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A Novel Adaptive Forecasting Technique for Forced Islanding Scheme

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ABSTRACT: Large interconnected power grids may be affected by severe occurrences that could lead to a cascade of automatic actions resulting in large-scale blackouts. Predetermined forced islanding scenarios along with load shedding scheme are applied once a prospective cascading outage initiating event is predicted using a contingency analysis. This paper discusses an adaptive forecasting technique for pre-determining the most appropriate islands adaptable to each contingency situation. Determinations of line and generator outages that lead to disastrous consequences, forced islanding scheme, an under-voltage load shedding scheme and a restoration sequence have been explored. An algorithm integrating these defense mechanisms is presented via a case study on a sample 6-bus system in MATLAB environment.

KEYWORDS: Adaptive forecasting; blackout; contingency analysis; forced islanding; load shedding; restoration.

I.INTRODUCTION

Power system blackout is the state when partial or complete areas of the system collapse due to cascading of failure events that causes mass scale tripping of transmission lines and generating units. The imbalance between generation capacity and load together with percentage loading of lines, percentage loading of generators, voltage levels and interchange levels are major contributors to cascading failures. A large disturbance in generation and load balance in a large interconnected system can lead to undesirable variations in power flows and bus voltages. Subsequently, because of action of protective relays, this disturbance spreads quickly and uncontrollably over an entire system causing blackout of large parts of the system.

Major blackouts often result in a condition where some areas detach from the rest of the system, then the subsystem is said to be islanded. This occurs on account of the action of relays installed at weak points in the system.

Several preventive and corrective methods to contain the possibility of blackouts occurring in the system have been discussed in the researches. Paper [6] proposes a methodology to split the power system across the weak areas of the network affected by a large disturbance, by opening the transmission lines with minimum power exchanged. A methodology for sectionalizing strategy based on spectral clustering is introduced in paper [7]. A dynamic zone division scheme based on sensitivity analysis of power system is presented in paper [10].

This paper explains, by case study, a method to prevent a cascading failure as soon as the initiating event is identified during contingency analysis. The methodology consists of exploring the use of predetermined islanding scenarios along with an under-voltage load shedding scheme. The choice of island boundaries is determined using an adaptive forecasting technique. An algorithm integrating all the above mentioned defense mechanisms is also provided.

II.POWER SYSTEM SECURITY – ANALYSIS AND DEFENSE MECHANISMS

System security involves practices adopted to keep the system operating when an imminent disturbance (contingency) occurs in the system [1]. 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 [8].

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A widely adopted security analysis method is contingency analysis. Contingency analysis explores the effect of change in the power system operations on the alternatives. System analysis gives information about the upcoming disturbances. Up-to-date information on the system conditions can be made readily available to the system operator. This information is the outcome of offline system studies using real time network data.

The most common defense mechanisms applied to mitigate wide-area disturbances are under-voltage load shedding, under-frequency load shedding, forced system separation (islanding), etc.

Islanding

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. Unintentional or natural islanding has the potential to damage equipment and compromise system security. On the other hand, to prevent system failure during extreme emergencies, it is recommended to execute forced splitting of the system into stable islands with generation and/or load shedding. Such forced islands are more stable than the unintentionally formed islands. They are also less prone to collapse and do not aggravate existing system conditions that lead to blackouts.

Load Shedding

The forced islands formed, when assessed for independent operation, may not be able to survive independently, thereby inducing the requirement for under-voltage load shedding. Load shedding is executed to reduce the imbalance between generation and load, and in order to avoid further collapse of the islands.

III.PROPOSED METHODOLOGY

The main purpose of this paper is the development of a power system forced islanding scheme aimed at preventing cascading events from propagating further across a transmission network, thereby reducing the possibility of large-scale blackout. This is done in response to major contingencies in power system.

To detect the state of the system, continuous load flow analysis is done on the base system. As soon as a contingency occurs in the system, a contingency analysis is performed to determine the risk involved. As contingency analysis is a time consuming process, we use an approximate linear model of the power system such as a DC power flow model to perform the analysis utilizing minimum time. One of the easiest ways to provide a quick calculation of possible overloads during a contingency is to use linear sensitivity factors such as Generation Shift Factors (GSF) and Line Outage Distribution Factors (LODF). These factors show the approximate change in line flows for changes in generation or line flows on the network configuration.

