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Power System Contingency Analysis to detect Network Weaknesses

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Abstract

Steady state power system insecurity such as transmission lines being overloaded causes transmission elements cascade outages which may lead to complete blackout. The power system operator must know the system state at any instant. The contingency analysis is used to predict which contingencies make system violations and rank the contingencies according to their relative severity. Contingency Analysis is useful both in the network design stages and for programmed maintenance or network expansion works to detect network weaknesses. The weaknesses can be strengthened by transmission capacity increase, transformers rating increase besides circuit breakers ratings increase. This work outlines mathematical models for the simulation of generator outages and transmission line and transformer outages so as to carry out a full AC load flow based contingency analysis and ranking. The method has been applied to Sudan National Grid (NG) and gives good results in determining the network weaknesses and suggesting the new transmission lines and transformers capacities which ensures better power system security.

1. Introduction

Contingency analysis is the study of the outage of elements such as transmission lines, transformers and generators, and investigation of the resulting effects on line power flows and bus voltages of the remaining system. It represents an important tool to study the effect of elements outages in power system security during operation and planning. Contingencies referring to disturbances such as transmission element outages or generator outages may cause sudden and large changes in both the configuration and the state of the system. Contingencies may result in severe violations of the operating constraints. Consequently, planning for contingencies forms an important aspect of secure operation. [1]

Contingency analysis allows the system to be operated defensively. Many of the problems which occur in the power system can cause serious troubles within a short time if the operator could not take fast corrective action. Therefore, modern computers are equipped with contingency analysis programs which model the power system and are used to study outage events and alert the operators of potential overloads and voltage violations [1].

The most difficult methodological problem to cope within contingency analysis is the accuracy of the method and the speed of solution of the model used. The operator usually needs to know if the present operation of the system is secure and what will happen if a particular outage occurs. Approximate models can be used as the DC load flow with respect to megawatt flows. When voltage is concern, full AC load flow analysis is required. The literature reviews in contingency analysis gave information about many methods that can be used to perform the contingency analysis. For seek of accuracy, full AC load flow analysis is performed post each outage using the outage simulation to obtain post-outage line flows and bus voltages.

Operations personnel must recognize which line or generator outages will cause power flows or voltages to go out of their limits. In order to predict the effects of outages, contingency analysis technique is used. Contingency analysis procedures model a single equipment failure event, that is one line or one generator outage, or multiple equipments failure events, that is two transmission lines, a transmission line and a generator, one after another in sequence until all credible outages have been studied. For each outage tested, the contingency analysis procedure checks all power flows and voltage levels in the network against their respective limits [1]. Figure (1) shows the single line diagram of Sudan National Grid which is used in this paper.

2. National Grid Data

National Grid data are given in Tables (1), (2) and (3). Figure (1) illustrates the single line diagram of Sudan National Grid.

Table (1) Generation Data:

Bus Number	Voltage (pu)	Active Power (MW)
1	1.0	---
5	1.0	360
7	1.0	180
18	1.0	180
19	1.0	14

