Intentional Islanding and Adaptive Load Shedding to Avoid Cascading Outages

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Abstract: Predetermined islanding scenarios along with automated load shedding schemes are applied once a prospective cascading outage condition is predicted. If required, additional distributed generation at specified locations in the system is also determined. The choice of different islands along with loads to be shed is then made available to the operator so as to be armed for action in case the system security is compromised. Determination of line outages that lead to disastrous consequences, intentional islanding schemes, and load shedding schemes have been explored individually. A plan integrating these defense mechanisms coupled with the possibility of using distributed generation where and when available is presented via case studies. Results obtained from the application of this technique indicate that it can be a powerful approach for secure operation of power systems.

Keyword: Catastrophic failure, blackout, countermeasures, load shedding, distributed generation.

I. INTRODUCTION

SYSTEM blackout is the state when the complete system or large areas of it may completely collapse. This state is usually preceded by a sequence of cascading failure events that knock out transmission lines and generating units. Any large disruption in generation and load balance in a massively interconnected system, as seen in the North American interconnections, can lead to undesirable variations in power flows and bus voltages. Occasionally, this imbalance can spread uncontrollably over an entire system causing blackout of large parts of the system. Although the reasons behind blackouts can vary from instance to instance, certain themes are evident from historically reported blackouts. Some of those deal with the level of interconnection, transmission line capacities, proximity of an event to major generation and loads, and how much power is already moving across areas.

Major blackouts very often result in a condition when some areas detach from the rest of the system causing power imbalance, the subsystem is said to be *islanded*. To contain the cascading outages several corrective and preventive schemes are being discussed in the research community [1-3]. Some of the schemes reported in the literature include system splitting strategies [4], slow coherency-based islanding [5] and various load shedding schemes-undervoltage load shedding (UVLS) [6], under-frequency load shedding (UFLS) [7]. Yet, because of lack of pre-planned separation of the system, absence of fast control measures, inadequate planning and operation studies for emergencies and other events that are near impossible to predict are the reasons blackouts continue to occur.

This paper introduces some blackout mitigation techniques that are based on simple rules, such as, strategic tripping of overloaded lines near the initial failure, followed by rational load shedding. In some cases, when load shedding does not help solve the problem, premeditated islanding is carried out. The removal of small amounts of loads tends to isolate the failure and prevent it from spreading. This prevents additional lines from becoming overloaded, thus helping avoid further outages.

The existing imbalance between generation capacity and transmission capacity together with percentage loading of lines, percentage loading of generators, voltage levels and interchange level are major contributors to cascading failures. This paper enumerates, by case studies, methods to seize a cascading failure as soon as the initiating event can be identified. The methodology consists of exploring the use of predetermined islanding scenarios along with automated load shedding schemes. If required, additional distributed generation at specified locations in the system is also determined. The choice of island boundaries along with specific loads and the amount to be shed is then made available to the operator. A plan outlining the integration of all the three defense mechanisms is also provided.

A. Cascading Failure - Blackout

Large blackouts are usually the outcome of cascading outages. In a typical scenario, the disturbance spreads quickly because of protective relays installed at critical nodes disconnected the key components in an attempt to isolate the damage. Other factors such as failure to trim trees under power lines, failing to rectify line sags and so on contributed to initiate the documented blackouts. Table 1 gives a summary of the blackouts occurred in North America over the years.

TABLE 1. MAJOR NORTH AMERICAN BLACKOUTS [8]

Date	Location	Load Interrupted
November 9, 1965	Northeast	20,000 MW
July 13, 1977	New York	6,000 MW
December 22, 1982	West Coast	12,350 MW
January 17, 1994	California	7,500 MW
December 14, 1994	Western US	9,336 MW
July 2, 1996	Western US	11,743 MW
August 10, 1996	Western US	30,489 MW
June 25, 1998	Midwest	950 MW
August 14, 2003	Northeast	61,800 MW

II. POWER SYSTEM SECURITY – ASSESSMENT AND DEFENSE SCHEMES

Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances [9].

A widely applied security assessment is contingency analysis. System analysis gives information about the oncoming tribulations. Pertinent up-to-date information on the system conditions can be

readily available to the system operator. This information is the outcome of offline system studies with real time network data.

The most common defense schemes devoted to circumventing wide-area disturbances are under-voltage load shedding, under-frequency load shedding, system separation (islanding), etc.

A. Islanding

As often seen, sometimes, during a disturbance, the system tends to break up into islands. This occurs on account of the tripping measures adopted by the grid's protective systems. Undervoltages created in such situations aggravate the existing condition and lead to individual island failures. Unintentional or natural islanding has the potential to damage equipment and compromise system security [4].

On the other hand, to prevent system failure during extreme emergencies, it is sometimes recommended to execute controlled splitting of the system into stable islands with generation and/or load shedding using special protection schemes. Controlled islands are more stable than the unintentionally formed islands. They are also less prone to collapse and do not aggravate existing conditions that lead to blackouts. However, these islands may still suffer from generation-load imbalances. To eliminate undesired consequences of a power imbalance, load or generation shedding is executed. The islanded areas can be pre-planned, and specified by offline studies.

