International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2000-000X
Vol. 2 Issue 7, July – 2018, Pages: 34-41

Static Security Analysis of Transmission System

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Abstract—*Power system security is the ability of the system to withstand contingencies that contain one or more component outages with the minimal disruption of service or its quality. Maintaining power system security employs to examine the system performance in case of post contingency. Consequently, studying of contingencies forms an important aspect for system security. The purpose of this paper is to study the effect of contingencies in terms of its severity in order to identify the most severe contingencies and then processing it into a secure operating state using a remedial action scheme. To achieve this study, both of a preliminary system load flow and reliability assessments are performed to specify bus voltage, MW active power flows and obtain the system reliability indices. 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 voltage of the remaining system. This paper uses contingency selection and ranking technique to identify the most severe contingencies from the contingency list by calculating both of voltage performance index (*PI_V*) and active power performance index (*PI_P*) for each severe contingency in MATLAB environment. Remedial Action Scheme (RAS) is used to handle the effect of the most severe contingencies and return the system into a secure state of operation. Both of load flow and reliability assessments for the corrected system are performed to investigate the effectiveness of the proposed RAS on the system. This proposed work is implemented on IEEE 14 bus system with the help of Digsilent software.*

Keywords—Newton Raphson Load Flow (NRLF); voltage performance index (PI_V); Remedial Action Scheme (RAS)

1. Introduction

A reliable, continuous supply of electrical energy is an essential part of today's complex societies. All over the world, countries are expanding their power system networks in other to meet up with developmental challenges and this is accompanied by increased contingencies referring to disturbances such as transmission element outages or generator outages which may result in severe violations of the operating constraints and also cause sudden and large changes in both the configuration and the state of the system.

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 [1] and [2]. Furthermore, it is revealed in [3] that some blackouts were caused by independent system component outages at the same time.

An essential task is security assessment which gives the idea about the system state in the event of contingency. So it is required to survey the power system security in order to investigate a secure system and existence a capable operating system conditions to deal with any credible contingency and ensure that power system reliability is almost not affected by the most severity contingency after using the remedial action strategy.

Consequently, planning for contingencies forms an important aspect of secure operation [4] and one of the major aims of power system planning and its operation is to study the effect of contingencies in terms of its severity [5]. In order to perform this study, several procedures must be carried out.

Firstly, pre contingency load flow and reliability assessments are performed to indicate the system steady state performance (i.e. bus voltages, active power flows) and obtain the system reliability indices respectively.

Secondly, 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 elements 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 [6].

References [6] and [7] illustrated the importance of power system security assessment for prediction of line flows and bus voltages following a contingency, and summarized the challenges faced for the practical implementation of security analysis algorithms.

Contingency analysis is a tedious task as a power system contains 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.

Thirdly, contingency selection technique is applied for each severe contingency to identify the most severe contingencies from the contingency list by calculating two kinds of performance indices; voltage performance index (PI_V) and active power performance index (PI_P) in MATLAB environment. PI_P reflects the active power limit violations of system component and PI_V reflects the bus voltage limit violations. Contingency ranking is a procedure of contingency selection in which contingencies are arranged in descending order, sorted out by the severity of contingency and given by considering the overall performance index (OPI) which is the summation of PI_V and PI_P [7]. Based on the values obtained, the contingencies are ranked in a manner where the highest value of OPI is ranked first. Contingency selection criterion based on the calculation of performance indices has been introduced by Ejebe and Wollenberg [8] where the contingencies are sorted in descending order of the values of performance index (PI) reflecting their severity.

The contingency analysis is performed to achieve the development of remedial action strategies for contingency cases resulting in violations. Fourthly, Remedial Action Scheme (RAS) is used to handle the effect of the most severe contingencies and return the system into a secure state of operation.

Reference [9] discusses a contingency analysis and fast remedial action program implemented in a personal computer environment using interactive graphics. Reference [10] studies the impacts of manual removing of transmission lines on composite system reliability. For doing so, the existing model is extended to consider optimal transmission switching (OTS) as a remedial action. The model minimizes total damage cost imposed by load curtailments. The extended model is formulated in mixed integer linear programming (MILP) format that can be easily solved via commercial solvers.

Finally, both of load flow and reliability assessments for the corrected system are performed to investigate the effectiveness of the proposed RAS on the system. This proposed work is implemented on IEEE 14 bus system with the help of Digsilent software.

2. Power System Reliability Evaluation

The reliability of a power system can be described using two sets of reliability parameters. These are the load point reliability indices and the system reliability indices [11].

2.1 Load Point Reliability Indices

The component reliability data of failure rate (λ) and outage time (r) is used to determine the load point reliability indices. These indices are expected values and represent the long run average value.

$$\lambda_j = \sum_{i}^{n} \lambda_i \qquad (1/a) \tag{1}$$

$$u_j = \sum_{i}^{n} \lambda_i * r_i \qquad (h/a) \tag{2}$$

$$r_j = {u_j}/{\lambda_j} \qquad (h) \tag{3}$$

Both of λ_i and r_i are the failure rate and the average repair time of the component *i*. λ_j, r_j and u_j are the average failure rate, repair time and unavailability at load point *j*.

