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# Remedies Scheme for Single and Multiple Severe Contingencies of Transmission System

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***Abstract*—***An important factor in the power system planning/operation is the desire to maintain system security by examining the system performance in post contingency cases. The purpose of this paper is to study the effect of contingencies in terms of its severity to select and rank all severe contingencies and processing them into a secure operating state using a Remedial Action Scheme (RAS). All severe contingencies are selected and 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. This paper underlines the necessity of considering a remedies scheme in all severe contingencies to reach the test system configurations for secure operation following all contingencies. This work is implemented on IEEE 14 bus system in Digsilent software.*

**Keywords—**Post contingency cases; Remedial Action Scheme (RAS); Voltage Performance Index ($PI_V$)

## 1. INTRODUCTION

The most important factor in planning and operation of a power system is the desire to maintain system security [1] and [2]. Power system security aims to keep the system operating in normal conditions and especially in abnormal conditions of equipment's outage/contingency [1]. Contingency in a power system is termed as a disturbance resulting from the outages of one or more equipment such as generator, transmission line and transformer [2]. This disturbance may be sudden changes in the system configuration and result in severe violations of the operational constraints (i.e. Equipment overloads and bus voltage margin's violation) [3]. A secured system is one which has the ability to undergo a set of outages with the minimal disruption of service or its quality and without the occurrence of constraint violation [4].

An essential task in a power system is a security assessment which indicates the system state in the event of a contingency. One of the major aims of this assessment is to study the effect of contingencies in terms of its severity to select and rank all severe contingencies and to design remedial action schemes necessary to withstand these contingencies [5]. Consequently, planning for contingencies forms an important aspect of system security [6].

The N-1 contingency criterion is widely used since it requires the system to be able to withstand an outage of any single part of the network [7]. Furthermore, it is revealed in [8] that some blackouts were caused by independent system component outages at the same time. References [3] and [9] illustrated the importance of power system security assessment for prediction of line flows and bus voltages following a contingency, and summarized the challenges faced in the practical implementation of security analysis algorithms.

A contingency analysis technique using Newton Raphson Load Flow (NRLF) method is applied for each contingency to investigate the resulting effects on power flows and bus voltages of the remaining system. The purpose of this technique is to analyze the power system in order to identify the bus voltage problems and the element overloading that can occur due to a contingency. It provides tools for managing, creating, analyzing, and reporting lists of contingencies and associated violations in power system. Contingency analysis is a tedious task as a power system contains a large number of components. Contingency selection is an essential task in this analysis to reduce the numerous computations. Practically, only selected contingencies will lead to limit violations in the power flow and bus voltage magnitude, thus this process eliminates the least severe contingencies and shortens the contingency list. Contingency selection criterion based on the calculation of performance indices has been introduced by Ejebe and Wollenberg [10]. A contingency ranking algorithm is a procedure in which all severe contingencies are ranked in descending order, sorted out by the severity of contingency. Ranking is given by considering the OPI of test systems [3]. Contingency selection and ranking algorithm are mainly used to select and rank all severe contingencies from the contingency list [11].

RAS approach alleviates bus voltage limit violations by raising/lowering a controllable reactive power source and/or adjusting a transformer tap ratios. It is also, alleviates the overloading constraints by re-dispatching of generators, line switching actions, load transfer and load shedding. It permits the operators to modify the power system operation if a contingency analysis technique predicts a serious problem in the event of the occurrence of a certain outage. Reference [12] discusses a contingency analysis and fast remedial action program implemented in a personal computer environment using interactive graphics. Reference [13] studies the impacts of manual removing of transmission lines on composite system reliability.

Only considering most severe contingency cases are not sufficient as other less severe contingencies may need other RAS not needed in most severe contingencies. Therefore, in this paper remedies scheme in all severe contingencies is considered to reach a final test system configuration which successfully recovers from any kind of N-1 contingencies. Load flow assessment is performed on each corrected system to validate the perfect effectiveness of the proposed RAS on the system operating constraints. Reliability analysis is performed to examine the effect of equipment unavailability on the system reliability.

The N-1-1 Contingency analysis is performed on the corrected system in the most severe contingency cases to detect the robustness of the remedy scheme and to obtain the new remedies scheme for all N-1-1 severe contingencies. This proposed work is implemented on the IEEE 14 bus system in DIgSILENT Power Factory environment.