B. Distributed Generation

Distributed generation has the potential to improve the reliability of the power system. It can reduce the need for new transmission lines. It can also be configured to meet the varying power demands. Distributed generation is usually either conventional or renewable. They are usually located close to the customer load. With careful planning and wise-spread adoption distributed generation can help stabilize the system and sometimes prevent blackouts. It can play a vital role in maintaining the generation-load balance in intentional islanding schemes by ensuring that each area is balanced. However, an oft-mentioned disadvantage of distributed generation is that it may not be available at the desired locations.

C. Load Shedding

Load shedding is sometimes executed to reduce the imbalance and reestablish the normal operating conditions in time to avoid system collapse. Under normal and unexpected emergency conditions voltage levels are maintained by undervoltage load shedding (UVLS). By identifying the weakest nodes in the system, the quantity and location of loads to shed is determined. Load shedding is an effective low cost measure to maintain normal operation during emergency conditions.

III. METHODOLOGY

A technique to predict and quickly analyze effective defense mechanisms following the outage of critical lines is presented in this paper. System studies can provide information on lines that are at or near capacity, lightly loaded lines and undervoltages/overvoltages. Potential line outages that may cause cascading outages are also analyzed by executing contingency analysis. The weaker areas of the system are then defined, a list of weak nodes is prepared, and probable island ties are devised. A simple and practical load shedding scheme for a reliable island operation is also formulated.

A. Selection of the Initiating Disturbance

Large blackouts are the common outcome of cascading outages in a power system. Uncontrolled cascading events are initiated by the loss of major transmission lines, as observed in both the 1996 [10, 11] and the 2003 blackouts [12, 13]. Depending on how the system

components are related, a disturbance can cause either a local interruption or create widespread cascading actions. This consequence is unpredictable and requires regular and systematic system analysis to keep the operator aware of any limitation or system stresses. For this study, a set of contingencies were pre-selected as reported in the companion paper [14].

B. Determining Pre-Disturbance Island Boundaries

Defining island boundaries just prior to an impending disturbance is not possible since the disturbance cannot be predicted. However, some island boundaries may be loosely defined based on continuously monitoring the line flows and calculating the line outage distribution factors (LODF). The transmission lines which are near capacity have the tendency to trip during system disturbances. These lines are closely observed while conducting load flow studies and contingency analysis. Such lines together with geographical aspects of the grid are taken into consideration while selecting island ties.

The islands formed are assessed for independent operation. Some islands may not be able to survive independently, inducing the requirement for load/generation shedding or undervoltage load shedding. To preserve the power balance, additional power in the form of distributed generation may be required.

Fig. 1 illustrates the basic steps involved in developing the projected technique. System data for a critical line outage condition is studied for line overloads and bus undervoltages. Voltages and line flows are the foremost indicators of system conditions.

Depending on system studies, a self-healing scheme and/or a practical strategy may be deployed. This practical strategy includes the islanding boundary definition and/or the self-healing scheme which includes load/generation shedding and additional generation.

C. Determining the location and amount of load shedding

An exhaustive search is engaged to determine the loads required to be shed to return the system to its nominal operating condition. Although load shedding is considered as the last resort; it is a method of reducing the load to restore the system power balance.
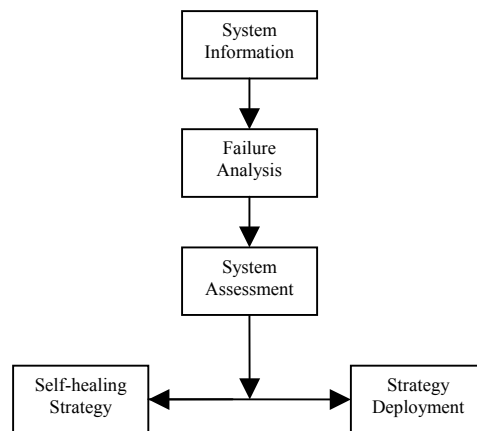

Fig. 1. The basic steps in the methodology

Determining the amount of load that needs to be shed is the chief problem involved. The critical event leading to an extensive cascading failure in Ohio and beyond during the August 2003 blackout, was the tripping a single line Sammis-Star 345-kV line [12]. The tripping was executed as a defensive measure against line overload and undervoltage at the buses. That and the similar tripping of a few other lines resulted in an unavoidable system blackout. The Task Force Report [13] concludes that load shedding, prior to the

critical tripping of the Sammis line, would have helped to contain the problem and prevented the system collapse.

Many methodologies have been proposed to ascertain the amount of load that is appropriate to shed under given conditions. Shedding load more than that required may create overvoltages or aggravate the existing situation. Similarly, tripping less amount of load will defeat the purpose and be ineffective in preventing cascading outages.

By calculating the power drawn by the load before and after the line outage the amount to be shed can be determined. This design is developed taking into account the predetermined critical line outage and island boundaries.

The location where the load is to be shed is a key factor that should be considered. For example, if the loss of a critical line causes an overload on a neighboring line, then the load connected at one of the ends of the line is considered first. Shedding applied to any of the neighboring buses by a percentage varying from 25% to 100%, may help relieve the overload. The objective is to avoid a system blackout which is achieved by implementing shedding schemes. Load shedding is not generally recommended except during critical conditions, such as critical contingencies.

D. Design Procedure

Since protecting the system against all possible contingencies is evidently impractical, the fundamental principle is to secure the system against only the critical contingencies. The analyses will assess bus voltages and line loadings against specified system constraints. The defense technique comprises of the following:

(1) System power flow studies.
(2) Contingency analyses.
(3) Diverse islanding scenarios for predetermined disturbances.
(4) Load shedding schemes based on overloads and undervoltages.
(5) Additional generation initiated at selected buses.

