International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 12, Number 11 (2019), pp. 1854-1863

Power System Security Assessment under N-1 and N-1-1 Contingency Conditions

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Abstract

The most important function in a power system planning and operation is the desire to keep the system in a secure state under normal and contingency conditions. Contingency is termed as a disturbance resulting from the components outages. This disturbance is a sudden change in the system configuration resulting in severe violations on the operating constraints. These violations may result in successive interruptions leading to partial or total blackout. The purpose of this paper is to study the effect of power system component outages in terms of their severity to select and rank all severe contingencies, and consequently to apply the Remedial Action Scheme (RAS) approach that is necessary to withstand these contingencies and return the system into a secure state. Both of RAS-1 and RAS-2 strategies are utilized to obtain a final system configuration which successfully recovers from any kind of N-1 contingency criterion. The most economical remedial scheme from RAS-1 and RAS-2 is discriminated. The N-1-1 Contingency Analysis (CA) is performed to investigate the technical robustness of the economically certificated scheme. This work is implemented on IEEE 9 bus system.

Keywords: Remedial Action Scheme (RAS) Approach, Severe Violations, Total Blackout

I. INTRODUCTION

A contingency in an electric power system is termed as a disturbance resulting from the outages of one or more equipment such as generator, transmission line and/or transformer [1-3]. This disturbance is a sudden change in the system configuration resulting in severe violations on the operating constraints such as branches overloads and bus voltage margin's violations [4-5]. These severe violations may result in successive interruptions leading to a partial or a total blackout. A secured system is one which has the ability to undergo a set of outages without any violations on the operating constraints and with the minimal disruption of service or its quality [4]. This means that the resulting effects of outages are investigated on the system operating constraints to prevent the blackout phenomenon.

An essential task in a power system is a security assessment aims to keep the system operation in a secure state under normal and contingency conditions [6]. Consequently, planning and studying for contingencies form an important aspect of secure operation [7-8]. Therefore, the purpose of this paper is to study the effect of power system component outages in terms of their severity to select and rank all severe contingencies, and consequently to apply the Remedial Action Schemes (RASs) that are necessary to withstand these contingencies and return the system into a secure state.

In this paper, the CA technique using Newton Raphson Load Flow (NRLF) method in a DIGSILENT Power Factory environment is applied for each outage to investigate the resulting effects on the system operating constraints. This technique provides tools for reporting list of all severe contingencies and its associated violations [9]. The most widely famous violations include branches overloads and deficient voltage levels. Based on the collected data, the operator can evaluates the relative severity of every contingency and decide if corrective actions ought to be started to alleviate the possible issues [10]. The CA is a hard work as a power system contains a large number of components. Thus, the contingency screening method is an essential task in CA technique to reduce the numerous computations by reducing the number of outage cases that should be investigated by load flow while evaluating the power system's security [11-12]. This method aims to curtail the contingency list by eliminating the outages having no violations on the system operating constraints. Generally, contingency screening methods use approximate network solutions to specify the outages causing system violations. AC load flow algorithms capture the impact of an outage on line flows and system voltages better than the DC load flow [13]. In this paper, the screening method is carried out by performing full AC NRLF in a DIGSILENT environment for each outage to quickly identify all contingencies that cause system violation.

Contingency ranking algorithms rank the contingencies in descending order based on their severity [11-12]. Most of researches on contingency ranking algorithm based on analytical techniques show that the Performance Index (PI) ranking method is widely accepted [14-15]. In this paper, all contingencies are ranked based on the Overall Performance Index (OPI) of test system considering Voltage Performance Index (PI_V) and Active Power Performance Index (PI_P) for each severe contingency case in MATLAB environment. PI_V is elected to measure the system inadequacy due to out-of limit bus voltages while PI_P is selected for quantifying the extent of branch overloads. In this paper, to achieve both effective and accurate results, contingency screening method and PI ranking method are used to select and rank all severe contingencies.

In general, the CA technique tends to approval the system reliability and security criterion under contingency conditions [16]. For example, the famous N-1 contingency criterion is broadly utilized in the power industry. This criterion is needed to ensure that the system has the ability to withstand single component outage [17-18]. It gives a performance table containing all severe contingencies to which planners must pay special attention. Reference [19] refers to another type of contingency criterion called the N-1-1. For this criterion, two component outages are applied sequentially rather than simultaneously [13]. It is defined based on the North American Electric Reliability Corporation (NERC) guidelines where there is lost one component, subsequent by changes in accordance with the electric power systems. The lost component is followed by the loss of a second component. This kind of criterion is represented by two consecutive interruptions and utilized to help with sustaining economic activity and personal satisfaction through reliable electric power delivery. This paper studies the power system security assessment under N-1 and N-1-1 contingency conditions.

