Static Security Assessment of Large Power Systems Under N-1-1 Contingency

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***Abstract*—Contingency analysis (CA) is one of the critical tools of a static security assessment (SSA). It is used to forecast the operating states of a power system under one or more outages of generators, transmission lines, transformers, etc. To perform SSA, repetitive load flow analyses are required for obtaining the bus voltages, bus injections, and line flows considering each possible outage. A repetitive load flow analysis demands huge computational efforts like efficient system modelling for faster load flow solutions, parallel programming and High performance computing (HPC). In this paper, an N-1-1 CA has been analysed using fast decoupled load flow (FDLF) with a strategy of screening and ranking the catastrophic contingencies. This paper explores a computationally efficient method to analyze the severity and the ranking of N-1-1 contingencies for large power system SSA. The performance of the FDLF based SSA method is demonstrated on two standard IEEE 14 and 118 bus systems.**

***Index Terms*—Contingency Ranking, Contingency Screening, Line Flows, Load Flow, Outage, Remedial Action, Static Security Assessment.**

I. Introduction

In wide area power systems, the security assessment plays a major role in reliable power supply. The static security assessment(SSA) is used to make appropriate control and operational decisions in the power system during element outage(s). However, performing SSA using the conventional approach is computationally challenging for larger power systems. The accurate SSA can be performed using repeated load flow analysis, which provides a steady state solution of the power system such as voltage magnitude, angles, bus injection and power flows transmission lines etc. Load flow analysis is a Non-Linear and computationally intense tool in the power system. There are many methods for load flow analysis such as Gauss-Seidel, Newton Raphson load flow (NRLF), fast decoupled load flow (FDLF) etc. Among these methods, the NRLF is the most accurate but computationally intensive, whereas FDLF is slightly less accurate with a significant reduction in computational burden. So FDLF methods are often used for SSA using contingency analysis (CA) [1], [2].

Contingency in a power system is be defined as an outage (or) loss of an element (or) combination of elements in the power system such as generators, transformers, or transmission lines. These outages can be planned or unplanned [3]. During the CA, any limit violations observed in transmission lines power flows or bus voltages for each outage are recorded. This information is used for preparing a necessary corrective action to ensure stable and reliable operation of the system during such outages in real time. For a system having N number of elements, N-1 CA corresponds to the analysis when any single element outage has occurred and N-k CA corresponds to a simultaneous outage of k elements. Whereas, the N-1-1 CA corresponds to the sequential outage of two system elements, where the second outage occurs after the necessary remedial/corrective action is taken for the first contingency [4]. In N-1-1 contingency, the operator performing has prior knowledge about the critical N-1 outages and corresponding actions to be taken in order to mitigate the effects of that outage. However, there can be possibilities of another outage after corrective action, which can be referred to as N-1-1 contingency. These sequential outages may have a strong impact on the system which might lead to severe blackouts. For the N-element system, the number of possibilities of N-1-1 Contingency is N*(N-1). Thus, performing N-1-1 Contingency analysis will be computationally challenging for large power systems. This mandates the need for computationally efficient SSA algorithms [5].

In [6] a contingency screening and ranking method using NRLF are proposed. In [7], line outage sensitivity factors (LOSF) and generator outage sensitivity factors (GOSF) are used for faster computation. A CA technique based on the network topology analysis has been proposed in [8]. In [9] contingency ranking based on Exact and Precise methods was used. These papers have been focused on efficiently ranking all possible contingencies during static security analysis without omitting any critical case contingency.In [10], [11], [12], [13], [14], various performance indices (PI) to estimate the severity of outage using post contingent values have been given for N-1 static security assessment. These methods use partial/approximate methods to identify the limit violations.

In this paper, the main focus of CA is on contingency selection i.e., from the list of possible contingency cases selecting the outage cases with the most severe limit violations. To reduce the list of possible contingency cases, two methods namely, Contingency ranking and Contingency screening are employed. The former uses a performance index to rank the outage severity, the effect of that particular outage on the system can be unfolded. The latter uses a distribution factor for a particular outage and prioritizes the most severe outage cases according to that distribution factor, eliminating the non-severe outage cases.

The Major Contributions in this work are:

1) Performing SSA using fast and approximate algorithms like FDLF.
2) Usage of Contingency screening and methods to identify important severe/critical cases for further analysis.
3) Consider the necessary corrective/remedial actions prior to the creation of a secondary outage to ensure n-1 reliability.