After contingency analysis and determination of risks involved in each contingency case, we pre-define appropriate islands such that it eliminates the risks with minimal load-generation imbalance during the forced islanding technique. The islands must be self-sufficient and stable to supply the local loads.

To determine the island boundaries for each contingency case, an adaptive forecasting method is introduced. In this method, the various possibilities of islands with minimum load-generation imbalances are chosen for each contingency case. These are then analyzed for voltage stability and the amount of load that must be shed in order to attain stability is determined. After the rigorous analysis of each islands, the most stable islands with minimum load shedding is chosen. Likewise, the most appropriate islands adaptable to each contingency case can be chosen.

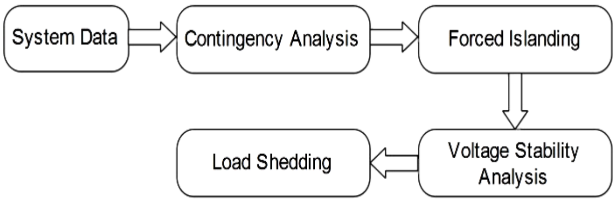

Fig. 1 Overview of the methodology

After forcefully splitting the system into pre-defined islands, the islands undergo a voltage stability analysis. Here, ±10% is chosen as the voltage tolerance limit. If the islands are found to be unstable, an under-voltage load shedding scheme is utilized to bring the islands to stable operating limits.

Test System

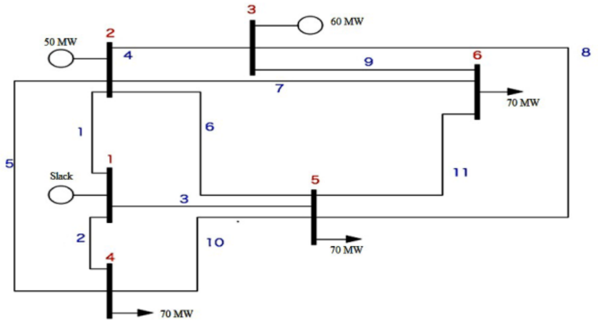

Fig. 2 Sample 6-bus system

TABLE I. Bus Data For 6-Bus System

Bus No.	**Bus Code**	**Voltage Magnitude**	**Angle**	**Generator**		**Load**		**Qmax**	**Qmin**
			Degree	***MW***	***MVAR***	***MW***	***MVAR***	***MVAR***	***MVAR***
1	1	1.05	0	0	0	0	0	100	-20
2	2	1.05	0	50	0	0	0	100	-20
3	2	1.07	0	60	0	0	0	100	-15
4	3	1	0	0	0	70	70	0	0
5	3	1	0	0	0	70	70	0	0
6	3	1	0	0	0	70	70	0	0

TABLE II. Line Data For 6-Bus System

Line No.	**Sending End Bus**	**Receiving End Bus**	**Resistance p.u.**	**Reactance p.u.**	**Half Susceptance p.u.**	**Power Limit**
1	1	2	0.1	0.2	0.02	30
2	1	4	0.05	0.2	0.02	50
3	1	5	0.08	0.3	0.03	40
4	2	3	0.05	0.25	0.03	20
5	2	4	0.05	0.1	0.01	40
6	2	5	0.1	0.3	0.02	20
7	2	6	0.07	0.2	0.025	30
8	3	5	0.12	0.26	0.025	20
9	3	6	0.02	0.1	0.01	60
10	4	5	0..2	0.4	0.04	20
11	5	6	0.1	0.3	0.03	20

IV.PROPOSED ALGORITHM

Contingency Analysis

Contingency Analysis (CA) is used on a live network at regular intervals to evaluate new system conditions [1]. The basic methodology is to disable a particular part (branch) and evaluate network stability using power flow equation. The number of branches disabled, say x, determines the (N - x) contingency analysis. If only one branch is disabled we have (N - 1) contingency analysis. Based on this analysis, operators can device a ranking to prioritize transmission planning.

In this work, we will not be concerned with all the events that can cause trouble on a power system. Instead, we will be concentrating on the possible consequences and remedial actions required by two major types of failure events - 1) Transmission-line outages and 2) Generation-unit failures.

Transmission-line failures cause changes in the flows and voltages on the transmission equipment remaining connected to the system. Therefore, the analysis of transmission line failures requires methods to predict these flows and voltages so as to be sure they are within their respective limits. Generation failures can also cause flows and voltages to change in the transmission system. In this work, we have preferred to predict the change in flows alone, to analyze these failures.