RASs are the proper actions which are required to alleviate the violations caused by a contingency and also to remedy all severe contingencies that initiate the actual system problems [20]. Therefore, these actions permit the operators to modify the power system operation if a CA technique forecasts a significant disturbance. In this paper, Remedial Action Scheme-1 (RAS-1) and Remedial Action Scheme-2 (RAS-2) strategies are proposed. The RAS-1 is applied to correct both of branches overloads and bus voltage magnitude violations [21]. It alleviates the voltage violations by raising/lowering a controllable reactive power source and/or adjusting a transformer tap ratios. It also alleviates the overloaded branches by re-dispatching of generators, line switching, load transfer and load shedding actions. The RAS-2 is applied to remove the probably load shedding in RAS-1. Load flow assessment is performed for each corrected system to validate the perfect effectiveness of RAS-1 and RAS-2 on the operating constraints. Considering only the most severe contingency case is not sufficient as other less severe contingencies may need other RASs not needed in the most severe contingency case. Therefore, this paper underlines the necessity of considering remedial actions in all contingencies to reach a final system configuration which successfully recovers from any kind of N-1 severe contingencies.

Reliability assessment is performed to study the impact of equipment unavailability on the system reliability. Reliability indices are obtained according to the load shedding in RAS-1. The most economical remedial scheme from the proposed RAS-1 and RAS-2 is discriminated to be used as a certificated remedial action from the economic point of view in the N-1 contingency criterion. After restoring the system from a contingency state to a secure state, the N-1-1 criterion is performed to investigate the technical robustness of the economically certificated action in N-1 criterion. The first contingency event of N-1-1 criterion is always represented by the most severe contingency case. Therefore, this criterion is similar to the N-1 criterion after excluding the most severe contingency case. This work is implemented on IEEE 9 bus system in DIgSILENT Power Factory environment.

II. RELATED WORK and PROBLEM FORMULATION

Steady state power system insecurity such as transmission lines overloads may result in successive interruptions leading to a partial or a total blackout. In general, the CA technique is used in network design procedures, scheduled maintenance and detection of network weakness zones leading to a blackout phenomenon. In this paper, this technique is used to detect which contingencies lead to violations on the system operating constraints. It is necessary to rank these contingencies according to their severity, and apply the RASs in order to withstand these contingencies and mitigate their consequences. To achieve these objectives, power system security assessment can be divided into two issues. The first issue is how to select and rank all severe contingencies, while the other issue is how to remedy these contingencies.

For the first issue, the contingency screening method and PI ranking method are performed to process this issue. Screening techniques use approximate network solutions such as Line Outage Distribution Factors (LODFs), generation shift factors, linearized load flow and local solution methods to detect the outages causing system violation. A major drawback of these methods which are determined from the DC load flow is no results on system voltages [22-23]. AC load flow algorithms capture the impact of an interruption on system voltages better than the DC load flow [13]. To achieve accurate screening, a full AC NRLF algorithm is used. In particular, the full AC NRLF is evaluated under normal and contingency conditions. For the base case, it is performed to ensure that the power system constraints operate within the allowable limits of operation. The post contingency load flow is performed to identify the operational issues and the associated violations.

In order to indicate the severity of contingencies and to rank them relative to each other, the set of system variables must be transformed into the scalar value PI, which is defined as the measure of system performance stress expressed in terms of network variables [12]. This means that, the system performance might be quantitatively assessed in terms of indices reflecting the severity of out-of-limit voltage values or branch overloads resulting from a given contingency [10]. There are two Performance Indices (PIs) widely used, namely PI_V and PI_P [12]. PI_V is selected to measure the system inadequacy due to out-of limit bus voltages while PI_P is selected for quantifying the extent of branches overloads. Theses indices are directly evaluated and used to distinguish the actual critical contingencies from non-critical ones and predict the relative severity of critical contingencies [24].

To characterize the system security state in terms of PIs, three different security levels have been considered for all contingencies; Class I (Most critical contingencies), Class II (Critical contingencies) and Class III (Non critical contingencies) [25]. Class I demonstrates that it is never protected under any working condition and requires prompt consideration and fast actions. It is classified according to the PI_V or PI_P value which must be greater than 0.8. Class II demonstrates that it is not covered and requires a proper remedial action since there are violations. Class III shows that it is forever secure. The PIs value for the Class II starting from 0.2 to 0.8 and less than 0.2 for Class III.

The contingency is ranked in descending order in terms of its PIs value. Subsequently, in light of the determined PIs, the system security level type and contingency ranking are performed.

For the second issue, the RASs are applied to remedy all severe contingencies to return the system into a normal state. These actions are classified into two parts, real power rescheduling and reactive power rescheduling for correcting of overloaded elements and bus voltage magnitude violation respectively [26-28]. Within the real power rescheduling aspect, four controlled elements of generation re-dispatching, line switching, load transfer and load shedding actions are available and used in a decreasing priority [21]. In the reactive power rescheduling aspect, two corrective actions of raising/lowering a controllable reactive power source and adjusting the transformer tap ratios are available [21]. In this paper, two approaches of RAS-1 and RAS-2 are performed. The RAS-1 includes real and reactive power rescheduling to correct both of overloaded branches and voltage violations. To remove load shedding, if any required by RAS-1, the RAS-2 is applied. Load flow assessment is performed on each corrected system to validate the perfect effectiveness of RAS-1 and RAS-2 on the operating constraints. Considering only the most severe contingency case is not sufficient as other less severe contingencies may need RASs not needed in the most severe contingency case. Thus, the remedial actions in all severe contingencies are considered to reach a final system configuration which successfully recovers from any kind of N-1 severe contingencies.