## 2. CONTINGENCY ANALYSIS

Contingency in a power system is termed as a disturbance resulting from the outage of one or more element, such as generators, transmission lines and transformers. Hence, contingency analysis is the study of the power system element outage to reveal its influence on the bus voltage profile and MW active power flows. It is a useful measure for power system security assessment to reveal which system element outage leads to the margin's violation.

Since contingency analysis involves the simulation of each contingency on the base case model of the power system, three major aspects are involved in this analysis. First is the development of the appropriate power system model, second is the choice of which contingency case to consider and third is the power flows and bus voltages computation which leads to enormous time consumption in the energy management system.

It is therefore apt to separate the off line contingency analysis into three different stages, namely contingency definition, selection and evaluation.

Contingency definition, comprises of the set of possible contingencies that might occur in a power system. It involves the process of creating the contingency list.

Contingency selection is a process of identifying the most severe contingencies from the contingency list that leads to violation in the power flows and bus voltage magnitude, thus this process eliminates the least severe contingencies and shortens the contingency list.

Contingency evaluation is then done which involves the RAS to mitigate the effect of most severe contingencies.

### 2.1 Performance Indices

The deviation of system variables such as line flows and bus voltages from its rated value is measured by the system performance indices [14]. To obtain the value of performance index (PI) for each contingency, a particular transmission line, transformer or a generator is simulated for outage condition and both of the individual power flow and the bus voltage are being calculated by NRLF method. There are three kinds of PI, which are of great use and shown as following.

#### 2.1.1 Voltage Performance Index ($PI_V$)

It reflects the bus voltage limit violations and provides a good measure of the severity of abnormal voltages as long as the generating units remain within their reactive power limits. It's mathematically given as:

$$PI_V=\sum_{i=1}^{N_{pq}} (0.5) * [\frac{(V_i-V_{inom})}{\Delta V_i^{lim}}]^2 \qquad (1)$$

Where:

$N_{pq}$ : Total number of load buses in the system.
$V_i$ : Post contingency voltage magnitude at bus $i$
$V_{inom}$ : Specified nominal voltage magnitude at bus $i$ (1 p.u).
$\Delta V_i^{lim}$: Voltage deviation limit = $(1/2)(V_{imax} - V_{imin}) = 0.05$.

For calculation of $PI_V$, it is required to know the maximum voltage limit $V_{imax}$ and minimum voltage limit $V_{imin}$, generally a margin of 5% is kept for assigning this deviation limit.

### 2.1.2 Active Power Performance Index ($PI_P$)

It reflects the active power limit violation of lines, transformers and generators. It mathematically given as:

$$PI_P = \sum_{i=1 \,\&\, j=1}^{L\_T} (0.5) * \left[\frac{P_{i,j}}{P_{i,jmax}}\right]^2; \quad P_{i,jmax} = \frac{V_i * V_j}{X_{i,j}} \qquad (2)$$

Where:

$L\_T$ : Total number of lines and transformers in the system.
$P_{i,j}$ : Active power flows in line $i$ and transformer $j$ respectively.
$P_{i,jmax}$: Maximum active power flows in line $i$ and transformer $j$ respectively.
$V_i$ , $V_j$ : Voltages at bus $i$ and bus $j$ obtained from NRLF solution.
$X_{i,j}$ : Reactance of the line $i$ or the transformer $j$ connecting bus $i$ and bus $j$.

### 2.1.3 Overall Performance Index (OPI)

It mathematically given as:

$$OPI = PI_V + PI_P \qquad (3)$$

## 3. REMEDIAL ACTION SCHEME

Remedial Action Scheme (RAS) permits the operators to modify the operation of the power system if a contingency analysis process predicts a serious problem in the event of the occurrence of a certain outage. RAS is classified into two major aspects, real power and reactive power re-scheduling for element overload correction and voltage limit violation correction respectively [12].

Within the real power re-scheduling aspect, three controlled elements of generator re-dispatching, line switching action and load shedding can be used in a descending order. In reactive power rescheduling, two corrective actions of raising or lowering a controllable reactive power source and adjustments to transformer tap ratios are used.

## 4. CASE STUDY

The proposed work is illustrated by application on IEEE 14 Bus System as shown in Fig. 1. The machines at buses 3, 6 and 8 are synchronous compensators. All data system have been taken from [15].