One way to gain speed of solution in a contingency analysis procedure is to use an approximate model of the power system. This method optimizes the computation time of contingency analysis. For many systems, the use of DC load flow models provides adequate capability. In such systems, the voltage magnitudes may not be of great concern and the DC load flow provides sufficient accuracy with respect to the megawatt flows.

One of the easiest ways to provide a quick calculation of possible overloads during such failures is to use linear sensitivity factors. These factors show the approximate change in line flows for changes in generation on the network configuration.

These factors can be derived in a variety of ways and basically come down to two types:
1) Generation shift factors
2) Line outage distribution factor

Generation Shift Factors (A_{1i})
The generation shift factors are designated A1i and have the following definition

$$A_{li} = \frac{\Delta f_l}{\Delta P_i} \tag{1}$$

where *l* is line index, *i* is bus index, Δf_l is change in megawatt power flow on line *l* when a change in generation, ΔP_i occurs at bus *i* and ΔP_i is change in generation at bus *i*.

The new power flow on each line in the network could be calculated using a pre-calculated set of '*A*' factors as follows:

$$\dot{f}_l = f_l^0 + A_{li}.\Delta P_i \; ; \qquad for\; l = 1, \dots L \tag{2}$$

where f_l^0 is flow before the failure, $\dot{f}_l$is flow on line *l* after the generator on bus *i* fails.

The “outage flow”, $\dot{f}_l$ on each line can be compared to its limit.

Line Outage Distribution Factor (D_{lk})
The line outage distribution factors are used in a similar manner, only they apply to the testing for overloads when transmission circuits are lost. By defining the line outage distribution factor has the following meanings.

$$D_{lk} = \frac{\Delta f_l}{f_k^0} \tag{3}$$

where D_{lk} is line outage distribution factor when monitoring line *l* after an outage on line *k*, Δf_l is the change in MW flow on line *l*, and f_k^0 is the original flow on line *k* before it was outaged (opened).

If one knows the power on line *l* and line *k*, the flow on line *l* with line *k* out can be determined using ’*D*’ factors.

$$\dot{f}_l = f_l^0 + D_{lk}\,.f_k^0 \tag{4}$$

An algorithm is formulated for contingency analysis on the test system using sensitivity factors as shown in figure 3 and implemented using MATLAB program. The flow chart for the algorithm is shown in figure 2. Here, 100 MVA is selected as the base for the sample 6-bus system. First, we calculate the dc power flow of the complete 6-bus system, which is used as the base case power flow. The sensitivity factors are then calculated using equations (1) and (3). Next, we intentionally impart an outage into the system, which can either be a generator outage or a line outage. We then find out the contingency power flow using the sensitivity factors and base case power flow. This contingency power flow is compared to the thermal limits of lines to find out the overloads in the system. The results of the contingency analysis are shown in tables IV and V.