For a reliable operation, the constraints that need to be satisfied, after the defense scheme has returned the system from an emergency condition to an operating state, are:

(1) System bus voltages should remain within limits.
(2) Line flows must not exceed the line's maximum loading limit.
(3) Number of loads sheds should be minimum.
(4) Additional generation at a bus: less than 100MW.
(5) Adequate spinning reserves exist (7%-10%).

Fig. 2 outlines the steps and shows how the different protective measures are incorporated together to generate the desired result, i.e., *reliable system operation* with lower level of security. System operation with lower level of security implies that the system is restored to an operable condition but may or may not be N-1 secure. System security is compromised but operation is guaranteed. N-1 criterion ensures the secure and reliable operation of the power system. It means that the system will operate normally and that the power is delivered reliably even when one of the lines is lost.

The load-generation power balance gives an evaluation of the system condition. If the total generation is greater than the total load, then the system is in a power surplus situation. In this state, shedding the generation will help rectify the problem. Surplus power in any system may cause overvoltages or line overloads. But, if the system is deficient in power, then either loads need to be shed or additional generation should be brought in.

If load shedding does not relieve the undervoltages or line overloads, then additional generation between the ranges of 25 MW to 100 MW is applied. The bus, at which generation is installed, is

selected using the same technique as load shedding. If the system consists of lines which are near capacity or have low maximum flow limits then it may require both load shedding and additional generation to restore the system. The addition of generation to the system is explained as an extension of this scheme. Fig. 3 depicts the steps involved. The algorithm given in the figure is used to determine if reducing generation alleviates the crisis, how much generation needs to be decreased and at which bus it is to be applied.

E. Optimal Scheme

Alternative schemes deal with achieving system reliable operation without the execution of island formation. For some system conditions, by adding generation at certain buses and/or shedding loads or generation can restore the system to its operable condition.
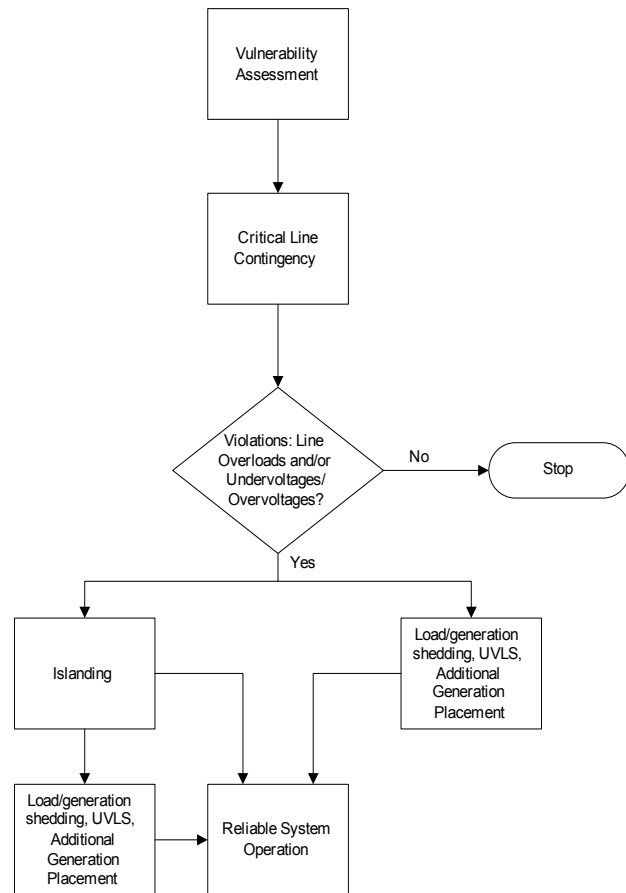

Fig. 2. Overview of the procedure

The algorithm sketched out in Fig. 4 is self explanatory, where it describes the load shedding scheme devised to eliminate system violations. The shedding scheme developed is a simple yet efficient way to combat the causes that create critical conditions in the system.

If adding a generator helps resolve the problem, it must be limited to less than 100 MW at a bus. If the generation deficiency is 100 MW, then this amount is split up and spread out to other buses to accommodate the constraint. It may not be possible to have the required amount of distributed generation at hand. In such cases, load shedding is employed to help the situation.

