A. Stankovic, C. Taylor, V. Vittal, "Causes of the 2003 Major Grid Blackouts in North America and Europe and Recommended Means to Improve System Dynamic Performance," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1922-1928, November 2005.

[3] J. De La Ree, Y. Liu, L. Mili, A. Phadke, L. Dasilva, Catastrophic Failures in Power Systems: Causes, Analyses, and Countermeasures," Proceedings of the IEEE, vol. 93, no. 5, pp. 956 – 964, May 2005.

[4] D.N. Kosterev, C.W.Taylor, W.A.Mittelstadt, "Model validation for the August 10, 1996 WSCC system outage," *IEEE Transactions on Power Systems*, Vol. 14, no. 3, pp. 967 – 979, Aug. 1999.

[5] C.W. Taylor, "Improving grid behavior," IEEE Spectrum, vol. 36, no. 6, pp. 40 – 45, June 1999.

[6] C.W. Taylor, D.C. Erickson, "Recording and analyzing the July 2 cascading outage [Western USA power system]," IEEE Computer Applications in Power, vol. 10, no.1, pp. 26 – 30, Jan. 1997.

VII. Biographies

Badrul H. Chowdhury (M'1983, SM'1993) obtained his Ph.D. degree in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1987. He is currently a Professor in the Electrical & Computer Engineering department of the University of Missouri-Rolla. From 1987 to 1998 he was with the University of Wyoming's Electrical Engineering department. Dr. Chowdhury's research interests are in power system modeling, analysis and control and distributed generation. He teaches courses in power systems, power quality and power electronics.

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