Increasing excessive paths in transmission networks have constantly been believed to be a good scheme to improve the service reliability. Nonetheless, network overlapping equations by power flows impose more operating constraints. Likewise, autonomous removing of lines may reduce the limits violation and improve the system reliability. Therefore, the system reliability should be analyzed after applying the RASs [29]. Reliability assessment is performed to study the impact of equipment unavailability on the system reliability. Reliability indices are obtained according to the load shedding in RAS-1. The most economical remedial scheme from the proposed RAS-1 and RAS-2 is discriminated to be used as a certificated action from the economic point of view in the N-1 criterion. This problem is done by reformulating of the annual Expected Interruption Cost (EIC) as Net Present Value (NPV) capitalizing the EIC in today marketing price [30]. This procedure is performed to allow a comparison between the NPV of EIC in RAS-1 and the Total Capital Cost (TCC) of the proposed investments in RAS-2 to specify which one is the most economical scheme.

Once the most economical remedial scheme is determined, the N-1-1 contingency criterion is performed on the corrected system of the most severe contingency case to investigate the technical robustness of its economically certificated remedial scheme. The reliability indices are calculated after obtaining the remedial actions for all N-1-1 severe contingencies [31-32] to examine the effect of equipment unavailability on the system reliability and discriminate the most economical remedial scheme under this criterion.

The following computations are required to process these issues:

- Determine the initial system performance of bus voltage magnitude and MW active power flows for each system component.
- Detect the resulting effects for each outage on the system performance.
- Select all severe contingencies that lead to system violations and calculate the PIs for every contingency.
- Rank all contingencies according to their severity.
- Remedy the contingencies by RAS-1 to return the system into a secure state.
- Remove the probably load shedding if any required by RAS-1.
- Validate the perfect effectiveness of the proposed RAS-1 and RAS-2 on the operating constraints.
- Examine the effect of equipment unavailability on the system reliability.
- Discriminate the most economical remedial scheme under N-1 criterion.
- Determine the technical robustness of the most economical remedial scheme.
- Obtain the remedial schemes for all N-1-1 severe contingencies.
- Evaluate the economies of N-1-1 remedial schemes

III. PROBLEM SOLUTION ALGORITHM

The algorithm of solving the contingency based power system security is summarized in the following steps:

Step 1: A pre contingency load flow assessment is performed to determine the initial system performance of bus voltages and MW active power flows.

Step 2: The N-1 CA technique using NRLF method in a DIGSILENT environment is performed for each outage to detect the resulting effects on the system performance. Contingency screening method and PI ranking method are used to select and rank all severe contingencies by determining $PI_V PI_V$, $PI_V PI_P$ and OPI for each contingency in MATLAB environment.

$$\mathrm{R(t) = P(T > t)R(t) = P(T > t)}PI_V = \sum_{i=1}^{N_{pq}} (0.5) * [\frac{(V_i - V_{inom})}{\Delta V_i^{lim}}]^2 \tag{1}$$

$$\Delta V_i^{lim} = (0.5 * (V_{imax} - V_{imin})) \tag{2}$$

$$PI_P = \sum_{i=1\ \&\ j=1}^{L\_T} (0.5) * [\frac{P_{i,j}}{P_{i,jmax}}]^2 \tag{3}$$

$$P_{i,jmax} = \frac{V_i * V_j}{X_{i,j}} \tag{4}$$

$$\text{OPI} = PI_V + PI_P \tag{5}$$

PI_V reflects the violation in bus voltage limits and provides a good measure of the severity of abnormal voltages as long as the generating units remain within their reactive power limits. The voltage deviation shown in Equation $2\Delta V_i^{lim}$ represents the threshold above which voltage level deviations are outside their limits, any contingency load flow with voltage levels outside this limit yields a high value of PI_V. When all the voltage level deviations from the rated voltage are within their limits, ΔV_i^{lim} the PI_V PI_V is small. Thus, this index PI_V measures the severity of the out-of limit bus voltages, and for a set of contingencies, this index provides a direct means of comparing the relative severity of the different outages on the system voltage profile [11]. PI_P reflects the extent of lines, transformers and generators overloads. This index PI_V has a small value when all branches flows are within their allowable limits and also, it has a high value when there are branches overloads. Thus, it provides a measure of the severity of branches overloads for a given state of the power system.

Step 3: The RAS-1 approach is applied to remedy all N-1 severe contingencies.

Step 4: The RAS-2 approach is applied to remove the probably load shedding in RAS-1.

If the security analysis indicates an unacceptably likelihood of a major power disturbance due to that the applied RAS-1 is not sufficient to remedy the contingencies, then further system modifications and upgrades may be justified such as installing of new transmission lines and power electronic based equipment as Flexible AC Transmission Systems (FACTS). This approach aims to enhance the system reliability. Load flow assessment is performed on each corrected system to validate the perfect effectiveness of the proposed RAS-1 and RAS-2 on the operating constraints in the N-1 CA.

Step 5: Reliability assessment is performed to study the impact of equipment unavailability on the system reliability.

Step 6: The most economical remedial scheme from RAS-1 and RAS-2 is discriminated to be used as a certificated scheme from the economic point of view in the N-1 CA.