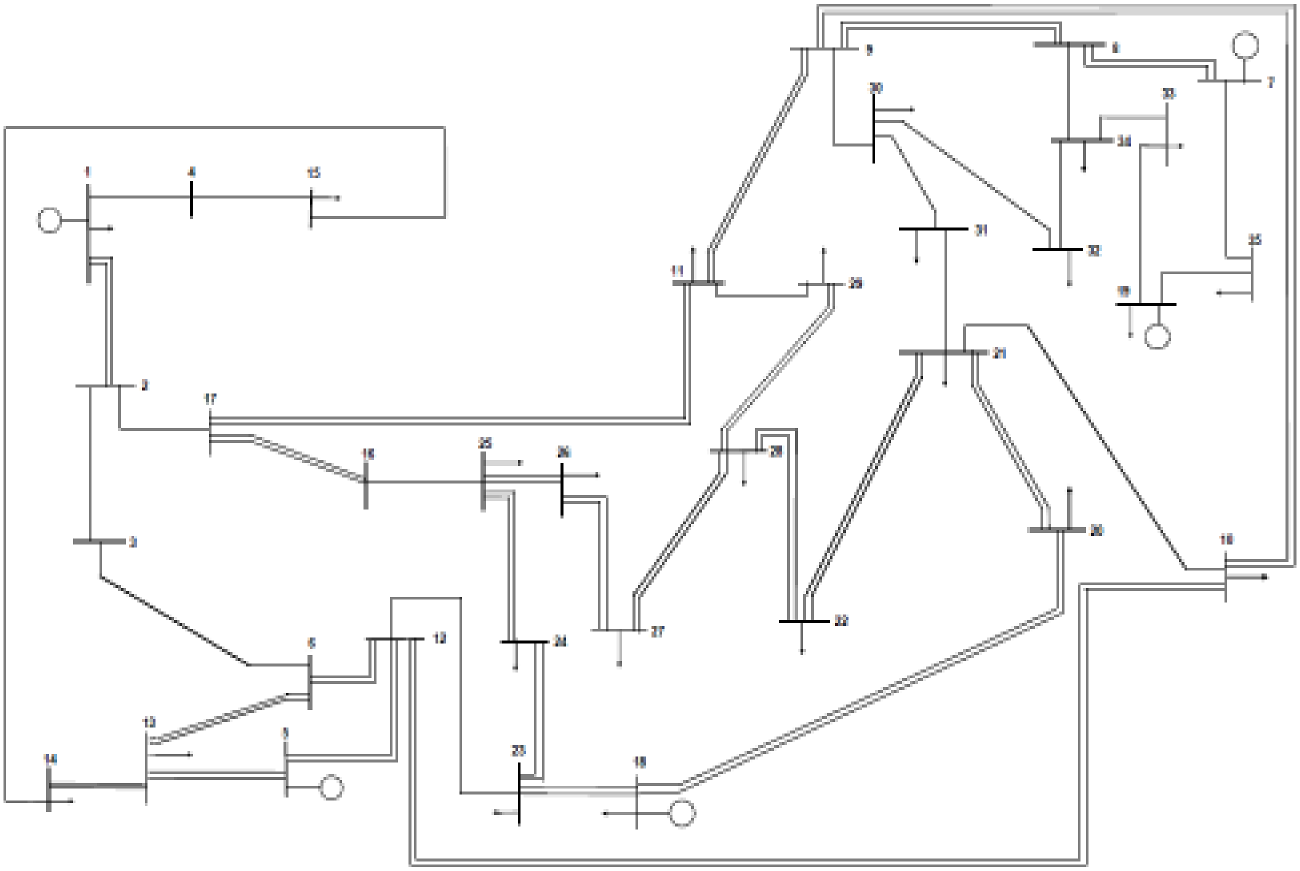

Figure (1) Sudan National Grid

Table (2) Load Data

Bus Number	Active Power (MW)	Reactive Power (MVAR)
1	35.5	21
2	0	0
3	0	0
4	0	0
5	0	0
6	30	15
7	0	0
8	0	0
9	0	0
10	0	0
11	24	12
12	0	0
13	6	3
14	15	6
15	49	33
16	0	0
17	40	15
18	35	25
19	35.1	20.2
20	93	52
21	52	32
22	43	28
23	40	21
24	39	12
25	83	45
26	40	21
27	40	24
28	44	30
29	14	7
30	10	14
31	24	10
32	37	15
33	30	20
34	38	18
35	12	5