The rest of the paper is organized as follows: Section II describes the Complete Methodology considered in this work for performing N-1-1 Contingency specifically about Load Flow Analysis technique, Contingency Screening and ranking method and Remedial/Corrective Actions Considered. The Simulations results for IEEE 14,118 bus systems were depicted and described in Section III. Section IV presents the conclusion and future scope that can be extended in this work.

II. System Modelling

A. N-1-1 Contingency

For a large power system network with N elements, there will be $N(N-1)$ number of outage contingency cases for the N-1-1 static security assessment. For each case, power flow equations are to be solved to get the current state of the system which is indeed computationally challenging [15].

B. Load Flow Analysis

Load Flow Analysis is the non-linear power flow analysis which is calculated iteratively by solving the set of sparse linear equations, Ax = b [16]. To account for the arising computational challenges in the system, FDLF is chosen to be the best algorithm. FDLF uses a constant Jacobian Matrix in each iteration unlike NRLF which modifies its Jacobian matrix in each iteration, so the complexity in computational perspective is also reduced by using the FDLF. [1] The basic FDLF equations are as follows:

$$\frac{\Delta P}{|V|} = B^{'} \Delta\delta \tag{1}$$

$$\frac{\Delta Q}{|V|} = B^{''} \Delta|V| \tag{2}$$

Where, $\Delta|V|$ & $\Delta\delta$ represents change in voltage magnitude and angle respectively. The coefficient matrices $B^{'}$ and $B^{''}$ are the constant matrix and are derived from the admittance matrix, Y. ΔP & ΔQ represent the change in Active and Reactive Power at each bus respectively. It is known as a power mismatch. Using FDLF algorithm, the state of the power system network in all possible contingency cases was analyzed. To make the system much more computationally efficient, it is essential to identify the critical cases in the order of severity w.r.t line flow violations and bus voltage limit violations.

C. Contingency Screening

A systematic approach to screening the possible N-1-1 contingency cases is required to identify the most critical contingencies. These critical sequential N-1-1 contingencies are needed to be analyzed on priority. Based on the FDLF, a contingency screening method is implemented. Significant changes in the line power flow and voltages at buses after a particular outage indicate the compensation for the outage of an element in the system [4]. It increases the computational burden to perform the load flow analysis for each possible N-1-1 contingency case. To reduce the computational burden, a line outage distribution factor(ACLODF) using AC load flow is implemented with considerable accuracy. Screening of secondary transmission line or generator outages which makes critical N-1-1 Contingencies are analyzed using pre and post-contingent load flows after the primary outage.

$$S_{LODF,ij} = \left(\frac{S_{ij} - S_{base,i}}{S_{base,j}}\right) * 100 \tag{3}$$

Where,
$S_{LODF,ij}$ - Percentage of MVA flow through j^{th} line that shows upon i^{th} line.
S_{ij} - MVA flow on line i^{th} for j^{th} line outage.
$S_{base,i}$ - Base case MVA flow on i^{th} line.
$S_{base,j}$ - Base case MVA flow on j^{th} line.

Steps to screen the contingencies are listed below:

1) Input selected IEEE system data.
2) Run the base case load flow i.e., pre contingent load flow.
3) Create N-1 Contingency i.e., Line outage and Generator outage and run the load flow for each individual outage. Note down the results obtained in each case.
4) calculate ACLODF using eq. (3) and screen the cases which are violating the threshold limit. These screened cases account for critical N-1-1 contingency.

D. Contingency Ranking

After screening all the possible contingencies, it is required to rank all possible contingencies according to the severity of the impact on the system. Ranking contingencies based on performing load flow post contingency helps the operator to identify the most critical outages in the system and to take immediate necessary action to ensure the stable operation of the system. To estimate the severity in the system, a performance index, PI which is a combination of Voltage performance index, PI_V and Active Power performance Index, PI_P is proposed and is given by the following eq 4 and 6:

$$PI = PI_P + PI_V \tag{4}$$

$$PI_P = \sum_{i=1}^{nl} \frac{W_i^P}{2\alpha} \left(\frac{S_i}{S_{base,i}}\right)^{2\alpha} \tag{5}$$