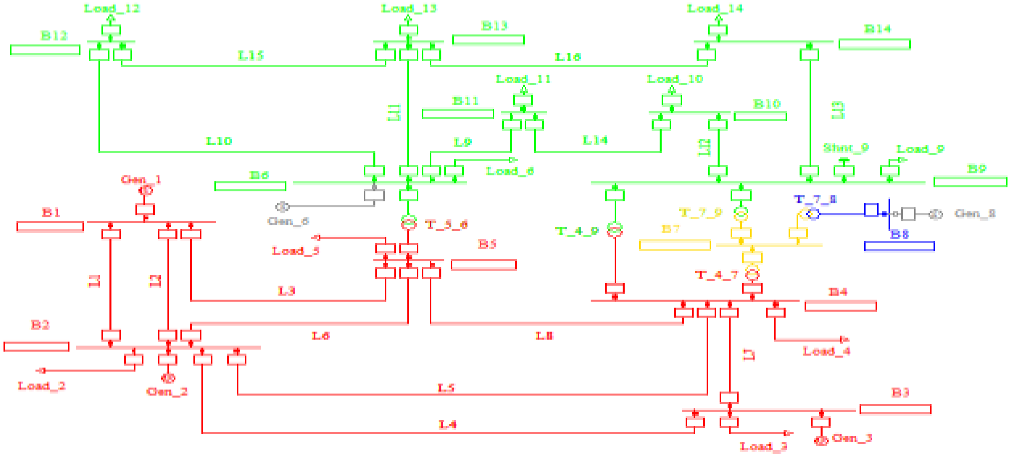

**Fig. 1.** *Single line diagram of IEEE14 bus system*

## 5. RESULTS AND DISCUSSION

Violations static of N-1 contingency as shown in Table 1 is specified according to the system operating constraints.

**Table 1**: Violations static of N-1 contingency

| Contingency Cases | Violations | Lower Voltage Limit |
|---|---|---|
| **L3** | 11 | 0.908 |
| **L4** | 5 | 0.900 |
| **L13** | 1 | 0.931 |
| **T_5_6** | 10 | 0.686 |

The main focus here is to perform the contingency selection process by calculating $PI_V$, $PI_P$ and OPI for each serious contingency. The performance indices and contingency ranking using NRLF is shown in Table 2.

**Table 2**: performance indices and contingency ranking

| Contingency Number | Severe Contingencies | $PI_V$ | $PI_P$ | OPI | Ranking |
|---|---|---|---|---|---|
| **1** | L3 | 11.54 | 0.0752 | 11.61 | 2 |
| **2** | L4 | 7.49 | 0.0890 | 7.58 | 3 |
| **3** | L13 | 1.3 | 0.0525 | 1.35 | 4 |
| **4** | T_5_6 | 99.36 | 0.1043 | 99.46 | **1** |

From Table 2, it can be deduced that contingency numbered 4 of T_5_6 will greatly impact the whole system, the highest value of OPI for this outage means that the highest attention must be taken during the operation. The graphical representation of PIv, PIp and OPI for all severe contingencies is shown in Fig. 2. Contingency ranking based on OPI is shown in Fig. 3.