Table (3) Line and Transformer Data

From	To	R (pu)	X (pu)	B(pu)	P_{Max} (MW)
1	2	0.0019	0.0189	0.1048	3133
1	4	0.0024	0.0232	0.1578	1566
2	3	0.0004	0.0042	0.7800	1566
2	17	0.0000	0.0848	0.0000	255
3	6	0.0000	0.0848	0.0000	255
4	15	0.0000	0.0848	0.0000	255
5	12	0.0042	0.0187	0.2382	810
5	13	0.0003	0.0016	0.0198	810
6	12	0.0021	0.0094	0.1192	810
6	13	0.0018	0.0081	0.1032	810
7	8	0.0066	0.0350	0.2304	551
7	35	0.0000	0.0698	0.0000	104
8	9	0.0111	0.0587	0.3868	551
8	34	0.0000	0.0339	0.0000	77
9	10	0.0034	0.0179	0.1180	551
9	11	0.0025	0.0112	0.1430	810
9	30	0.0000	0.1395	0.0000	117
10	12	0.0010	0.0044	0.0556	810
10	21	0.0000	0.0187	0.0000	194
11	17	0.0053	0.0237	0.3016	810
11	29	0.0000	0.0660	0.0000	128
12	23	0.0000	0.0579	0.0000	389
13	14	0.0080	0.0359	0.4566	810
14	15	0.0097	0.0437	0.5558	810
16	17	0.0014	0.0063	0.0794	810
16	25	0.0000	0.0630	0.0000	255
18	20	0.0016	0.0070	0.0032	311
18	23	0.0033	0.0133	0.0120	405
19	33	0.1726	0.2088	0.0196	52
19	35	0.0288	0.0348	0.0032	52
20	21	0.0052	0.0229	0.0106	311
21	22	0.0022	0.0087	0.0078	405
21	31	0.0805	0.0974	0.0092	52
22	28	0.0008	0.0033	0.0038	405
23	24	0.0089	0.0356	0.0318	405
24	25	0.0022	0.0089	0.0080	405
25	26	0.0026	0.0103	0.0092	405
26	27	0.0027	0.0108	0.0096	405
27	28	0.0030	0.0122	0.0110	405
28	29	0.0100	0.0400	0.0358	405
30	31	0.0086	0.0104	0.0010	52
30	32	0.2215	0.2679	0.0252	52
32	34	0.1582	0.1914	0.0180	52
33	34	0.1007	0.1218	0.0114	52

3. Contingency Analysis

The AC load flow analysis used to perform contingency analysis can be termed *AC contingency analysis routine.* The advantage of AC contingency analysis routine is that it provides the post-outage power factor of the branch power flows besides detecting the bus voltage limit violations post contingencies.

A set of single and multiple contingencies are performed on Sudan National Grid using full AC load flow analysis applying the simulation of lines and generators outage. Line power flow is said to be violated when the actual power flow post contingency exceeds the line flow limits which depend on the protection relay settings. Some contingencies lead to line flow violations, and some of them do not lead to any violations.

Probability of single contingencies occurrence is higher than that of multiple contingencies occurrence, but for maintenance and transmission system expansion, scheduled and planned outages may include dropping out of multiple elements. Thus it is important to study multiple outages effect as well as single outages. The programming of the above procedure for contingency analysis is straightforward and has been implemented in MATLAB.

4. Simulation of Line Outage

The simulation of transmission line outage is carried out by the formulation of the corresponding admittance matrix [3]. Assume that the line connected between buses *m* and *n* will be outage. The elements of the admittance [*Y*] matrix that will be affected are Y_{mm}, Y_{nn}, Y_{mn}, and Y_{nm}, and the new values of those admittances for the (π) mode of representation of transmission lines will be given by:

$$Y'_{mm} = Y_{mn} - \frac{1}{(R_{mn}+jX_{mn})} - \frac{jB_{mn}}{2} \quad (1)$$

$$Y'_{nn} = Y_{nn} - \frac{1}{(R_{nm}+jX_{nm})} - \frac{jB_{nm}}{2} \quad (2)$$

$$Y'_{mn} = Y_{mn} - \frac{1}{(R_{mn}+jX_{mn})} = 0.0 \quad (3)$$

$$Y'_{nm} = Y_{nm} - \frac{1}{(R_{nm}+jX_{nm})} = 0.0 \quad (4)$$

Where:

Y'_{mm},Y_{mm}: Self admittance at bus m post and pre-contingency.

Y'_{nn}, Y_{nn} : Self admittance at bus n post and pre-contingency.

$Y'_{mn} = Y'_{nm}$: Mutual admittance between bus *m* and *n* post contingency.