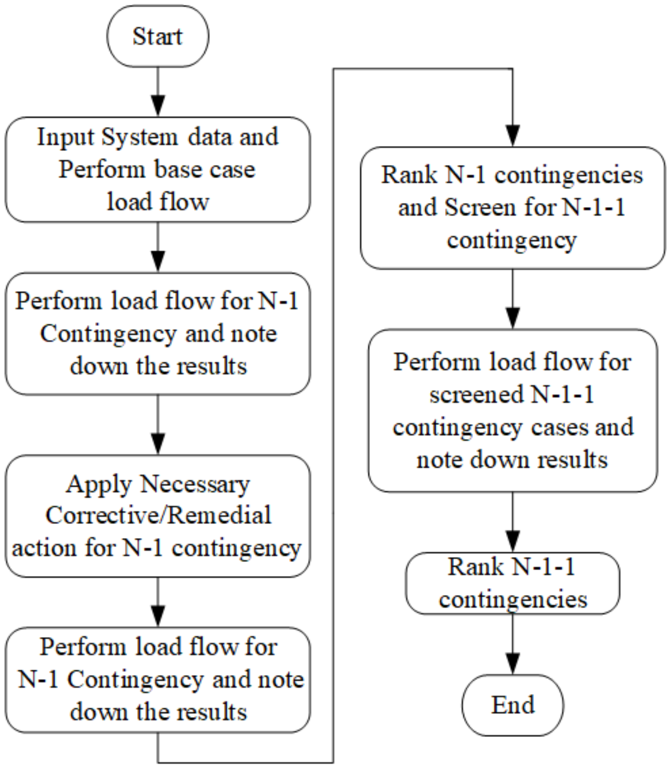

Fig. 1: Flow chart for contingency screening and ranking

$$PI_V = \sum_{i=1}^{nb} \frac{W_i^V}{2\alpha} \left(\frac{V_i - V_{base,i}}{\Delta V_{limit}} \right)^{2\alpha} \tag{6}$$

Where,
S_i - MVA flow in i^{th} line during contingency.
$S_{base,i}$ - Base MVA flow value for the i^{th} line.
V_i - Post contingency voltage at i_{th} bus.
$V_{base,i}$ - Base Voltage obtained in pre-contingency load flow.
ΔV_{limit} - (=0.05) maximum of 5% variation is accepted.
W_l^P - Weighting factor for i^{th} line.
W_i^V - Weighting factor for i^{th} bus.

Steps to rank the contingencies are listed below:

1) Input selected IEEE system data.
2) Run the base case load flow i.e., pre contingent load flow.
3) Create N-1 Contingency i.e., Line outage and Generator outage and run the load flow for each individual outage. Note down the results obtained in each case.
4) Calculate Voltage and Active Power Performance Indices using eq. (5) and eq. (6) for each individual Outage.
5) Calculate the Performance Index using eq. (4) and rank them in descending order.
6) For N-1-1 Contingency, repeat steps 4 & 5 for each N-1 Contingency with their respective screened secondary outages.

E. Remedial Action

As discussed N-1-1 contingency analysis is the sequential events of two contingencies so prior to the application of the second contingency, system adjustments (or) necessary corrective actions are to be taken based on the primary contingency to achieve N-1 reliability. In [17], a security constrained unit commitment problem has been implemented to achieve the system reliability. In [18], a security-constrained optimal power flow (SCOPF) is implemented for over-stressed power systems as a corrective measure. In [19], transmission switching combined with optimal power flow with mixed integer non-linear problem (MINLP) to reduce the effects of transmission congestion. The main objective of this paper is to work in all ways to reduce the computational time and burden on the system. So rather than using the complex day-ahead analysis algorithms, basic system adjustments were considered as corrective actions for the online SSA. The adjustment/remedial actions considered are:

1) Varying Active(P_{gen}) Power Generation within the limits.
2) Varying Reactive (Q_{gen}) Power Generation within the limits.
3) Using Shunt/Series Compensation techniques
4) Transformer tap changing

III. Results and Discussion

In this section, MATLAB simulations using sequential computation are performed on a 64-bit Windows operating system with Intel(R) Core(TM) i7-7500U CPU Processor with 2.70GHz frequency and 16GB RAM. Contingency screening and ranking methods described in Section-II were tested on standard IEEE 14, 118 bus systems.