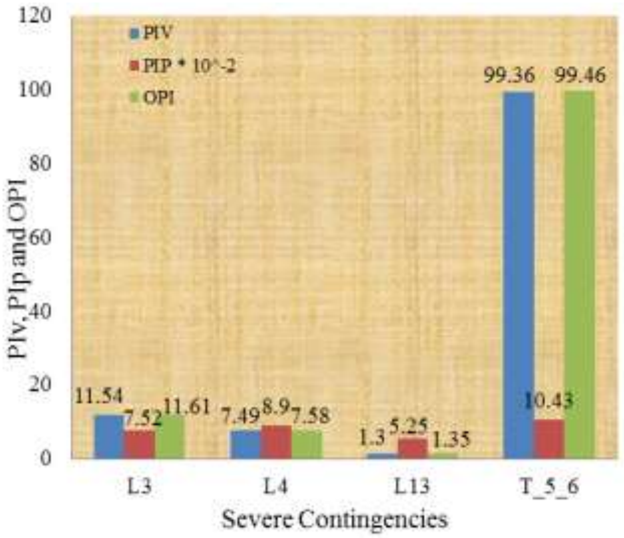

**Fig. 2.** *PIv, PIp and OPI values for all severe contingencies*

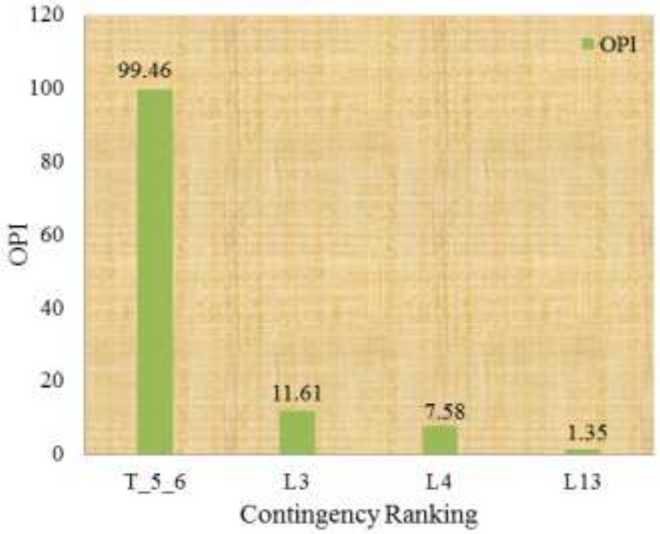

**Fig. 3.** *Contingency ranking based on OPI*

Post contingency analysis for the most severe contingency of T_5_6 has been performed for identifying the associated system violations. Pre and post contingency bus voltages have been detailed in Table 3. The MW active power flows corresponding to the pre and post contingency states have been detailed in Table 4.

**Table 3**: Pre and post contingency bus voltages

| Bus Number | Pre contingency Voltage (p.u) | Post contingency Voltage (p.u) |
|---|---|---|
| **B1** | 1.060 | 1.060 |
| **B2** | 1.041 | 1.022 |
| **B3** | 1.010 | 0.977 |
| **B4** | 1.001 | 0.949 |
| **B5** | 1.004 | 0.976 |
| **B6** | 1.023 | 0.698 |
| **B7** | 1.015 | 0.884 |
| **B8** | 1.015 | 0.884 |
| **B9** | 1.011 | 0.847 |
| **B10** | 1.005 | 0.811 |
| **B11** | 1.010 | 0.751 |
| **B12** | 1.007 | 0.686 |
| **B13** | 1.003 | 0.694 |
| **B14** | 0.989 | 0.754 |

**Table 4**: Pre and post contingency MW active power flows and loading percentage of lines and transformers

| System Component | Pre contingency MW Flows | (Loading %) | Post contingency MW Flows | (Loading %) |
|---|---|---|---|---|
| **L1** | 78.969 | (32.72) | 83.354 | (34.65) |
| **L2** | 78.969 | (32.72) | 83.354 | (34.65) |
| **L3** | 74.818 | (31.46) | 74.019 | (32.75) |
| **L4** | 74.235 | (31.19) | 78.511 | (33.89) |
| **L5** | 56.175 | (23.87) | 62.971 | (29.10) |
| **L6** | 41.504 | (18.10) | 38.666 | (18.12) |
| **L7** | 22.829 | (11.98) | 19.142 | (13.97) |
| **L8** | 61.216 | (27.28) | 101.15 | (47.44) |
| **L9** | 7.156 | (13.25) | 19.858 | (52.95) |
| **L10** | 7.751 | (13.90) | 3.973 | (10.57) |
| **L11** | 17.653 | (32.45) | 3.815 | (9.60) |
| **L12** | 5.426 | (12.57) | 34.147 | (85.20) |
| **L13** | 9.597 | (18.01) | 29.429 | (69.55) |
| **L14** | 3.602 | (6.490) | 24.392 | (62.11) |
| **L15** | 1.574 | (2.980) | 2.194 | (5.58) |
| **L16** | 5.493 | (9.880) | 12.521 | (33.37) |
| **T_4_7** | 28.194 | (28.64) | 58.942 | (77.85) |
| **T_4_9** | 16.328 | (17.00) | 34.134 | (46.11) |
| **T_5_6** | 43.761 | (50.41) | 0.0000 | (0.000) |
| **T_7_9** | 28.194 | (28.01) | 58.942 | (76.14) |

From Table 3, there are violated constraints in bus voltage magnitude. So, RAS, which can be considered as both of running/ connecting Gen_6 and adjusting the tap changer on T_4_9 is applied to solve and remedy these violations. Connecting of Gen_6 to the system leads to improve the voltage profile at all buses except both of B12 and B13 whose voltages remain outside allowable limits by 0.940 p.u and 0.941 p.u; and hence, the process of adjusting transformer tap changer on T_4_9 at the high voltage side to 5 % instead of 3.1 % is required to raise the voltage values to 0.951 p.u and 0.952 p.u.

Referring to Table 1 and Table 2, T_5_6 is the most severe contingency case, but it is also clear that L3, L4 and L13 contingencies have a serious impact on the system. Not only T_5_6 contingency case is correct but also these contingencies, to obtain all remedies scheme for all severe contingencies as shown in Table 5 and hence get the system back to its normal operation.