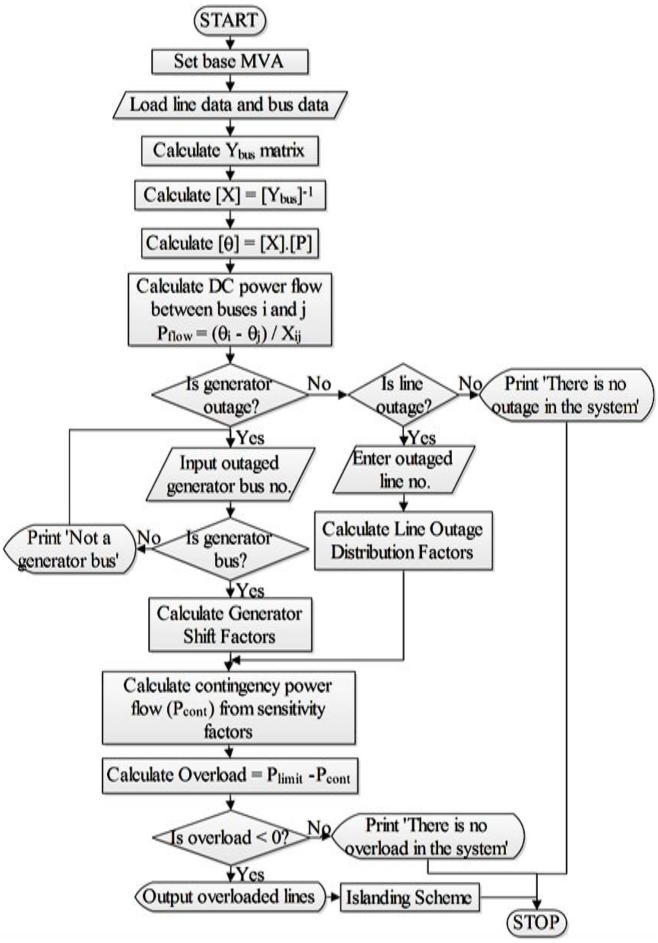

Fig. 3 Contingency analysis procedure

Forced Islanding

An algorithm is developed for forced islanding, the flow chart of which is shown in figure 4.

For implementation of the forced islanding scheme, islands for each outage case are pre-defined. The islands are selected in such a way that load demand approximately equals generation in these islands. The most appropriate islands for each contingency case are chosen by an adaptive forecasting technique. The adaptive forecasting technique is explained using Table III and the pre-defined islands so chosen for each contingency case of the 6-bus system are given in table IV.

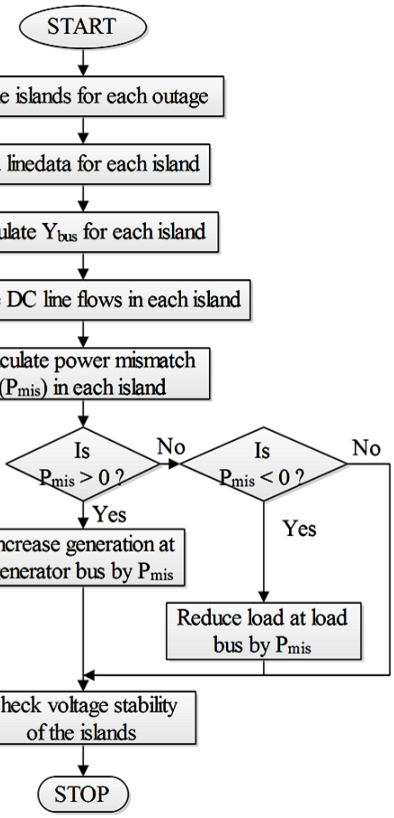

Fig. 4 Flow chart for Forced Islanding Scheme

TABLE III. Adaptive Forecasting Technique For Generator 2 Outage Case

Island 1	Island 2	Stability Analysis Result	Load Shedding Result
1, 2, 4, 6	3, 5	Both islands unstable	Island 1 - 36MW Island 2 - 29MW
1, 2, 5, 6	3, 4	Matrix singularity in island 2	-
1, 2, 4, 5	3, 6	Island 1 unstable	Island 1 - 1MW
2, 3, 4, 5	1, 6	Matrix singularity in island 2	-
2, 3, 5, 6	1, 4	Island 2 unstable	Island 1 - 1MW
2, 3, 4, 6	1, 5	Load Flow does not converge	-

From Table III, it is clear that the islands with bus numbers [1, 2, 4, 5] and [3, 6] is more stable with a minimum load shed of 1 MW. Hence, this is the most appropriate island boundary for generator 2 outage case. Likewise, islands are determined for each contingency case separately. The islands chosen in this manner are listed in table IV for each contingency case.

After splitting the system into islands, load flow analysis is done on each island and power mismatch is calculated in each island, to warn for an increase of generation or a decrease of load in each island if the mismatch is positive or negative, respectively, by an amount equal to the mismatch. Also, voltage stability of the islands is analyzed considering a tolerance limit of ±10% for the voltage.

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TABLE IV. Pre-Defined Islands

Outage Case	Island 1	Island 2
Gen 2	1, 2, 4, 5	3, 6
Gen 3	2, 3, 5, 6	1, 4
Line 1	1, 2, 4, 5	3, 6
Line 2	1, 2, 3, 5	3, 6
Line 3	1, 2, 4, 6	3, 5
Line 4	No Island	
Line 5	1, 2, 4, 5	3, 6
Line 6	1, 3, 5, 6	2, 4
Line 7	1, 2, 4, 5	3, 6
Line 8	1, 2, 4, 5	3, 6
Line 9	1, 2, 4, 6	3, 5
Line 10	No Island	
Line 11	No Island	

Load Shedding

If any one of the islands or both are found to be unstable, then using an under-voltage load shedding scheme the system can be brought back to stability. Such a scheme is proposed in the load shedding algorithm, the flow chart for which is developed in figure 4. First, a load priority is set set (here [6, 5, 4] is order of load priority from low to high). Then, the lowest priority load is shed in steps of 1 MW till the system regains stability. Stable islands can operate independently.