A. Test Case1: IEEE 14 Bus System

An IEEE 14 Bus system with 14 buses, 5 generators and 20 transmission lines and 9 loads was selected for the demonstration of static security assessment under the N-1-1 contingencies. The total No. of components is 25 (i.e., No. of Generators and Transmission lines). No. of possible and screened cases of N-1 and N-1-1 Contingencies for the 14-bus system were listed in Table I. In this system, the outage of Line-14 (Bus-7&8) results in the singular jacobian matrix so load flow analysis calculation is not possible. Hence, the line-14 outage is considered to be the most critical contingency and is given the highest priority.

TABLE I: List of contingency cases for IEEE 14 Bus System

No. of Possible N-1 Contingency Cases	25
No. of Possible N-1-1 Contingency Cases	600
No. of Screened N-1-1 Contingency Cases	80

Table II shows the Performance Indices values and ranks of line and generator outages i.e., N-1 contingencies on IEEE 14 bus system pre and post applying the necessary remedial actions for each outage and the numbers in brackets in the

TABLE II: Ranking N-1 Contingencies on IEEE 14 Bus System

Outage	PI_P	PI_V	PI	Rank	Remedial Action	PI_P	PI_V	PI	Rank
Line-01(1-2)	38.13	0	38.13	4	Increasing Active Power (P_{gen}) Generation at Bus-2&3	16.61	0	16.61	20
Line-02(1-5)	22.15	0	22.15	16	Increasing Active Power (P_{gen}) Generation at Bus-1,2&3 Adding Shunt Element at Bus-5	15.91	0.04	15.95	24
Line-03(2-3)	35.81	1	36.81	5	Increasing Active Power (P_{gen}) Generation at Bus-3	15.60	1	16.60	21
Line-04(2-4)	22.98	0	22.98	15	Increasing Active (P_{gen}) Power Generation at Bus-3 Increasing Reactive (Q_{gen}) Power Generation at Bus-3 Adding Reactive Component at Bus-5	18.09	0	18.09	18
Line-05(2-5)	19.24	0	19.24	23	Increasing Active Power (P_{gen}) Generation at Bus-1,2&3 Adding reactive Component at Bus-4	16.31	0.01	16.32	23
Line-06(3-4)	21.05	0.15	21.20	18	Increasing Active Power (P_{gen}) Generation at Bus-2&3	19.17	0.15	19.32	15
Line-07(4-5)	33.45	0.25	33.70	8	Increasing Active Power (P_{gen}) Generation at Bus-1,2&3	16.34	0.25	16.59	22
Line-08(4-7)	35.16	0	35.16	7	Increasing Active Power (P_{gen}) Generation at Bus-2&3 Adding Shunt Element at Bus-9&10 Changing Tap Positions of Transformers on line-9	28.07	0.82	28.89	5
Line-09(4-9)	24.98	0	24.98	13	Changing Tap Positions of Transformers on lines-8&10	27.87	0.09	27.96	7
Line-10(5-6)	86.15	0.07	86.22	2	Increasing Active Power (P_{gen}) Generation at Bus-1,2&3	80.86	0.07	80.93	2
Line-11(6-11)	23.86	0.13	23.99	14	-	23.86	0.13	23.99	11
Line-12(6-12)	32.28	0.08	32.36	9	Increasing Active Power (P_{gen}) Generation at Bus-2&3 Increasing Reactive Power Generation at Bus-2	27.60	0.08	27.68	8
Line-13(6-13)	77.46	0.45	77.91	3	-	77.46	0.45	77.91	3
Line-14(7-8)	**	**	**	1	”No Remedial Action”	**	**	**	1
Line-15(7-9)	35.19	0.07	35.26	6	-	35.19	0.07	35.26	4
Line-16(9-10)	25.90	0.24	26.14	11	-	25.90	0.24	26.14	9
Line-17(9-14)	28.57	0.18	28.75	10	-	28.57	0.18	28.75	6
Line-18(10-11)	20.46	0.01	20.47	21	Adding Reactive Component at Bus-10	18.53	0.28	18.81	17
Line-19(12-13)	18.85	0	18.85	24	-	18.85	0	18.85	16
Line-20(13-14)	20.92	0.02	20.94	20	-	20.92	0.02	20.94	13
Generator-01(@Bus-1)	18.66	0.19	18.85	25	Increasing Active Power Generation at Bus-2 & 3	15.70	0.19	15.89	25
Generator-02(@Bus-2)	21.78	0.19	21.97	17	Increasing Active Power Generation at Bus-3	16.99	0.19	17.18	19
Generator-03(@Bus-3)	22.98	2.07	25.06	12	-	22.98	2.07	25.05	10
Generator-04(@Bus-6)	20	0	20	22	-	20	0	20	14
Generator-05(@Bus-8)	20	1	21	19	-	20	1	21	12

outage column correspond to the bus numbers between which the line exists and the bus number at which the generator exists. Table III displays the most severe N-1-1 screened contingencies in the IEEE 14 bus test system.