2.2 System Reliability Indices

Additional reliability indices will be calculated in order to obtain an overall representation of the systems performance and their reliability [12] and [13] as following:

- System Average Interruption Frequency Index (SAIFI)

  This is a measure of the average frequency of interruptions experienced by the system.

  $$SAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\Sigma \lambda_j\ *\ N_j}{\Sigma\ N_j} \quad (1/Ca) \qquad (4)$$

- System Average Interruption Duration Index (SAIDI)

  This is a measure of the average duration of interruption experienced by the system.

  $$SAIDI = \frac{total\ \ customer\ interruption\ durations}{total\ number\ of\ customers\ served} = \frac{\Sigma u_j\ *\ N_j}{\Sigma\ N_j} \quad (h/Ca) \qquad (5)$$

- Total Energy Not Supplied (EENS)

  $$EENS = \sum L\ (Disconnected\ Load\ (MW)) * u\ (hr/yr) \quad (MWh/a) \qquad (6)$$

- Expected Interruption Cost Index (ECOST)

  $$ECOST = L(Disconnected\ Load\ (MW) * \Sigma\ (\ f(r) * \lambda\ ) \quad (K\$/a) \qquad (7)$$

  Where $f(r)$ *is the SCDF (sector customer damage function in $/kW)*

- Interrupted Energy Assessment Rate Index (IEAR)

  $$IEAR = ECOST\ /\ EENS = f(r) * \lambda_j\ /u_j \quad (\$/kWh) \qquad (8)$$

3. CONTINGENCY ANALYSIS

Contingency in 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 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 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 voltages 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.

3.1 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.

3.1.1 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 mathematically given as:

$$PI_V = \sum_{i=1}^{N_{pq}} (0.5) * [\frac{(V_i - V_{inom})}{\Delta V_i^{lim}}]^2 \qquad (9)$$

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).
ΔV_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.

3.1.2 Active Power Performance Index (PI_P)

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

$$PI_P = \sum_{i=1 \,\&\, j=1}^{L\_T} (0.5) * [\frac{P_{i,j}}{P_{i,jmax}}]^2; \quad P_{i,jmax} = \frac{V_i * V_j}{X_{i,j}} \qquad (10)$$

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.

3.1.3 Overall Performance Index (OPI)

It mathematically given as:

$$OPI = PI_V + PI_P \qquad (11)$$

4. 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 [9].

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.

5. 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.

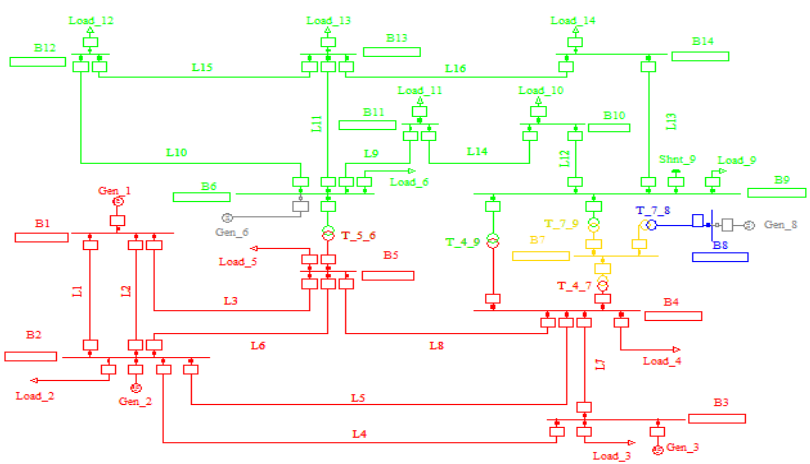

Fig. 1. *Single line diagram of IEEE14 bus system*

The bus data and load data of test system have been taken from [15]. The line data and transformer data are shown in Table 1 and Table 2 respectively.

Table 1: Line data of IEEE 14 bus system

From bus	To Bus	Line number	R (Ω)	X (Ω)	R (p.u)	X (p.u)	λ (1/a)	r (h)
1	**2**	**L1**	6.753542	20.619560	0.03876	0.11834	0.011820	10
1	**2**	**L2**	6.753542	20.619560	0.03876	0.11834	0.011820	10
1	**5**	**L3**	9.414187	38.862490	0.05403	0.22304	0.009273	10
2	**3**	**L4**	8.187537	34.494280	0.04699	0.19797	0.009600	10
2	**4**	**L5**	10.12509	30.722000	0.05811	0.17632	0.009273	10
2	**5**	**L6**	9.922968	30.296850	0.05695	0.17388	0.009273	10
3	**4**	**L7**	11.67582	29.800270	0.06701	0.17103	0.009273	10
4	**5**	**L8**	2.326104	7.337246	0.01335	0.04211	0.020625	35
6	**11**	**L9**	1.034332	2.166021	0.09498	0.19890	0.046	8
6	**12**	**L10**	1.338490	2.785771	0.12291	0.25581	0.0139	8
6	**13**	**L11**	0.720374	1.418640	0.06615	0.13027	0.046	8
9	**10**	**L12**	0.346411	0.920205	0.03181	0.08450	0.046	8
9	**14**	**L13**	1.384228	2.944439	0.12711	0.27038	0.0139	8
10	**11**	**L14**	0.893524	2.091643	0.08205	0.19207	0.046	8
12	**13**	**L15**	2.405819	2.176693	0.22092	0.19988	0.0139	8
13	**14**	**L16**	1.861428	3.789938	0.17093	0.34802	0.0139	8