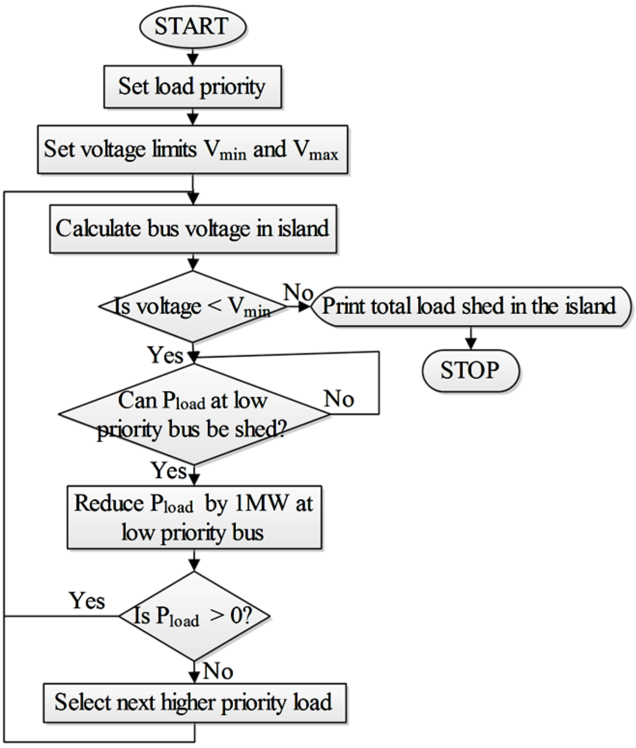

Fig. 5 Flow chart for Load Shedding Scheme

Restoration

Since the islands were formed to eliminate the risk of blackout during a contingency, it has to be integrated to the main grid as soon as the fault is cleared. For that, a restoration sequence has been formulated. The developed algorithm is depicted in the flow chart shown in figure 5. Prior to restoration, the tie-lines are defined (here lines 1 and 4) and line priority is set (here [9, 2, 3, 5, 7, 6, 8, 10, 11] is order of line priority from high to low). During restoration, the tie-lines are restored first to allow exchange of power from one island to another. After restoration of the tie lines, if the system is found to be stable, the load can be restored according to the load priority, in possible steps (1 MW in this work) till system goes out of stability. And if the system is found to be unstable, the next line according to the line priority is restored instead of restoring the load. This process is repeated till all the lines and loads are restored.

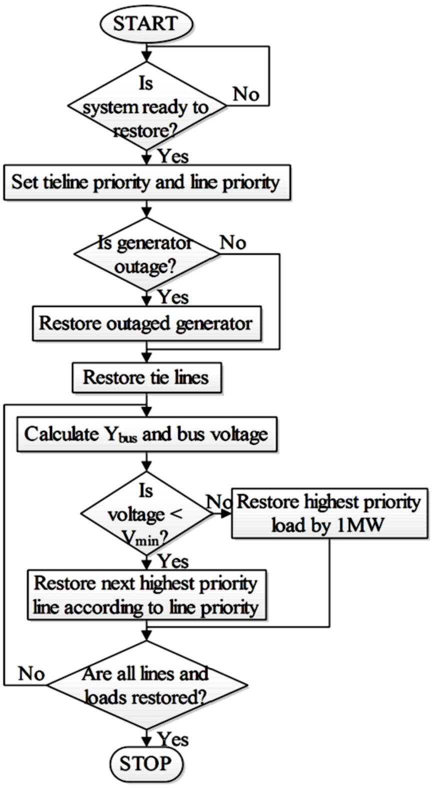

Fig. 6 Flow chart for Restoration

V.RESULTS

Contingency Analysis

The sensitivity factors, contingency power flows and overloads in each line as calculated by the algorithm for generator 2 outage case are given in table IV. An outage on generator 2 causes overload in lines 1, 2 and 3 as indicated by the negative values for overload in these lines. Similarly, results can be obtained for each outage case which is summarized in table V.