Even if the system is islanded into smaller areas, the scheme described in Fig. 4 for load shedding does not need any modifications. Load flow studies are conducted several times in this scheme to ensure that the system is evaluated thoroughly.
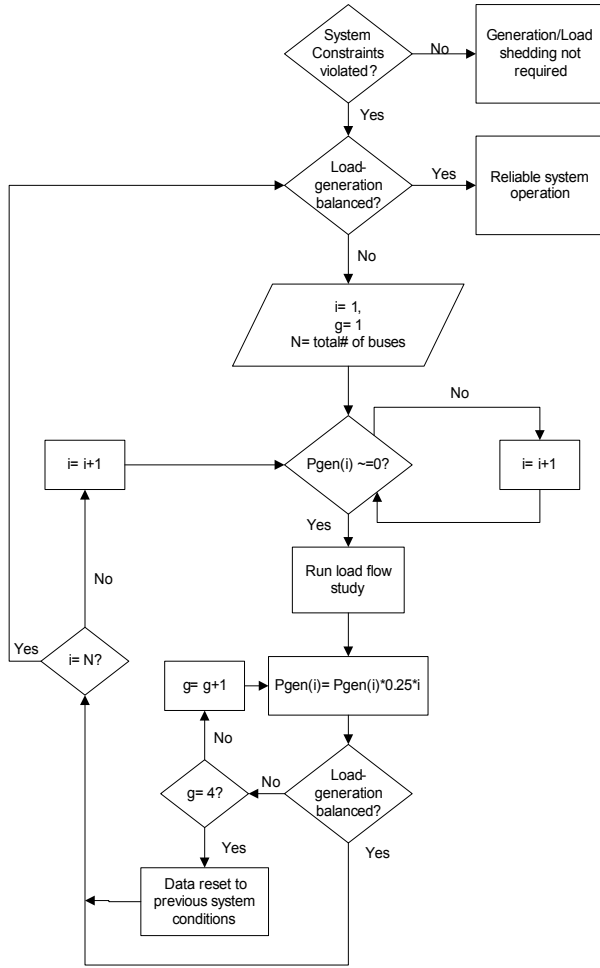
Fig. 3. Generation addition/reduction algorithm

<u>Intentional Islanding to Avoid Cascading Outages</u>

Intentional, forced or controlled islanding is probably the best venture put together for tackling emergency conditions. The data of island boundaries is then used to provide information to the system to implement the exact island condition in the system. Flowchart for the proposed scheme to prevent system blackouts due to cascading blackouts is given in Fig. 5.

After the procedure is set with various island cases, it is checked for system reliability. If the islands cannot survive independently due to system constraint violations, then a load shedding scheme is applied to lead the islands to nominal operating conditions. Each island scenario for the specified outage is considered and analyzed.

The final outputs of this technique are independent islands capable of operating under reduced generation or load conditions for each of the critical line outages. This scheme is verified using the 118-bus test system.
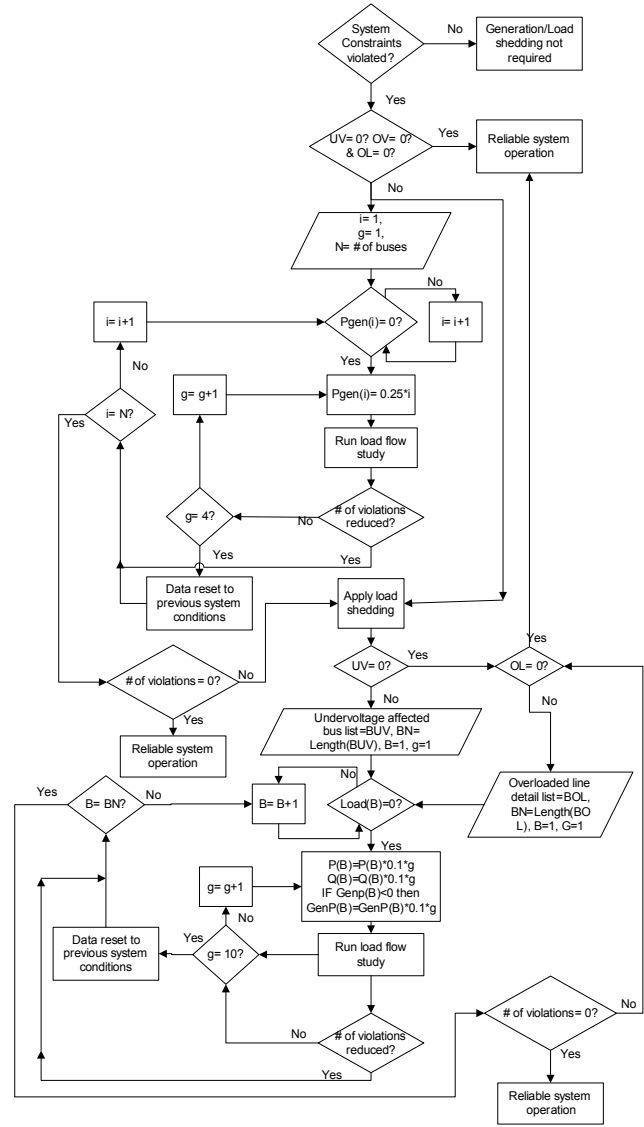

Fig. 4. Load shedding and additional generation placement algorithm (OL = line overloads, UV = undervoltages, OV = overvoltages)