Table 2: Transformer data of IEEE 14 bus system

From Bus	To Bus	Transformer Number	Ur (HV) KV	Ur (LV) KV	X (p.u)	λ (1/a)	r (h)
4	**7**	**T_4_7**	132	1	0.20912	0.001	168
4	**9**	**T_4_9**	132	33	0.55618	0.003	130
5	**6**	**T_5_6**	132	33	0.25202	0.003	130
7	**8**	**T_7_8**	11	1	0.17615	0.015	200
7	**9**	**T_7_9**	33	1	0.11001	0.015	120

6. Results and Discussion

Violations static of N-1 contingency as shown in Table 3 is specified according to the system operating constraints.

Table 3: Violations static of N-1 contingency

Contingency cases	Violations	Maximum loading %	Upper voltage Limit	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 PIV, PIP and OPI for each serious contingency. The performance indices and contingency ranking using NRLF is shown in Table 4.

Table 4: performance indices and contingency ranking

Contingency number	Contingency cases	PI_V	PI_P	OPI	Ranking
1	L3	11.5348	0.0752	11.610	2
2	L4	7.4938	0.0890	7.5828	3
3	L13	1.2982	0.0525	1.3507	4
4	T_5_6	99.358	0.1043	99.4623	**1**

From Table 4, 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. Post contingency analysis for this 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 5. The MW active power flows corresponding to the pre and post contingency states have been detailed in Table 6.

Table 5: 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 6: 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 5, there are violated constraints in bus voltages 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 high voltage side to 5 % instead of 3.1 % is required to rise the voltage values to 0.951 p.u and 0.952 p.u. Both of load flow and reliability assessments are performed for the corrected system to investigate the effectiveness of the proposed RAS. The corrected system bus voltages and MW active power flows of lines and transformers are shown in Table 7 Table 8 respectively.

Table 7: 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 8: 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 load point reliability indices of pre contingency and corrected system states are shown in Table 9. The system reliability indices of pre contingency and corrected system states are shown in Table 10.

Table 9: Pre contingency and corrected system load point reliability indices

	Pre contingency system			**Corrected system**		
Load Point	**LPIF (1/a)**	**LPIT (h/a)**	**AID (h)**	**LPIF (1/a)**	**LPIT (h/a)**	**AID (h)**
Load_2	0.023640	0.011820	0.5	0.000000	0.000000	0.0
Load_3	0.033240	0.241200	7.256318	0.009600	0.004800	0.5
Load_4	0.018546	0.009273	0.5	0.018546	0.009273	0.5
Load_5	0.039171	0.019586	0.5	0.039171	0.019586	0.5
Load_6	0.003000	0.001500	0.5	0.021546	0.098867	4.588624
Load_9	0.000000	0.000000	0.0	0.021546	0.010773	0.5
Load_10	0.046000	0.023000	0.5	0.067546	0.378773	5.607630
Load_11	0.092000	0.046000	0.5	0.113546	0.056773	0.5
Load_12	0.013900	0.006950	0.5	0.035446	0.105817	2.985288
Load_13	0.059900	0.029950	0.5	0.081446	0.128817	1.581619
Load_14	0.027800	0.013900	0.5	0.049346	0.128923	2.612633

Table 10: Pre contingency and corrected system reliability indices

	Pre contingency system	Corrected system
SAIFI (1/Ca)	0.031208	0.041613
SAIDI (h/Ca)	0.024	0.059
CAIFI (1/aff.Ca)	0.034328	0.045774
CAIDI (h)	0.769	1.428
ASUI	0.0000027402	0.0000067816
ASAI	0.9999972598	0.9999932184
ENS (MWh/a)	11.502	7.155
AENS (MWh/Ca)	1.046	0.650
EIC (M$/a)	0.027	0.036
IEAR ($/kWh)	2.332	5.039

7. CONCLUSION

Contingency analysis has been simulated in digsilent software by forced outage for each element in order to reveal which element outage leads to margin's violation. Contingency selection and ranking which are important procedures for contingency analysis to identify the most severe contingencies have been done for IEEE 14 bus system by evaluating PIV, PIP and OPI for each serious contingency. From the results of PIV 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. Both of reliability and load flow assessments have been performed for the corrected system to investigate the effectiveness of the proposed RAS. From the load flow assessment, the hazard resulting from T_5_6 has been overcome and there is no bus voltages violation. From the reliability assessment, it can be deduced that both of interruption duration and expected interruption cost are closer to that indices of base case operating system.

8. CONCLUSION

In future work, not only the most severe contingencies of T_5_6 should be corrected, but also the contingencies that have a serious impact on the system. The purpose of this work is to specify the proper configuration of test system which dealing with any kind of N-1 contingency.

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