Step 7: The N-1-1 CA is performed on the corrected system of the most severe contingency case to investigate the technical robustness of its economically certificated action.

The novelty of this algorithm is to perform the power system security under N-1 and N-1-1 contingency conditions. Fig. 1 shows the flow chart of contingency based power system security problem solution algorithm.

IV. CONTINGENCY ANALYSIS TECHNIQUE

When studying a CA, the following requirements are performed as follows:

1. Implementation of a pre contingency load flow assessment to calculate the initial operating constraints of loading and voltage wise.
2. Implementation of a post contingency load flow assessment. It is performed by forced outages for each component to detect the post contingency operating violations.

Since CA includes the simulation of every contingency case on the system basic model, three major aspects of developing the appropriate model, choosing of which contingency case to consider and computing the MW active power flows and bus voltages are involved. It is in this way able to divide the off-line CA into various phases of contingency definition, contingency screening, contingency ranking/contingency evaluation and remedial schemes strategy [33-34].

Contingency definition involves the possible outages that occur in a power system. It is a process of creating the contingency list. Contingency screening is a process of selecting all contingencies that lead to violations on power flows and bus voltage margins. Thus, it is an essential task to curtail the contingency list and reduce the computations. Contingency ranking algorithm is a procedure in which all severe contingencies are ranked in descending order, sorted out by the severity of contingency and given by considering the OPI [33]. The system PI is quantitatively assessed in terms of indices reflecting the severity of out of limit voltage values PI_V and branch overloads PI_P resulting from a given contingency. Remedial strategy is then applied to remedy all severe contingencies to return the system into a secure state. The system reliability should be studied after performing the RASs [29].

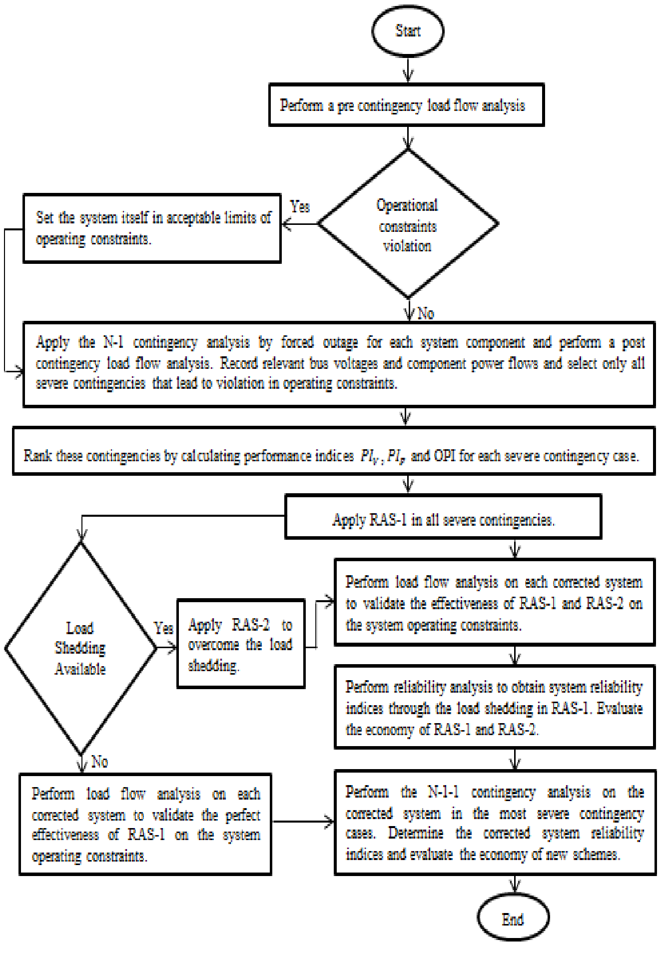

Fig. 1. Flow chart of problem solution algorithm

V. RELIABILITY ASSESSMENT

In this paper, the reliability of a composite generation and transmission system (i.e. Hierarchical Level Two (HLII)) requires the assessment for basic reliability indices of the individual load points [35-36] and the overall system [37].

There are several practical evaluation techniques for bulk transmission system reliability of state space technique, network solution technique and remedial/corrective actions [38]. This paper uses the RAS approach to assess the reliability, enabling FEA with constraints by completing load flows for each outage. If the total generation is greater or equal to the total load, there will be no load curtailments, otherwise, load curtailments will occur [21]. In reliability assessment, firstly generator re-dispatching, line switching and load transfer actions are attempted. These actions do not effect on the reliability indices and therefore the system is 100 % reliable. If these actions do not remove system violations, the load shedding actions will take place that effect on the system reliability. So, reliability indices of basic bulk transmission system are calculated after obtaining the remedial actions for all N-1 severe contingencies [31]. These actions specify which contingencies will lead to load interruptions and if so, which loads will be interrupted and for how long. The RAS-2 approach is applied to remove the probably load shedding in RAS-1 approach. Load flow assessment is performed on each corrected system to validate the perfect effectiveness of the proposed RAS-1 and RAS-2 on the operating constraints in the N-1 CA.