IV. TEST RESULTS

A. System diagram and operating conditions

The IEEE 118 bus test system, shown in Fig. 6 is used for testing the cascading outage schemes. Four principle areas are defined in the system as shown in the diagram. The 4 areas constitute the natural pre-disturbance islands. These pre-defined island boundaries are used to determine similar island boundaries during critical cascading circumstances. There are 118 buses, 186 lines with bus 65 being the swing bus. Island boundaries were predetermined based on the procedure outlined in an earlier section. The criteria used for determination of these islands were:
(1) Generation-load balance
(2) System bus voltages should remain within limits
(3) Line flows must not exceed loading limit.
(4) The number of loads shed should be less than 5
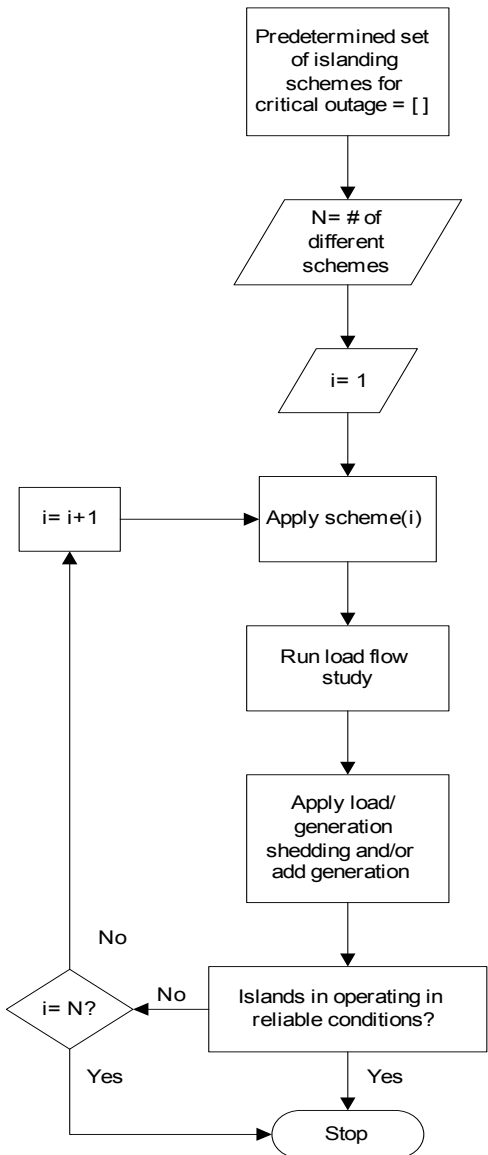(5) Additional generation at a bus should be less than 100 MW

Fig. 5. Flowchart of Proposed Scheme

TABLE 2 PRE-DETERMINED ISLAND TIES

Islands	Area 1	Area 2	Area 3	Area 4
Area 1	-	34 - 43, 37 - 39; 37 - 40; 38 - 65	24 - 70; 24 - 72	-
Area 2	37 - 43; 37 - 39; 37 - 40; 38 - 65	-	47 - 69; 49 - 67; 65 - 68	-
Area 3	24 - 70; 24 - 72	47 - 69; 49 - 67; 65 - 68	-	92 - 100; 92 - 102; 94 - 100; 98 - 100; 99 - 100
Area 4	-	-	92 - 100; 92 - 102; 94 - 100; 98 - 100; 99 - 100	-

The areas and the different tie lines are listed in Table 2. The area ties are predominantly heavily loaded lines, making them excellent candidates for island boundaries. During system outages or disturbances, these lines may violate their limits, causing them to trip. By defining them as the island ties, forced outage of these lines as a mitigation measure is in fact conducive to the situation. In the process of islanding, loss of these ties may cause overloads on other lines.

B. Critical Contingencies

Owing to the large size of the power grid, numerous contingencies have to be assessed. Out of these, only a handful can create worst case scenarios. A total of 13 critical contingencies were identified which could potentially result in cascading outages, leading to a system blackout in each case [14]. Out of these, only five are shown in this paper for reasons of brevity. Detailed system analysis has shown that cascading failures were triggered by one of these single outages eventually capable of producing a sequence of events leading to system-wide failures. Blackout mitigation schemes are tested for these five critical contingencies.

C. Case 1 – Outage of Line 4-5

This outage falls in Area-1 of the 118-bus test system and it is a line component with a loading of over 75%. Loss of this power path will require the neighboring lines to adjust and provide compensations as shown in Fig. 7. Large amounts of power was being transferred from bus 5 to bus 4 to serve the loads in this area. This power is supplied predominantly by the large generators at buses 10 and 26. The power that was being fed by line 4-5 to the load is now shared by lines 3-5, 5-6, 5-11, 6-7 and 7-12.

Under pre-disturbance conditions line 5-11 was loaded to 67% of its maximum capacity. But losing line 4-5, - a heavily loaded line; overloads line 5-11 to about 120%. This can cause the line to be tripped out by relaying equipment, initiating a sequence of cascading events leading to a possible system blackout.

Appropriate islanding scenarios, load shedding and additional generation are executed to thwart the cascading failure and eliminating the overload on line 5-11 in its course. Load shedding and placement of the required additional generation is determined by the proposed scheme described earlier. Table 3 illustrates the different schemes adopted to avoid a probable blackout condition, bringing the system to an operable condition without any system constraint violations. Scheme-1 operates the system in an islanded condition. There are two islands formed which are capable of operating independently with the help of additional generation and load shedding.

For Area-1, generation is added at bus 11 to alleviate the overload on 5-11, and the load at bus 36 is dropped. Disconnecting the island ties for the formation of the two areas create undervoltages at buses 36 and 38. Clearly, Scheme-2 is the superior alternative. It requires additional generation of 75 MW at bus 11 without instigating any island configuration.