$Y_{mn} = Y_{nm}$: Mutual admittance between bus *m* and *n* pre-contingency.

5. Simulation of Generating Unit Outage

This simulates mainly outage of one unit (or more) in a power station. Let the total generation for the station at bus (*m*) be P_{gm}, and assume that there exist identical (*g*) units, then:

$$P'_{gm} = P_{gm} - n\frac{P_{gm}}{g} \quad (5)$$

Where:

P'_{gm} : Active power generated at bus m post the outage.

P_{gm} : Active power generated at bus m before the outage.

n : Number of outage generation units in the station.

$\frac{P_{gm}}{g}$: Active power generated at bus m per a generator unit.

6. Contingency Ranking

In practice, electric power engineers use their judgment and past experience for selecting and investigating severe contingencies. In some instants, however, this approach may not identify all of the critical contingencies especially in large systems. Therefore, the development of a contingency ranking algorithm which would rank contingencies based upon their relative severity is desirable. The contingencies can be ranked based upon their effects on line loading or bus voltages [4].

A variety of algorithms are developed which can be classified into two groups. One is the performance index (*PI*) based method [5], [6] which utilizes a wide system scalar performance index to quantify the severity of each case by calculating their *PI* values and ranking them accordingly. The other is the screening method [7], [8] which is based on approximate power flow solutions to eliminate those non-critical contingencies. With the advancement of artificial intelligence, expert systems and fuzzy theory are proposed to estimate the severity of various contingencies [9]. Also artificial neural networks approaches based on (*PI*) have been proposed for contingency selection. In this study contingencies are ranked using a *PI* based method.

System performance indices are not unique and obtain different forms depending on the parameters that are of most importance to the engineer. However in selecting a *PI*, physical properties of the system should be taken into consideration. The most common form of system performance indices give a measure of the deviation from rated values of system variables such as line flows, bus voltages and bus power injections.

The ranking method used in this paper is a fast and accurate method to rank the contingencies according to their severity on the power system. The ranking technique utilizes a system wide scalar *PI* to quantify the severity of each contingency with actually calculating the post contingency line flows and bus voltages using full AC load flow analysis. Contingencies are ranked in the order of their performance index values and processed starting with the most severe contingency at the top of the list proceeding down the ranking to the less severe ones. The performance indices are calculated for contingency cases with real flow violations and voltage violations. The masking problem is successfully addressed by changing the exponent of the performance index from 2 to higher values. The post contingency line flows and bus voltages are obtained from the load flow solution after the application of the outage simulation. The exponent (*m*) of the performance index is changed in the range from 2 to 30 to avoid masking errors. Outages are then ranked on the basis of their corresponding performance indices. In this study the contingencies are ranked on the basis of line loading.

For the active line flow ranking, it is straight forward; the performance index will be the accumulation of the post contingency line flow over the line limit. Any overloaded line will make the fraction greater than one. This will increase the value of the performance index, and so specify the lines which need to be paid more attention. If there are many lines operating near their limit the value of the Active Power Loading Performance Index (APLPI) will increase while there may be another case which is one line overloaded but the value of the APLPI is small. This occurs with small values of (*m*) and leads to miss-ranking where severe contingencies appear as not severe and vise versa. This error is known as masking error and it decreases as the value of (*m*) increases.

The system performance index is a measure that can be used to evaluate relative severity of a contingency. Due to the weak coupling between real power and reactive power equations, two separate performance indices are defined. A contingency may be severe in the point view of line loading but do not affect the system bus voltages and vise versa.

6.1 Active Power Loading Performance Index (*APLPI*)

APLPI is the active power loading performance index corresponding to line real power flow violations. It is formulated by (6) and gives measure of line MW overloads [4].

$$APLPI = \sum_{i=1}^{NL} W_{pi} \left(\frac{P_{ipc}}{P_{iLim}} \right)^{2m} \tag{6}$$

Where:

P_{ipc} : The post-contingency active power flow on line (i)
P_{iLim} : The active power flow limit on line (i)
W_{pi} : The weight factor of active power flow on line (i)
NL : Number of transmission lines.
m: Is a positive integer.