An important requirement in a reliability cost/benefit assessment is the ability to quantitatively evaluate the customer damage, costs due to supply interruptions [39]. The commonly used method is to derive a Sector Customer Damage Function (SCDF) from surveys to individual customers and to calculate the expected total cost of power supply interruptions to the customers [40]. From reliability assessment, the most economical remedial scheme from the proposed schemes RAS-1 and RAS-2 is discriminated to be used as a certificated scheme from the economic point of view in the N-1 CA. This problem is carried out by reformulating of EIC as NPV [41] capitalizing the annual expected interruption cost in today marketing price as follows.

$$NPV = \sum_{t=1}^{T} \left[\frac{EIC}{(1+R)^t}\right] \qquad (6)$$

This procedure is performed to allow comparison between the NPV of EIC in RAS-1 and the TCC of the proposed investments in RAS-2 to specify which one of these schemes is the most economical scheme. The N-1-1 CA is performed on the corrected system of the most severe contingency case to investigate the technical robustness of its economically certificated scheme.

VI. CASE STUDY

The proposed work is performed on IEEE 9 bus system shown in Fig. 2. The system consists of one slack bus numbered 1, two generator buses numbered 2, 3 and six load buses numbered 4, 5, 6, 7, 8 and 9. It has total six transmission lines and three transformers.

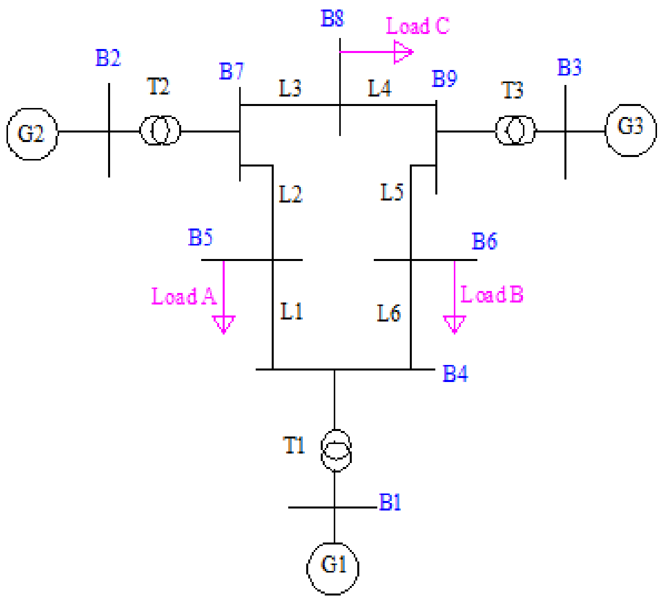

Fig. 2. Single line diagram of IEEE 9 bus system

VII. RESULTS and DISCUSSION

Violations statistic of N-1 CA shown in Table 1 is specified according to the system operating constraints. The minimum and maximum limits of allowed voltages were taken by 0.95 p.u and 1.05 p.u. The maximum thermal loading of elements is taken by 80 % and 100 % under normal and contingency conditions respectively. The performance indices and contingency ranking using NRLF are shown in Table 2. In this table, the performance indices and contingency ranking using Back Propagation Artificial Neural Network (BP-ANN) are obtained to clearly demonstrate the readability of work. The latest tendencies using ANN have brought lot of development inside the speed of contingency screening. Contingency ranking using BP-ANN is performed in MATLAB environment.

Table 1. Violations statistic of N-1 contingency

Severe Contingencies	Violations	Lower Voltage Limit
L1	1	0.839
L2	1	0.938
L6	1	0.942

Table 2. Violations statistic of N-1 contingency

	NRLF Algorithm				BP-ANN Algorithm			
Severe Contingencies	PI_V	PI_P	OPI	Rank	PI_V	PI_P	OPI	Rank
L1	5.737	0.0455	5.782	1	5.659	0.0452	5.754	1
L2	1.027	0.0539	1.081	2	1.025	0.0521	1.062	2
L6	0.992	0.0288	1.020	3	0.991	0.0267	1.016	3

L1 outage is the most severe contingency, having the highest OPI value. Fig. 3 and Fig. 4 show both of the graphical representation of PI_V PI_V, PI_P PI_P and OPI for all severe contingencies and the contingency ranking based on the OPI.