No load shedding is required in this case. Turning on generation of 75 MW in the form of distributed generation is feasible. Other alternatives include schemes 3 and 4, where only load shedding (i.e., without the application of additional generation) is employed. Since, there is no assurance that distributed generation will be available at all times, it is essential to explore such cases.
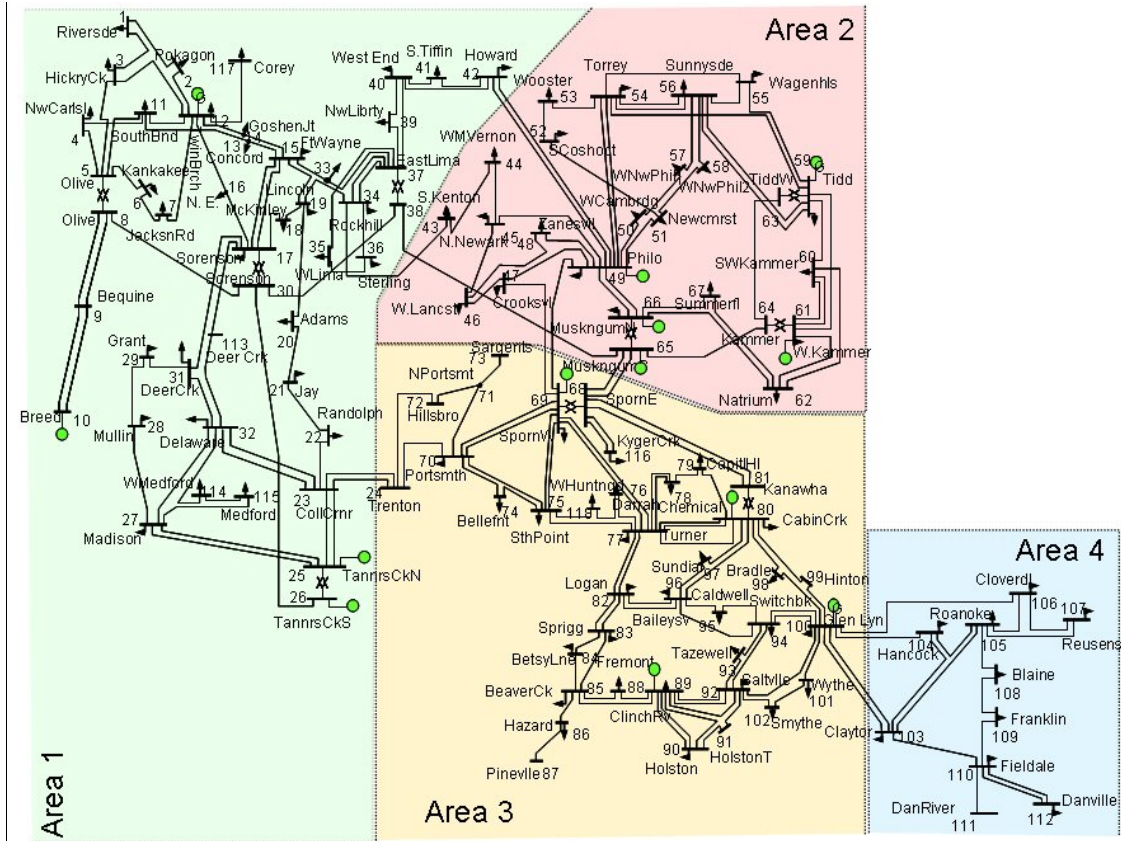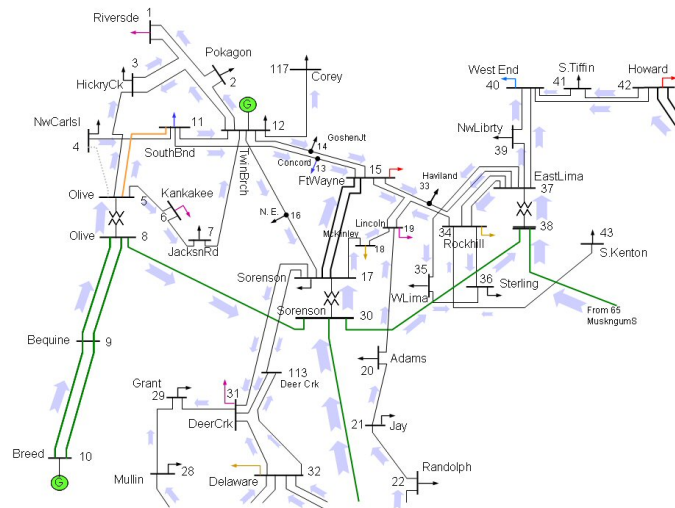
Fig. 6. The 118-bus test system.

Fig. 7. Line 4-5 Outage

TABLE 3. MITIGATION SCHEMES FOR LINE OUTAGE: 4-5

Scheme (#)	Details of the Scheme	Loads Shed	Gen Added
1	Island 1- Area 1	1	75 MW
1	Island 2- Area 2-3-4	0	50 MW
2	Entire System	0	75 MW
3	Entire System	1	-
4	Island 1- Area 1	3	-
4	Island 2- Area 2-3-4	1	-

D. Case 2 – Outage of transformer 37-38

Losing a transformer can cause severe violations. It creates numerous undervoltages in Area-1 and Area-2. The power that is being distributed by this transformer is fed to the loads at buses 33, 34, 35, 39and 40. As shown in Fig. 8, this transformer carries power from the large generators at buses 10, 26 and 65.