B. Test Case1: IEEE 118 Bus System

IEEE 118 Bus System with 118 buses, 54 generators and 186 transmission lines and 64 loads were represented in a single line diagram as shown in the fig.3. The total No. of components is 240 (i.e., No. of Generators and Transmission lines). No. of possible and screened cases of N-1 and N-1-1 Contingencies for the 118-bus system were listed in Table 2. In this system Outage of Lines-9 (Bus-9 & Bus-10), 113 (Bus-71 & Bus-73), 133 (Bus-85 & Bus-86), 134 (Bus-86 & Bus-87), 176 (Bus-110 & Bus-111), 177 (Bus-110 & Bus-112),183 (Bus-68 & Bus-116), 184 (Bus-12 & Bus-117) results in singular Jacobian matrix so that load flow analysis calculation is not possible. so Line-9,113,133,134,176,177,183,184 Outages are considered to be most critical/severe, are given highest priority and excluded from calculation part.

Table V shows the Performance Indices values and Ranks of Line and Generator Outages i.e., N-1 Contingencies on IEEE 118 bus system pre and post applying the necessary corrective/remedial actions for each outage and the numbers in brackets in the outage column corresponds to the bus numbers between which the line exists and the bus number at which the generator exists. Table IV displays the most severe N-1-1 screened contingencies of the IEEE 118 bus system.

TABLE III: Top Ten N-1-1 Contingencies on IEEE 14 Bus System

N-1-1 Contingency		PI_P	PI_V	PI
Outage-1	Outage-2			
Line-17(9-14)	Line-20(13-14)	702.82	5.44e+03	6.15e+03
Line-16(9-10)	Line-18(10-11)	138.49	5.44e+03	5.58e+03
Line-12(6-12)	Line-19(12-13)	122.87	5.44e+03	5.56e+03
Line-16(9-10)	Line-11(6-11)	107.49	5.44e+03	5.55e+03
Line-10(5-6)	Gen-02(Bus-2)	4.78e+03	0.16	4.78e+03
Line-10(5-6)	Gen-03(Bus-3)	3.26e+03	1.95	3.25e+03
Line-10(5-6)	Gen-05(Bus-8)	3.25e+03	1	3.25e+03
Line-10(5-6)	Gen-04(Bus-6)	3.25e+03	0	4.78e+03
Line-8(4-7)	Gen-02(Bus-2)	931.52	0.75	932.27
Line-12(6-12)	Gen-02(Bus-2)	705.70	0.19	705.89

Fig. 2: List of Contingency cases for IEEE 118 Bus System

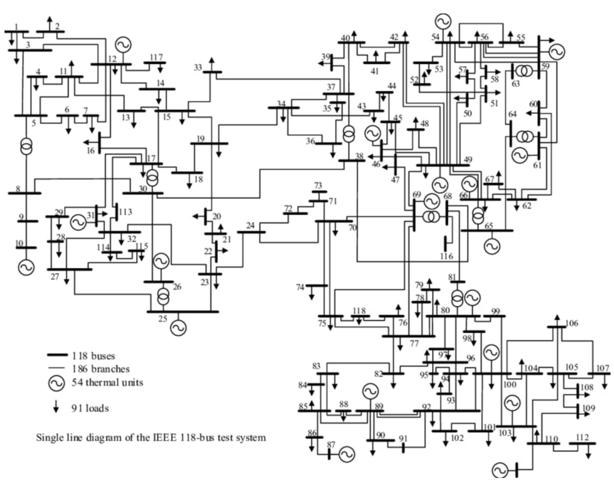

Fig. 3: Network Diagram of IEEE 118 Bus System

No. of Possible N-1 Contingency Cases	240
No. of Possible N-1-1 Contingency Cases	57360
No. of Screened N-1-1 Contingency Cases	100