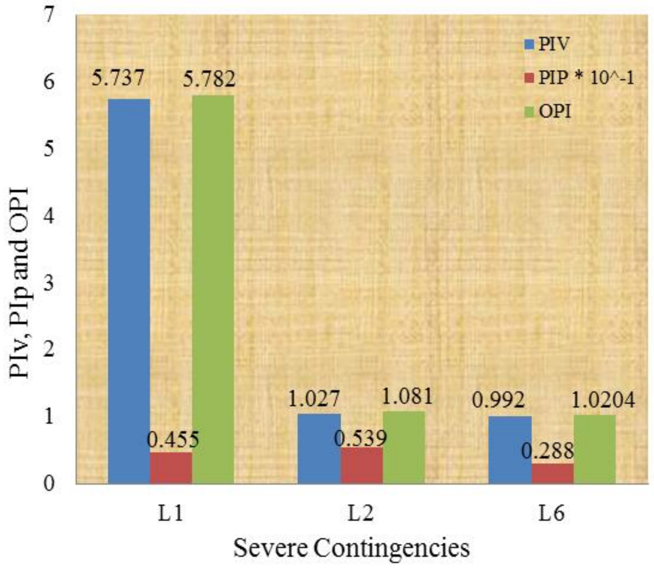

Fig. 3. PI_V, PI_P and OPI values for all severe contingencies

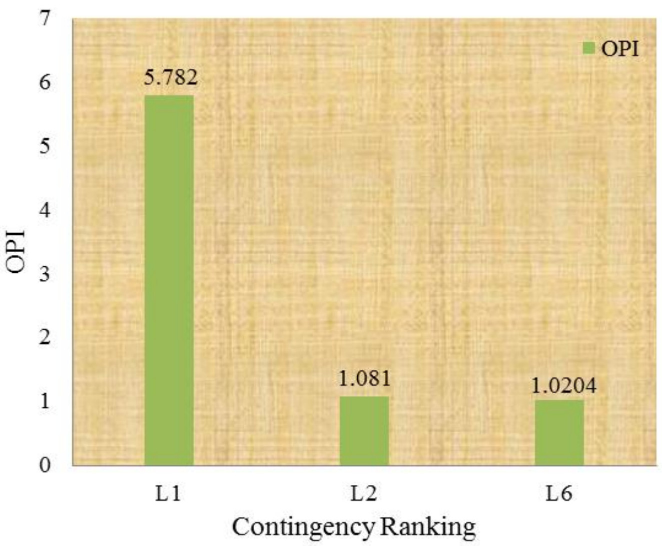

Fig. 4. Contingency ranking based on the OPI

Post CA for all severe contingencies has been performed to investigate the bus voltage magnitude violations and the branches overloads. Pre contingency bus voltages and post contingency bus voltages of the most critical contingency case (L1 Outage) are detailed in Table 3; the MW active power flows and its loading percentage are detailed in Table 4.

Table 3. Pre and post contingency bus voltages

	Voltage (p.u)	
Bus Number	**Pre contingency**	**Post contingency**
B1	1.040	1.040
B2	1.025	1.025
B3	1.025	1.025
B4	1.026	1.039
B5	0.996	0.839
B6	1.013	1.020
B7	1.026	0.988
B8	1.016	0.989
B9	1.032	1.024

Table 4. Pre and post contingency MW active power flows and loading percentage

	Pre contingency		Post contingency	
System Component	**MW Flows**	**Loading %**	**MW Flows**	**Loading %**
L1	40.9	14.2	0.00	0.00
L2	86.6	21.5	133	40.3
L3	76.4	18.9	30.2	8.34
L4	24.2	8.5	70.6	19.7
L5	60.8	15.4	14.5	5.9
L6	30.7	8.6	76.6	18.9
G1	71.6	30.9	76.6	31
T1	71.6	29.5	76.6	29.5
G2	163	85	163	92.3
T2	163	79.6	163	86.1
G3	85	67	85	66.5
T3	85	55.7	85	55.3

Referring to Table 2, L1 outage is the most severe contingency case, but it is also clear that L2 and L6 outages have a serious impact on the test system. Therefore, the remedial actions for all N-1 severe contingencies are necessary as detailed in Table 5 in order to obtain a final system configuration which successfully recovers from any kind of N-1 severe contingencies.

Table 5. Remedial schemes for all N-1 severe contingencies

Severe Contingencies	**RAS Category**	**RASs**	
		RAS-1	**RAS-2**
L1	2nd	• Adjusting T2 tap changer (6 %). • Load shedding of Load A, P = 116 MW and Q = 40 Mvar.	• Adjusting T2 tap changer on (6 %). • Shunt capacitor of 0.96 Mvar per step for totally seventeen steps.
L2	1St	• Adjusting T1 tap changer (2.5 %).	–
L6	1St	• Adjusting T3 tap changer (1 %).	–

The bus voltages magnitude violation associated with L1 outage as shown in Table 3 implies the use of RAS-1 of adjusting the tap changer on T2 at high voltage sides to 6 % and applying the load shedding of Load A as shown in Table 5. To overcome the load shedding action in RAS-1, RAS-2 requires connection of seventeen steps shunt capacitor, 0.96 Mvar each at B5. The first category of transformer tap ratios and the second category that combines transformer tap ratios and load shedding are performed. The results shown in Table 5 show that considering RAS-1 in the most severe contingency case is necessary but not sufficient to remedy the consequences of less severe contingencies (L2/L6 outages). This conclusion also reinforces the necessity of considering RAS-1 in all severe contingencies to reach the test system configurations to a secure proper operation. Also, RAS-1 needs augmentation underlined in RAS-2 to enhance the system reliability in post contingency condition.

Load flow assessment is performed on each corrected system to validate the perfect effectiveness of RAS-1 and RAS-2 on the operating constraints. The bus voltages and both of the MW active power flows and loading percentages related to the corrected system of L1 outage case are shown in Table 6 and Table 7. The effectiveness of RAS-1 on the system operating constraints related to the most severe contingency case is illustrated in Fig. 5.