7 Results and Discussion of Contingency Ranking

Contingencies are ranked according to their relative severity using the *APLPI*. The most severe contingencies are ranked at the top of the list and the non severe contingencies at the end.

7.1 Results of Contingency Ranking using *APLPI*

Forty four contingencies have been done and the results of contingency ranking are shown in Table (4). Figure (2) shows the curves of all contingencies, the curves are *APLPI* against the exponent (*m*) and it is seen that for severe contingencies the value of *APLPI* increases with (*m*).

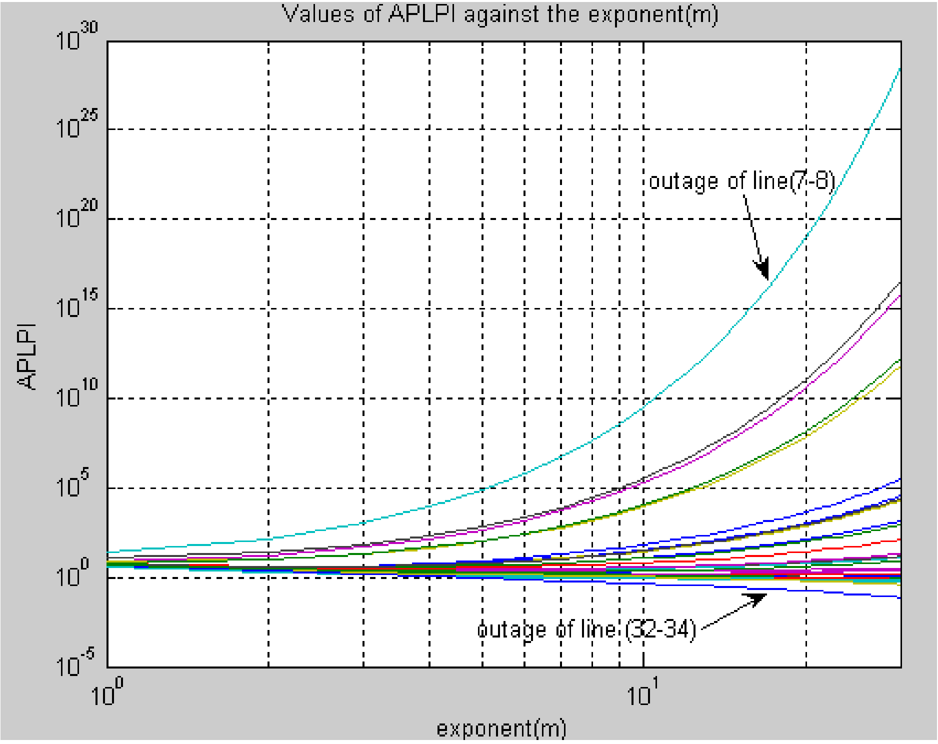

Figure (2) *APLPI* curves of all contingencies against the exponent (*m*)

Table (4) Contingencies Ranking using *APLPI* with (*m*=30)

Outage Element		APLPI with *m*=30
From	To	
7	8	2.95 X 10^{28}
8	34	3.81 X 10^{16}
7	35	7.04 X 10^{15}
19	35	1.84 X 10^{12}
8	9	6.43 X 10^{11}
19	33	2.81 X 10^{5}
12	23	3.45 X 10^{4}
30	32	2.45 X 10^{4}
18	20	1.88 X 10^{4}
9	10	1.27 X 10^{3}
9	11	8.88 X 10^{2}
9	30	1.25 X 10^{2}
16	17	19.50
16	25	19.30
11	29	14.50
2	17	12.00
33	34	8.000
28	29	3.000
21	31	2.900
10	21	2.540
20	21	1.610
1	2	1.190
24	25	0.960
22	28	0.930
3	6	0.920
2	3	0.910
23	24	0.907
11	17	0.907
4	15	0.907
1	4	0.907
6	12	0.890
14	15	0.880
13	14	0.880
5	12	0.870
6	13	0.860
5	13	0.860
18	23	0.850
25	26	0.850
26	27	0.810
27	28	0.710
21	22	0.700
10	12	0.590
30	31	0.390
32	34	0.070

7.2 Contingency Analysis Results For the most severe contingencies

It is found that there are 21 severe contingencies (Single element or double elements). Table (5) shows the results of the power flows in the overloaded elements of the network in case of the most severe contingencies.