TABLE V. Result For Generator 2 Outage

Line No.	**Maximum Power flow**	**Base case Power flow**	**Sensitivity Factors**	**Contingency Power flow**	**Overload**
1	30	25.3284	-0.4706	53.5658	-23.5658
2	50	41.5672	-0.3149	60.4605	-10.4605
3	40	33.1045	-0.2145	45.9737	-5.9737
4	20	1.8537	0.0544	-1.4132	21.4132
5	40	32.4776	0.3115	13.7895	26.2105
6	20	16.2189	0.0993	10.2631	9.7369

Line No.	Maximum Power flow	Base case Power flow	Sensitivity Factors	Contingency Power flow	Overload
7	30	24.7781	0.0642	20.9264	9.0736
8	20	16.9317	0.0622	13.2010	6.7990
9	60	44.9220	-0.0077	45.3858	14.6142
10	20	4.0448	-0.0034	4.2500	15.7500
11	20	0.2999	-0.0565	3.6878	16.3122

TABLE VI. Summary Of Contingency Analysis Results

Outage Case	Overloaded Lines
Gen 2	1,2, 3
Gen 3	5, 8, 9
Line 1	2,3
Line 2	1, 3, 5
Line 3	1, 2, 6, 7, 8
Line 4	No Overload
Line 5	2, 6, 8
Line 6	8
Line 7	6, 9
Line 8	6
Line 9	7, 8
Line 10	No Overload
Line 11	No Overload

Forced Islanding

The analysis result of the forced island formed during generator 2 outage case is briefly discussed below:

Island 1 (2, 3, 6):

Power Flow result -

From Bus	To Bus	Power Flow
2	3	25.4545
2	6	44.5455
3	6	25.4545

Voltage at buses -
$V_2 = 1$
$V_3 = 1.07$
$V_6 = 0.9863$

Bus voltages are within limits.

Island 2 (1, 4, 5):

Power Flow result -

From Bus	To Bus	Power Flow
1	4	77.77
1	5	62.22
4	5	7.77

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Voltage at buses -
V_1 = 1.05
V_4 = 0.7996
V_5 = 0.7227

Bus voltage is below limit.

Load Shedding

The lowest priority load in the islands, which had voltage below the specified limit, is shed in steps of 1MW till the system reaches stable limit. The total amount of load shed to make the system stable and the steady state voltages are given below for the generator 2 outage case:

The total amount of load shed on bus 5 in island 2 is 66MW and 66MVAr and the steady state voltage in island 2 obtained after the load shed is:
V_1=1.05
V_4=0.9006
V_5=0.9947

Restoration

Following are the sequence of steps taken during restoration of load and system for line 3 outage case:

- After connecting the tie line (here line 4), the voltage is:

V_1	V_2	V_3	V_4	V_5	V_6
1.05	1.05	1.07	0.9867	0.9008	0.9023

- Since the voltages are within limits, load on bus 5 is switched on by a total amount of 1MW.

V_1	V_2	V_3	V_4	V_5	V_6
1.05	1.05	1.07	0.9868	0.8954	0.9023

- As the voltage has gone below limit, lines 9 and 3 are reconnected consecutively, according to the line priority. Then the voltage comes to:

V_1	V_2	V_3	V_4	V_5	V_6
1.05	1.05	1.07	0.9850	0.9864	1.0249

- As the voltage is within limits, load at bus 5 is connected in steps of 1 MW till the system goes below the limit after connecting a total load of 28MW and 28 MVAr at bus 5 and 20 MW and 20 MVAr at bus 6. The voltage after restoration of load is:

V_1	V_2	V_3	V_4	V_5	V_6
1.05	1.05	1.07	0.9869	0.9227	1.0062

- As all the loads are reconnected, only system restoration remains. So, according to line priority, lines 6, 10 and 11 are switched on consecutively.

VI.CONCLUSION

This paper has discussed a forced islanding scheme in response to the risk of outages occurring in the power system. With this scheme, we aim to eliminate the risk of blackouts in the system. The method is incorporated by conducting a contingency analysis on the base system, utilizing sensitivity factors to determine the overloads in the lines during an outage. For each outage, the forced islands to be formed are predefined by an adaptive forecasting technique. By this technique, the most appropriate island boundary for each outage can be chosen. Results show that such chosen islands have minimum load shed. After forming forced islands, the islands are analyzed for stability. If they are not stable, then an under-voltage load shedding scheme is proposed. The proposed work is carried out on a sample 6 bus system using MATLAB program.

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