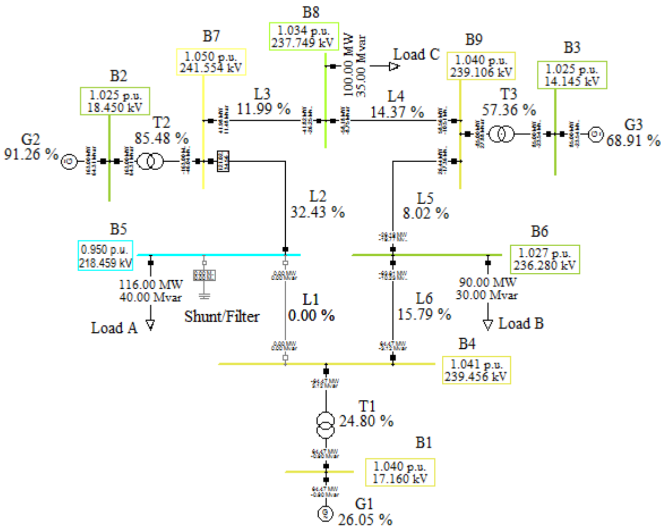

Fig. 5. The impact of RAS-1on the operating constraints

Table 6. Corrected system bus voltages

	Voltage (p.u)	
Bus Number	**RAS-1**	**RAS-2**
B1	1.040	1.040
B2	1.025	1.025
B3	1.025	1.025
B4	1.041	1.041
B5	0.950	0.952
B6	1.027	1.027
B7	1.050	1.050
B8	1.034	1.033
B9	1.040	1.037

Table 7. Corrected system MW active power flows and loading percentage

	RAS-1		RAS-2	
System Component	**MW Flows**	**Loading %**	**MW Flows**	**Loading %**
L1	0.000	0.000	0.000	0.000
L2	121.0	32.43	130.7	34.24
L3	41.98	11.99	32.32	10.39
L4	58.56	14.37	68.30	16.72
L5	26.44	8.020	16.70	6.720
L6	64.47	15.79	74.28	18.04
G1	64.47	26.05	74.28	30.01
T1	64.47	24.80	74.28	28.57
G2	163	91.26	163	91.24
T2	163	85.48	163	85.46
G3	85	68.91	85	68.74
T3	85	57.36	85	57.23

Reliability assessment is performed to study the impact of equipment unavailability on the system reliability, and also to discriminate the most economical remedial scheme from the proposed RAS-1 and RAS-2 to be used as a certificated remedial action from the economic point of view in the N-1 contingency criterion. According to the load shedding action in RAS-1 as shown in Table 5, the load point and system reliability indices of the bulk transmission system are obtained as detailed in Table 8 and Table 9.

Table 8. Load point reliability indices of IEEE 9 bus system

Load Point Reliability Indices	**LPIF (1/a)**	**LPIT (h/a)**	**AID (h)**	**LPENS (kWh/a)**
Load A	0.005497	0.0687125	12.5	618.4125

Table 9. IEEE 9 bus system reliability indices

System Reliability Indices	**IEEE 9 Bus System**
SAIFI (1/C/a)	0.005497
SAIDI (h/C/a)	0.0687125
CAIFI (1/A/a)	0.005497
CAIDI (h)	12.5
ASUI	0.000007844
ASAI	0.999992156
EENS (MWh/a)	0.6184125
AENS (MWh/Ca)	0.6184125
EIC (M$/a)	0.0045215
IEAR ($/kWh)	7.311528

EIC was estimated at about 4521.5 dollars per year. For a time period of 30 years and a discount rate of 8 %, this annual cost is being calculated in $50,902 as a NPV. This value is compared with the TCC of the 16.32 Mvar capacitor bank investments in RAS-2 as shown in Table 10 to specify which one of these two schemes is the most economical remedial scheme in the N-1 contingency criterion.

Table 10. Comparison of NPV of EIC in RAS-1 and TCC of proposed investment in RAS-2, considering all contingencies

Specifications	**Load Shedding Action**		**Associated Cost (M$)**		
	EENS (MWh/a)	EIC (M$/a)	NPV	TCC	Sum
RAS-1	0.6184125	0.0045215	0.050902	-	0.050902
RAS-2	-	-	-	0.49776	0.497760

The estimated TCC of the 230 kV, 16.32 Mvar capacitor bank at B5 is $497,760 [42]. So, this investment in RAS-2 is rejected due to its accompanying high cost, unless customers are willing to pay for reliable supply. The remedial actions in RAS-1 are selected to be a certificated scheme from the economic point of view in the N-1 contingency criterion. The N-1-1 CA is performed on the corrected system of L1 outage to detect the technical robustness of its economically certificated RAS-1 using new remedial actions as shown in Table 11.