8. Determinations of the Network Weaknesses

Generally, results of contingency analysis give an idea about weak lines whose capacity must be increased mainly in projects of transmission system improvements to withstand contingencies, and to ensure secure operation during contingencies [10]. Network weaknesses are the lines or transformers which always become overloaded in case of different outages. Based on the probability of outage occurrence, the network most weak element is the transformer between bus-bars 8-34, 16 different outage cases lead to this transformer overload. It is found that the highest percentage loading is (183.8 %). Table (6) shows the second weakest element which is the transmission line connecting bus-bars 10-21, where 10 different outage cases lead to this line overload with highest percentage loading equal to (119 %). Table (6) shows the network weaknesses ranked based on number of outages lead to lines overload starting with the weakest element besides each element highest percentage loading.

Whereas based on the worst transmission capacity selected during the network design, the weaknesses can be considered in the manner of the largest value of percentage loading. According to that the network weakest element is the transformer between bus-bars 19-35. Table (7) shows the network weaknesses ranked based on the largest percentage loading starting with the weakest element besides each element highest percentage loading.

Table (5) the power flows in the overloaded elements for the severe contingencies

Outaged Element		APLPI (m=30)	Overloaded Elements		Actual Flow (MW)	Maximum Flow Limit (MW)	Amount of Overload (MW)	Percentage Loading
From	To		From	To				
7	8	$2.95X10^{28}$	19	35	155.0	52.0	103.0	298 %
			19	33	134.0	52.0	82.0	258 %
			7	35	180.0	104.0	76.0	173 %
			33	34	69.8	52.0	17.8	134.2 %
8	34	$3.81X10^{16}$	19	35	98.3	52.0	46.3	189 %
			19	33	77.2	52.0	25.2	148.5 %
			30	32	61.8	52	9.8	118.8 %
			7	35	116.9	104	12.9	112.4 %
7	35	$7.04X10^{15}$	8	34	141.5	77	64.5	183.8 %
			33	34	69.6	52	17.6	133.8 %
19	35	$1.84X10^{12}$	8	34	123.3	77	46.3	160 %
			33	34	54.1	52	2.1	104 %
8	9	$6.43X10^{11}$	8	34	121.1	77	44.1	157.3 %
			32	34	60.5	52	8.5	116.3 %
19	33	$2.81X10^{5}$	8	34	94.9	77	17.9	123.2 %
12	23	$3.45X10^{4}$	10	21	230.9	194	36.9	119 %
			8	34	77.1	77	0.1	100.1 %
30	32	$2.45X10^{4}$	8	34	91.1	77	14.1	118.3 %
18	20	$1.88X10^{4}$	10	21	228.6	194	34.6	117.8 %
			8	34	78.2	77	1.2	101.6 %
9	10	$1.27X10^{3}$	10	21	218.5	194	24.5	112.6 %
9	11	$8.88X10^{2}$	10	21	217.2	194	23.2	112 %
			8	34	78.2	77	1.2	102 %
9	30	$1.25X10^{2}$	8	34	83.4	77	6.4	108.3 %
			10	21	195.7	194	1.7	100.9 %
16	17	19.50	10	21	203.7	194	9.7	105 %
			8	34	77.01	77	0.01	100.01 %
16	25	19.30	10	21	203.6	194	9.6	104.9 %
			8	34	77.02	77	0.02	100.03 %
11	29	14.50	10	21	202.4	194	8.4	104.3 %
			8	34	77.9	77	0.9	101.2 %
2	17	12.00	10	21	202.0	194	8.0	104.1 %
33	34	8.000	19	35	53.8	52	1.8	103. 5 %
28	29	3.000	8	34	77.8	77	0.8	101.04 %
			10	21	194.6	194	0.6	100.3 %
21	31	2.900	8	34	78.4	77	1.4	101.8 %
10	21	2.540	8	34	78.2	77	1.2	101.6 %
20	21	1.610	8	34	77.6	77	0.6	100.8 %