**Table 5**: Remedies scheme for all severe contingencies

| Severe Contingencies | Ranking | RAS Category | RAS |
|---|---|---|---|
| T_5_6 | 1 | $3^{rd}$ | •Connecting of Gen_6.<br>•Adjusting the tap changer on T_4_9 (- 5 %). |
| L3 | 2 | $2^{nd}$ | •Connecting of Gen_6. |
| L4 | 3 | $3^{rd}$ | •Connecting both of Gen_6 and Gen_8<br>•Adjusting the tap changer on T_5_6 (0.0 %) and T_7_8 (- 5 %). |
| L13 | 4 | $1^{st}$ | •Adjusting the tap changer on T_5_6 (- 10 %). |

RAS is divided into three main categories. The first category is the process of transformer tap ratios adjustment, the second category is the process of injection for reactive power sources while the third category combines the two previous categories. It is clear that the remedies of T_5_6 contingency case are necessary but not sufficient for all severe contingencies. Synchronous compensators of Gen_6 and Gen_8 cannot be disposed because they are required to remedy the severe contingencies of L3, L4 and T_5_6. Inserting these compensators to the system and adjusting the tap changer on several transformers represent the proper test system configuration to cover any kind of N-1 severe contingency case.

Both of load flow and reliability assessments are performed in the corrected system of the most severe contingency case to investigate the effectiveness of the proposed RAS. The corrected system bus voltages and MW active power flows of the lines and transformers are shown in Table 6 and Table 7 respectively.

**Table 6**: Corrected system bus voltages

| Bus Number | Corrected System Voltage (p.u) |
|---|---|
| **B1** | 1.060 |
| **B2** | 1.043 |
| **B3** | 1.010 |
| **B4** | 1.000 |
| **B5** | 1.015 |
| **B6** | 0.965 |
| **B7** | 1.007 |
| **B8** | 1.007 |
| **B9** | 1.004 |
| **B10** | 0.989 |
| **B11** | 0.974 |
| **B12** | 0.951 |
| **B13** | 0.952 |
| **B14** | 0.960 |

**Table 7**: Corrected system MW active power flows and loading percentage of lines and transformers

| System component | MW flows | (Loading %) |
|---|---|---|
| **L1** | 81.17 | (33.69) |
| **L2** | 81.17 | (33.69) |
| **L3** | 73.56 | (30.57) |
| **L4** | 76.85 | (32.25) |
| **L5** | 61.56 | (26.06) |
| **L6** | 37.66 | (16.05) |
| **L7** | 20.31 | (10.99) |
| **L8** | 100.2 | (43.26) |
| **L9** | 19.89 | (36.63) |
| **L10** | 4.340 | (9.85) |
| **L11** | 3.920 | (15.91) |
| **L12** | 33.22 | (58.58) |
| **L13** | 27.59 | (48.61) |
| **L14** | 23.87 | (42.29) |
| **L15** | 1.81 | (4.40) |
| **L16** | 11.71 | (22.00) |
| **T_4_7** | 56.77 | (57.83) |
| **T_4_9** | 33.54 | (35.69) |
| **T_5_6** | 0.000 | (0.000) |
| **T_7_9** | 56.77 | (56.56) |
| **T_7_9** | 56.77 | (56.56) |

The effect of equipment unavailability on system reliability is examined on the corrected system. This means that the remedies scheme for N-1-1 severe contingencies is obtained and analysed as shown in Table 8 to obtain the reliability indices. The load point and system reliability indices of this corrected system are shown in Table 9 and Table 10.

**Table 8**: Remedies scheme for N-1-1 severe contingencies of corrected system

| Severe Contingencies | RAS |
|---|---|
| L1 | • Adjusting the tap changer on T_4_9 (- 10 %). |
| L2 | • Adjusting the tap changer on T_4_9 (- 10 %). |
| L3 | • Connecting of Gen_8.<br>• Adjusting the tap changer on T_7_8 (- 5 %). |
| L4 | • Connecting of Gen_8.<br>• Adjusting the tap changer on T_7_8 (- 5 %), T_4_7 (- 4.4 %), T_7_9 (1 %) and T_4_9 (- 5 %).<br>• Load shedding of Load_3, P = 91 MW and Q = 18 Mvar. |
| L5 | • Connecting of Gen_8. |