Table 11. Remedial actions of the economically certificated scheme under N-1-1 contingency conditions

Severe Contingencies	RASs	
	RAS-1	**RAS-2**
L2	• Adjusting T2 tap changer (0.00 %). • Load shedding of Load A, P = 0.0 MW. Q = 0.0 Mvar.	• Adjusting T2 tap changer on (6 %). • Shunt capacitor of 0.96 Mvar per step for totally seventeen steps. • Additional line from B5 to B7 carries L2 data.
L3	• Adjusting T2 tap changer (5.0 %). • Load shedding of Load A, P = 116 MW. Q = 40 Mvar.	• Adjusting T2 tap changer (5 %). • Shunt capacitor of 0.96 Mvar per step for totally seventeen steps.
L4	• Adjusting T2 tap changer (5.0 %). • Load shedding of Load A, P =71.643 MW. Q =31.601 Mvar.	• Additional line from B5 to B7 carries the data of L2. • Installing of Synch. Gen. of 163 MW and transformer unit at B2.
L5	• Adjusting T2 tap changer (6.5 %). • Load shedding of Load A, P = 116 MW. Q= 40 Mvar.	• Adjusting T2 tap changer (0 %). • Additional line from B5 to B7 carries the data of L2.
L6, G1 and T1	• Re-dispatching of G3, P=108.8MW • Adjusting T2 tap changer (5.0 %). • Load shedding of Load A, P = 85.743 MW Q = 36.463 Mvar.	• Additional line from B5 to B7 carries the data of L2. • Synch Gen of 163 MW and transformer unit at B2. • Re-dispatching of G3, P=108.8 MW. • Adjusting T2 tap changer (0 %) and T3 (3 %)
G2 and T3	• Adjusting T1 tap changer (- 0.5 %) and T2 (6.0 %) • Load shedding of Load A, P = 116 MW and Q = 40 Mvar.	• Additional line from B5 to B7 carries the data of L2. • Adjusting the tap changer on T2 (0 %).

Load flow assessment is performed on each corrected system to validate the effectiveness of RAS-1 and RAS-2. Remedial actions results show that RAS-1 is not technically supported for each severe contingency in the N-1-1 CA. This is because of the load shedding augmentation. Reliability assessment is again performed in the N-1-1 criterion to discriminate the most economical remedial scheme from the utilized schemes. The load point and system reliability indices of the corrected system are detailed in Table 12 and Table 13.

Table 12. Load point reliability indices of the corrected system under N-1-1 contingency conditions

Load Point Reliability Indices	**LPIF (1/a)**	**LPIT (h/a)**	**AID (h)**	**LPENS (kWh/a)**
Load A	0.044982	1.972275	43.84587	54448.5

Table 13. Corrected system reliability indices

System Reliability Indices	**IEEE 9 Bus System**
SAIFI (1/C/a)	0.044982
SAIDI (h/C/a)	1.972275
CAIFI (1/A/a)	0.044982
CAIDI (h)	43.84587
ASUI	0.000225146
ASAI	0.999774854
EENS (MWh/a)	54.4485
AENS (MWh/Ca)	54.4485
EIC (M$/a)	0.41033533
IEAR ($/kWh)	7.53621

EIC was estimated at about 410335.33 dollars per year. For a time period of 30 years and a discount rate of 8 %, this annual cost is being calculated in $4,619,500 as a NPV. This value is compared with the TCC of the 230 kV, 16.32 Mvar capacitor banks ($497,760), the additional line ($500,000) and the 18 kV, 163 MW synchronous generators and its associated transformer at B2 ($3,000,000) [42] investments in RAS-2 as shown in Table 14 to specify which one of these two proposed schemes is the most economical remedial scheme.

Table 14. Comparison of NPV of EIC in RAS-1 and TCC of investments in RAS-2of N-1-1, considering all contingencies

Specifications	**Load Shedding Action**		**Associated Cost (M$)**		
	EENS (MWh/a)	EIC (M$/a)	NPV	TCC	Sum
RAS-1	54.4485	0.41033533	4.6195	-	4.6195
RAS-2	-	-	-	3.99776	3.99776

All investments in RAS-2 incur less investment. Thus, RAS-2 is economically and technically accepted under N-1-1 criterion.

VIII. CONCLUSION

Contingency analysis using NRLF algorithm has been simulated in DIgSILENT software by forced component outages in order to detect all outages causing system violations. Contingency screening method and PI ranking method have been performed on IEEE 9 bus system to select and rank all severe contingencies. These methods have been concluded that the contingency case of L1 outage is the most severe contingency case, L2 and L6 outages have a serious impact on the system. These outages have been classified as critical contingencies. The performance indices and contingency ranking using BP-ANN have been performed to verify the validity of the proposed algorithm.

The RAS-1 has been applied for all contingencies. The RAS-2 has been applied for the most severe contingency case. Remedial actions have been shown that only considering L1 outage is necessary but not sufficient as (L2/L6) outages need other actions not needed in L1 outage. This conclusion reinforces the necessity of considering remedial actions in all contingencies. Load flow assessments have been performed on each corrected system to validate the perfect effectiveness of RAS-1 and RAS-2 on the operating constraints. From these assessments, the hazard resulting from all severe contingencies has been overcome.

Reliability assessment has been concluded that the RAS-1 is the economically certificated scheme under N-1 criterion. The remedial actions of N-1-1 contingencies have been shown that the economically certificated RAS-1 is not technically supported under N-1-1 criterion. Reliability assessment has been concluded that the RAS-1 is also not economical under N-1-1 criterion. Therefore, RAS-2 has been selected as the certificated scheme under N-1-1 criterion.

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