Table (6) Weaknesses ranked based on number of outages lead to overloads

Overloaded Elements		Number of outages lead to overload	Highest Percentage Loading
From	To		
8	34	16	183.8 %
10	21	10	119 %
19	35	3	298 %
33	34	3	134.2 %
19	33	2	258 %
7	35	2	173 %
30	32	1	118.8 %
32	34	1	116.3 %

Table (7) Weaknesses ranked based on the largest percentage loading

Overloaded Elements		Number of outages lead to overload	Highest Percentage Loading
From	To		
19	35	3	298 %
19	33	2	258 %
8	34	16	183.8 %
7	35	2	173 %
33	34	3	134.2 %
10	21	10	119 %
30	32	1	118.8 %
32	34	1	116.3 %

9. Network Strengthening and Security Improvement

To strengthen the network and improve its flow security the weak transmission lines and transformers power handling capacity should be increased. Table (8) shows the power flows in the overloaded elements for the most severe contingencies using new capacities for the weak transmission lines and transformers. Figure (3) shows *APLPI* curves of all contingencies against the exponent (*m*) after increasing weak elements capacity, it is clear that values of *APLPI* here decrease when *(m)* increases.

Table (8) power flows in the overloaded elements for the most severe contingencies using new capacities for the weak transmission lines and transformers

Overloaded Elements		Old Flow Limit P_{Max} (MW)	Actual Flow (MW)	New Flow Limit P_{Max}(MW)	Old Highest % Loading	New Highest % Loading
From	To					
19	35	52.0	155.1	156.0	298 %	99.4 %
19	33	52.0	134.0	135.0	258 %	99.3 %
8	34	77.0	141.5	142.0	183.8 %	99.6 %
7	35	104.0	180.0	181.0	173 %	99.4 %
33	34	52	69.6	70.0	134.2 %	99.4 %
10	21	194	230.9	233.0	119 %	99.1 %
30	32	52	61.8	62	118.8 %	99.7 %
32	34	52	60.5	62	116.3 %	97.6 %