Therefore, outage of this transformer causes undervoltages at buses 33, 34, 35, 36, 37 and 43. Undervoltages are partially due to the insufficiency of reactive power flow, requiring the need for supplemental generation. Overloads on lines 15-33, 19-34, 40-42 and 43-44 is the result of a division of the flow distribution. Line 15-33 is the overloaded the most since it has to provide the lost power to the load at bus 33. The only other line initially providing power to this load was 33-37 through 37-38.

Table 4 lists the different schemes to keep the system operating at reliable conditions. Either by shedding a load and/or adding generation at 33 and 34 facilitates operable conditions in the system. Depending on the circumstances, either of the schemes can be selected by the operator.

TABLE 4. MITIGATION SCHEMES FOR LINE OUTAGE: 37-38

Scheme (#)	Details of the Scheme	Loads Shed	Gen Added
1	Entire System	1	50 MW
2	Entire System	2	-

E. Case 3 – Outage of line 38-65

This line is a tie-line for Area-1 and Area-2 and carries large amounts of power with a percentage loading of 65 %. It supplies power to Area-1 from where it is distributed out to supply the load demands in Areas 1 and 2. Outage of this line causes several line

overloads without considerable voltage fluctuations, clearly shown in Fig. 9. Both the areas suffer the consequences of the outage.
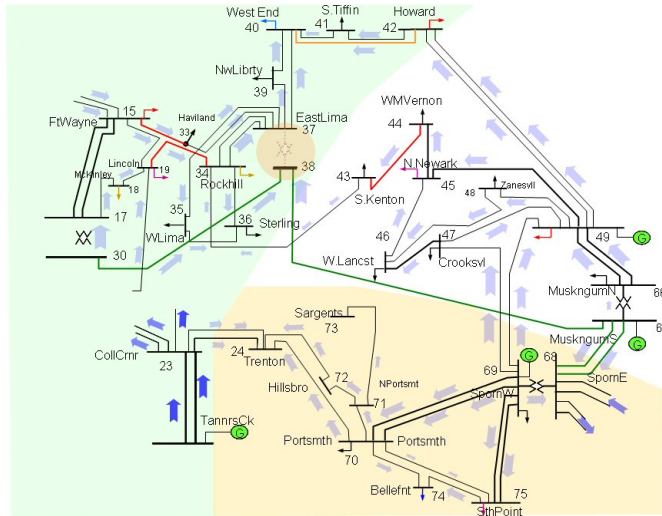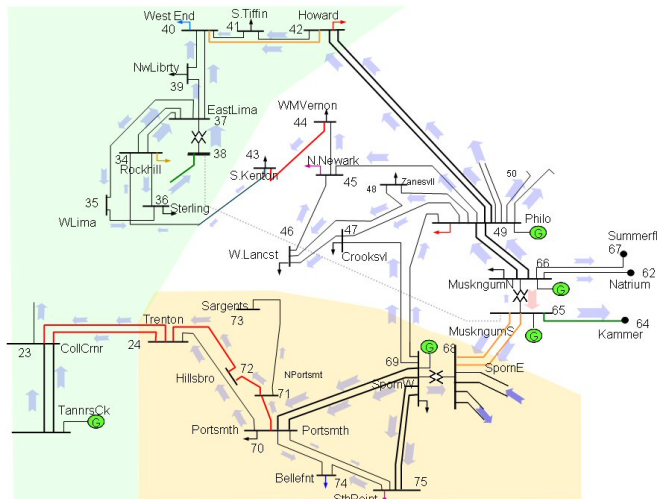

Fig. 8. Line 37-38 Outage

Fig. 9. Line 38-65 Outage

Inadequate maintenance of power supply among the load buses is the reason for the overloads. This is alleviated by providing extra generation at two buses; generation of 50 MW at buses 1 and 2 each. Since buses 1 and 2 are further away from the point of outage, they are not selected. Additional generation of 25 MW in Area-1 is desired for this scheme. Scheme 2 is evidently the better choice as seen from Table 5, even though it requires islanding the system into two areas.

TABLE 5. MITIGATION SCHEMES FOR LINE OUTAGE: 38-65

Scheme (#)	Details of the Scheme	Loads Shed	Gen Added
1	Entire System	0	100 MW
2	Island 1- Area 1-2	0	25 MW
2	Island 2- Area 3-4	0	0
3	Entire System	3	-
4	Island 1- Area 1	1	-
4	Island 2-Area 2-3-4	1	-
5	Island 1- Area 1-2	3	-
5	Island 2- Area 3-4	0	-

F. Case 4 – Outage of line 64-65

The line is located in Area-2, and has a percentage loading of 66%, distributing power through transformers to loads at buses 56, 57, 62, 66, and 67 as shown in Fig. 10.