TABLE IV: Top ten N-1-1 Contingencies on IEEE 118 Bus System

N-1-1 Contingency		PI_P	PI_V	PI
Outage-1	Outage-2			
Gen-11(Bus-25)	Line-96(38-65)	1.61e+08	0.06	1.61e+08
Gen-5(Bus-10)	Line-107(68-69)	2.06e+07	0.02	2.06e+07
Gen-11(Bus-25)	Gen-5(Bus-10)	5.44e+06	2	5.44e+06
Line-54(30-38)	Line-37(8-30)	2.46e+06	0.07	2.46e+06
Line-96(38-65)	Gen-05(Bus-10)	1.78e+06	2	1.78e+06
Gen-12(Bus-26)	Line-107(68-69)	1.53e+06	0.02	1.53e+06
Gen-40(Bus-89)	Line-107(68-69)	9.58e+05	0.02	9.58e+05
Line-107(68-69)	Gen-05(Bus-10)	7.53e+05	1.80	7.53e+05
Line-54(30-38)	Gen-05(Bus-10)	7.41e+05	2	7.41e+05
Line-107(68-69)	Line-67(42-49)	5.83e+05	10	5.83e+05

C. Discussions

In the above subsections, An efficient SSA method was tested on IEEE 14,118 bus systems. In the table- II & V the necessary corrective/remedial actions taken for each outage are listed in remedial action column. These remedial actions are which has a considerable impact on the system reliability under N-1 contingency. The remedial action for each outage on these systems includes changing tap positions of transformers and adding shunt components, active and reactive power scheduling of the generators etc. The empty rows in the remedial action column of table-II& V show that there is no any such corrective/remedial action for that outage to make significant changes in power flows to enhance the N-1 reliability.

IV. Conclusions & Future Scope

This paper mainly focuses on the reduction of computational complexity in the SSA of large power systems under the N-1-1 contingency. For effective SSA contingency screening and ranking, methods are used. The former uses an outage distribution factor to represent the effect of an outage on the power flow through the transmission line and the latter uses performance indices based on transmission line flows and bus voltages values pre and post contingencies to screen and rank the outages respectively. In N-1-1 contingency prior to the creation of the second contingency, necessary remedial actions like changing the tap position of transformers, varying the active and reactive power of generators, usage of shunt/series compensation techniques etc., have been taken based on the severity of the N-1 contingency.

In this work, a sequential computation procedure is implemented for SSA. To accelerate the computation time of the static security assessment, a state-of-the-art technology, High-Performance Computing (HPC) will be used where this model can be used in Parallel computing and distributed computing.

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TABLE V: Top Ten N-1 Contingencies on IEEE 118 Bus System

Outage	PIp	PIv	PI	Rank	Remedial Action	PIp	PIv	PI	Rank
Line-107(68-69)	1.68e+05	0.02	1.68e+05	1	Increasing Active Power Generation at Bus-3,12,76,77,80 &100 Adding Reactive Component at Bus-14,20,29,41,44,50	1.49e+05	0.02	1.49e+05	3
Line-96(38-65)	1.57e+05	0.07	1.57e+05	2	Increasing Active Power Generation at Bus-1,4,12,24,25,26,27,56,65,66,46,49	745.10	0.06	745.16	10
Generator-5(@Bus-10)	2.22e+04	2	2.22e+04	3	Increasing Active Power Generation at Bus-18,19,46,70,72	5.52e+03	2	5.52e+03	2
Line-54(30-38)	1.50e+04	0.07	1.50e+04	4	Increasing Active Power Generation at Bus-18,24,26,49,80,100	1.0e+03	0.08	1.0e+03	9
Generator-12(@Bus-26)	7.88e+04	0.23	7.88e+04	5	-	7.88e+04	0.23	7.88e+04	1
Line-7(8-9)	4.83e+03	0.04	4.83e+03	6	Increasing Active Power generation at Bus-15,15,19,24,2731,32,40,42,77,99,113 Adding Shunt Components at Bus-2,23,71,81,82	2.43e+03	0.04	2.43e+03	8
Generator-11(@Bus-25)	4.42e+03	5	4.42e+03	7	Increasing Active Power Generation at Bus-40,46,65,66,70,72	960.47	5	965.47	15
Generator-40(@Bus-89)	3.29e+03	0.67	3.29e+03	8	Increasing Active Power Generation at Bus-40,42,46,70	2.98e+03	0.67	2.98e+03	4
Line-51(38-37)	2.90e+03	0.74	2.90e+03	9	-	2.90e+03	0.74	2.90e+03	6
Line-141(89-92)	2.48e+03	39	2.52e+03	10	-	2.48e+03	39	2.52e+03	7

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