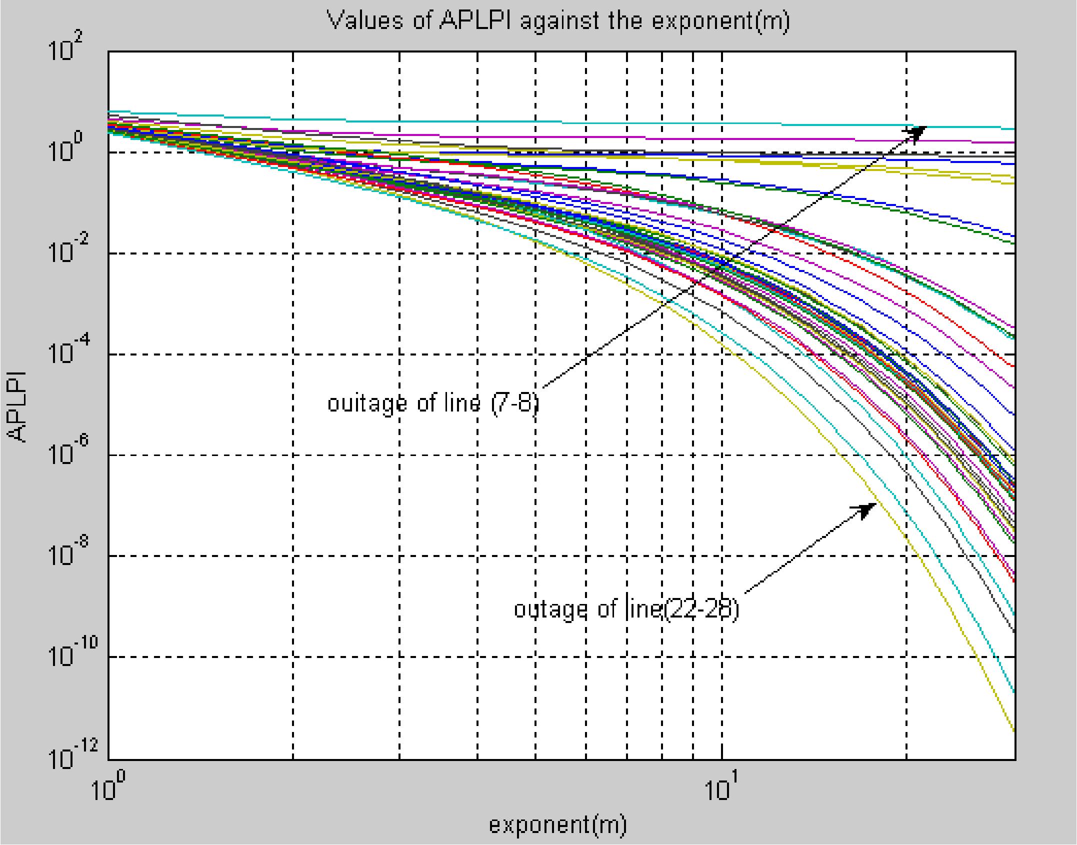

Figure (3) *APLPI* curves of all contingencies against the exponent (*m*) after increasing weak elements capacity

10. Conclusion

Contingency analysis is performed for Sudan National Grid and the weaknesses of the transmission system have been detected and the new capacities have been suggested. The new capacities ensure better power system security should any single contingency or any of the set of multiple contingencies occurs.

References

[1] Wood, A. J.; Wallenberg, B. F., “Power Generation, Operation and Control”. *2nd ed., New York/USA: John Wiley& Sons*, 1996, pp. 410-432.

[2] Arthur R. Bergen, “Power Systems Analysis”*, Prentice-Hall Series in Electrical and Computer Engineering*, 1986, pp. 130-134.

[3] Yaser Nadhum Al-Aani, “Generation Rescheduling for Alleviating Overloads caused by Contingency”, *M. Sc. Thesis. Baghdad University, Baghdad, Iraq*, 1999.

[4] Emtethal N. Abdallah “Contingency Ranking in Static Security Assessment”, *Eights Middle East Power Systems Conference MEPCON’2001*, Cairo, Egypt, pp 13-19, December 2001.

[5] F. Albuyeh, A. Bose and B. Heath, “Reactive Power Considerations in Automatic Contingency Selection”. *IEEE Trans. On Power Apparatus and Systems, Vol. PAS – 101, No. 1*, pp. 107-112, Jan. 1982

[6] K. Nara, K. Tanaka, H. Kodama, R. R. Shoults, M. S. Chen, P. Van Olinda and D. Bertagnolli, "On-Line Contingency Selection for voltage Security Analysis", *ibid, Vol. PAS – 104*, pp. 847-856, April 1985.
[7] Hiroyuki Mori, Hideya Tanaka and Junya Kanno, "A Preconditioned Fast Decoupled Power Flow Method for Contingency Screening"*, ibid, pp.357-363*, Feb.1996.
[8] Shanggou Hao, Alex Papalexopoulos and Tie-Mao Peng, "Distributed Processing for Contingency Screening Applications," *IEEE Trans. On Power Systems, Vol. 10, No.* 2, pp. 838-844, May 1995.
[9] A. S. Maouche and Neil Adams, "Expert System Approach for Security Assessment of Electrical Power Network", *Fifth Middle East Power Systems Conference MEPCON'97*, Alexandria, Egypt, pp. 436-441, Jan. 1997.
[10] Salah Eldeen Gasim M. Hassan, "Transmission Line overload Alleviation by Generation Rescheduling and Load Shedding in the National Grid of Sudan" pp.125. *M. Sc. Thesis. Karary Academy of Technology, Khartoum, Sudan*, Jan. 2005.