The overloads on lines 62-66, 62-67 and 66-67 are the result of the line outage taking away the path for power flow to supply the demand. As listed in the Table 6, the various schemes are able to restore operable condition to the system. Scheme 1, where islanding is not an option, an additional generation of 50 MW each is required at four buses (39, 55, 60 and 62). The distribution of additional generation is executed to in this fashion supply the maximum power possible to the load without causing any line overloads. Employing load shedding exclusively is advised in the case of absence of distributed generation in this area.
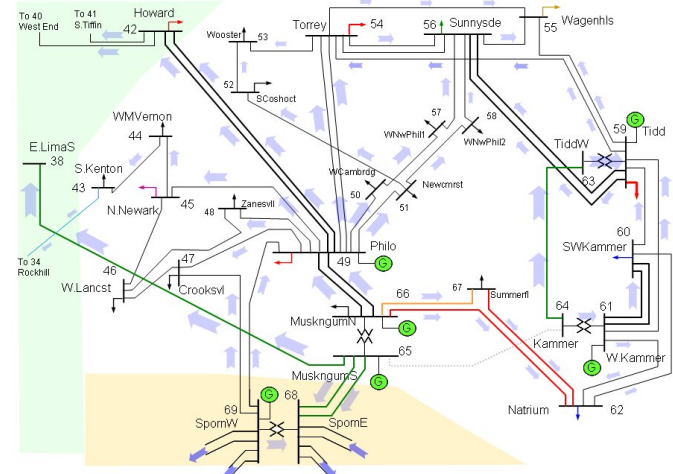

Fig. 10. Line 64-65 Outage

TABLE 6. MITIGATION SCHEMES FOR LINE OUTAGE: 64-65

Scheme (#)	Details of the Scheme	Loads Shed	Gen Added
1	Entire System	0	200 MW
2*	Island 1- Area 2	1	-
2*	Island 2- Area 1-3-4	2	-
3	Entire System	2	-

Scheme 2* involves islands of Area-1 and Area 2-3-4, but the island boundaries have been modified to help the situation. Since the outage involves a generator bus, designated as the slack bus, more than four loads need to be shed to help the situation. Since the outage involves a generator bus, designated as the slack bus, more than four loads need to be shed to help the situation. In order to avoid this, Area-1 boundaries have been changed from the original case which included buses 1 - 38 to the modified case that included buses 1 - 42. The part of the system consisting of buses 39 to 42 have been known to create overloads due to the insufficient generation. This helps to reduce the number of loads shed in Area 2-3-4.

G. Case 5 – Outage of line 89-92

This is a line in Area-3 which carries huge amounts of power since bus 89 is connected to the largest generator in the entire system. The outage of line 89-92 creates the most number of overloads when compared to the other contingencies. This is due to shortage of paths to serve the loads available in this part of the system. Area-3 consists of numerous heavy loads making it a highly volatile area with the incidence of a contingency, as shown in Fig. 11.

As Area-3 harbors numerous loads, it is apparent that additional generation might be needed to keep the system from plunging into a blackout. In order to relieve the lines from overloading, generation of 50 MW at each of the buses 82, 92 and 93 is recommended. Table 7 lists the different schemes considered for this outage.
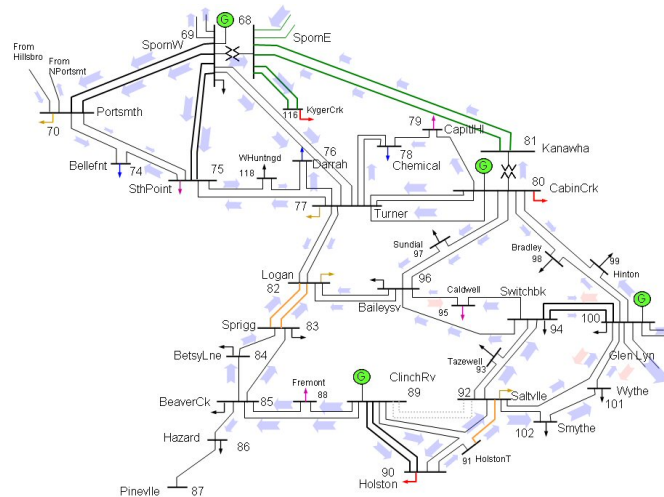

Fig. 11. Line 89-92 Outage

TABLE 7. MITIGATION SCHEMES FOR LINE OUTAGE: 89-92

Scheme (#)	Details of the Scheme	Loads Shed	Gen Added
1	Island 1- Area 1-2	0	50 MW
1	Island 2- Area 3-4	0	150 MW
2	Entire System	0	150 MW
3	Island 1- Area 1-2	1	-
3	Island 2- Area 3-4	3	-
4	Entire System	3	0

If islanding is opted, then Area 1-2 will require additional generation (50 MW) as well. But, non-islanded schemes works better with less generation added and fewer number of loads shed.

V. CONCLUSIONS

Results obtained from the application of this technique indicate that it can be a powerful approach for the secure operation of power systems. A plan integrating three defense mechanisms -intentional islanding, distributed generation and automated load shedding was presented. Any combination of these schemes may be applied once an initiating cascading outage condition is predicted. The operator may be armed in this way with various possible mitigating schemes.

It was observed, through case studies, that simply intentional islanding may not be the best choice to restore the system to an operable condition. But, if the need arises strategic islanding may prevent catastrophic situations. Island boundaries tend to vary with the outages. In some case, particularly when multiple security violations, such as overloads and undervoltages are noticed, the only possible scheme to keep the system operating is to island certain buses.

Each island may have its own share of overloads and undervoltages. The island ties are predominantly heavily loaded lines, making them excellent candidates for defining island boundaries. During system disturbances, these lines may violate their limits, causing them to sometimes trip. By defining them as the island ties, forced outage of these lines is in fact conducive to the situation.

The final outputs of this technique are independent islands capable of operating under reduced generation or load conditions for each of the critical line outages. This study takes a step toward proving that most cascading failures are avoidable but at some cost. Although, load shedding works effectively in most cases, intentional islanding helps in many cases to save the system from completely collapsing.

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