| | |
|---|---|
| | •Adjusting the tap changer on T_7_8 (- 5 %). |
| L6 | •Adjusting the tap changer on T_4_9 (- 10 %). |
| L7 | •Adjusting the tap changer on T_4_9 (- 10 %). |
| L8 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_4_9 (- 10 %). |
| L9 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 5 %), T_4_7 (2.5 %), T_7_9 (2 %) and T_4_9 (- 10 %).<br>•Load shedding of Load_12, P = 4.5 MW and Q = 1 Mvar. |
| L10 | •Adjusting the tap changer on T_4_9 (- 10 %). |
| L11 | •Adjusting the tap changer on T_4_9 (- 10 %). |
| L12 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 5 %), T_4_7 (6.6 %) and T_4_9 (- 12.5 %).<br>•Load shedding of Load_6, P = 7.5 MW and Q = 3.5 Mvar,<br>•P and Q changed by - 3.7 MW and - 4 Mvar.<br>•Load shedding of Load_10, P = 0.0 MW and Q = 0.0 Mvar. |
| L13 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 10 %), T_4_7 (6.6 %), T_7_9 (- 3 %) and T_4_9 (- 10 %).<br>•Load shedding of Load_6, P = 0.0 MW and Q = 0.0 Mvar.<br>•Load shedding of Load_14, P = 9.4 MW and Q = 2 Mvar. |
| L14 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 5 %), T_7_9 (6 %) and T_4_9 (5 %).<br>•Load shedding of Load_6, P = 7.5 MW and Q = 3.5 Mvar. |
| L16 | •Adjusting the tap changer on T_7_9 (- 1 %) and T_4_9 (- 10 %). |
| T_4_7 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 5 %). |
| T_4_9 | •Connecting of Gen_8.<br>•Adjusting the tap changer on T_7_8 (- 5 %). |
| T_7_9 | •Adjusting the tap changer on T_4_9 (- 12.5 %).<br>•Load shedding of Load_9, P = 19 MW and Q = 16.6 Mvar. |

**Table 9**: Load point reliability indices of corrected system

| | **Corrected System** | | | | | |
|---|---|---|---|---|---|---|
| **Load Point** | LPIF (1/a) | LPIT (h/a) | AID (h) | EENS (Kwh/a) | IEAR ($/Kwh) | EIC (M$/a) |
| Load_3 | 0.0096 | 0.096 | 10 | 307.2 | 7.11305 | 0.002185129 |
| Load_6 | 0.1059 | 0.8472 | 8 | 3968.64 | 6.976 | 0.0276852332 |
| Load_9 | 0.015 | 1.8 | 120 | 18900 | 7.615567 | 0.1439342 |
| Load_10 | 0.046 | 0.368 | 8 | 3312 | 6.976 | 0.023104512 |
| Load_12 | 0.046 | 0.368 | 8 | 588.8 | 6.976 | 0.0041074688 |
| Load_14 | 0.0139 | 0.1112 | 8 | 611.6 | 6.976 | 0.004266522 |

**Table 10**: Corrected system reliability indices

| | **Corrected System** |
|---|---|
| SAIFI (1/Ca) | 0.0394 |
| SAIDI (h/Ca) | 0.5984 |
| CAIFI (1/aff.Ca) | 0.0394 |
| CAIDI (h) | 15.18782 |
| ASUI | 0.0000683105 |
| ASAI | 0.9999316895 |
| EENS (MWh/a) | 27.68824 |
| AENS (MWh/Ca) | 4.6147 |
| EIC (M$/a) | 0.2 |

| | |
|---|---|
| IEAR ($/kWh) | 7.25 |

## 6. CONCLUSION

Contingency analysis has been simulated in digsilent software to reveal which element outage leads to the margin's violation. Contingency selection and ranking algorithm have been done for IEEE 14 bus system by evaluating $PI_V$, $PI_P$ and OPI for each serious contingency to identify the most severe contingencies. From the results of $PI_V$ and OPI, it can be concluded that, T_5_6 contingency case is the most severe contingencies. Post contingency load flow analysis of T_5_6 has been performed for identifying the system thermal overloading and voltages violation. It can be further concluded that these violations require extra attention which can be achieved by applying the RAS of connecting Gen_6 to the system and adjusting the tap changer on T_4_9. Not only the most severe contingencies of T_5_6 has been corrected, but also all contingencies that have a serious impact on the system to specify the proper configuration of test system which dealing with any kind of N-1 contingency. Both of reliability and load flow assessments have been performed in the corrected system of T_5_6 to investigate the effectiveness of the proposed RAS.

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