Transmission Lines Overload Alleviation by Generation Rescheduling and Load Shedding

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Abstract

In this paper, transmission lines overload alleviation for Sudan National Grid has been performed. Resizing the transmission system elements is not suitable during the operation. The suitable solution to alleviate transmission lines overload during operation is the generation rescheduling. Decreasing a generation station output reliefs some transmission lines overload, but to maintain the power equilibrium other generation stations output must be increased taking into account no additional transmission lines are being overloaded. A simple, efficient, fast and accurate technique for the alleviation of line overloads by corrective generation rescheduling and load shedding is applied to alleviate the overloads. The method ensures that alleviation of the existing violations does not create any new violations. The load shedding is used as a last choice in case of generation rescheduling did not completely alleviate the overloads; an overload being unable to be alleviated by just rescheduling the generation is always due to the system design weaknesses. The method gives good results in alleviating lines overloads in case of the most severe contingencies.

1. Introduction

Steady state power system insecurity such as transmission lines being overloaded creates cascade outages till complete blackout occurs. In order to improve the situation and ensure power system security during normal operation and during contingencies, the operator must be familiar with the system state at any instant. Contingency analysis is perform to predict which contingencies create lines overload, rank the contingencies according to their relative severity and take corrective actions to return the system to operate within limits [1].

Alleviation of the transmission lines overload is an important tool in power system secure operation. Hence the engineers in the control center must take corrective actions in minimum time so as to reduce the line overload and make line loading be within the security limits in order to avoid the risk of damage of equipments or perhaps even worse a cascading outage resulting in the blackout of the entire system.

In order to make a quick decision to alleviate elements overload and turn back the power system to a secure operating point, it appears that a simple, fast and efficient algorithm for evaluation of a schedule which is reasonably accurate and can be implemented in real-time to mitigate emergencies is more important than an evaluation of a very accurate schedule which cannot be implemented in real time.

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. The results of contingency analysis are given in Table (4) which shows the outages that result in line overloads.

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

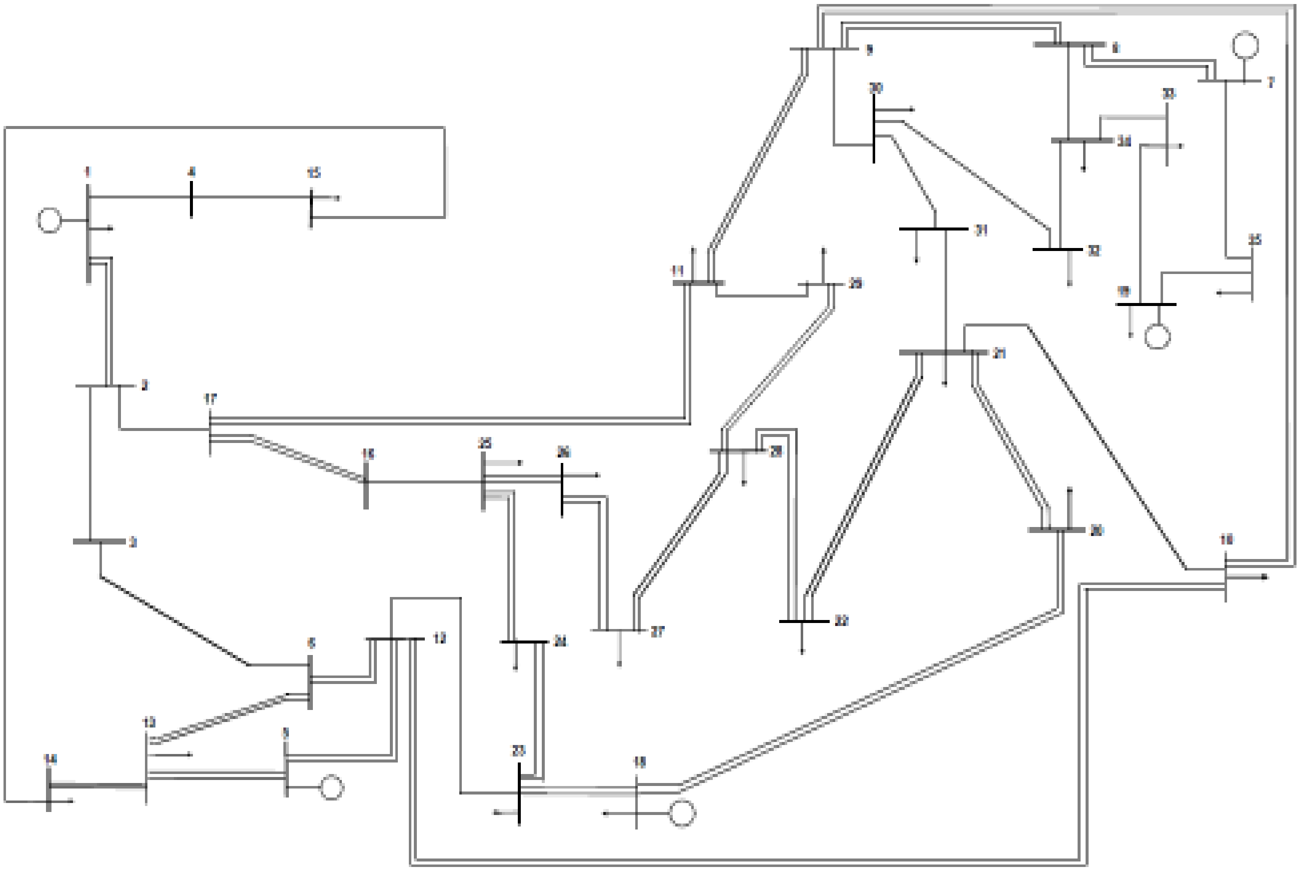


Figure (1) Sudan National Grid

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

Table (4) Results of contingency analysis ranked starting with the most severe contingency

Outaged Element		APLPI (m=30)	Overloaded Elements		Actual Flow	Maximum Flow Limit	Amount of Overload	% Loading
From	To		From	To				
7	8	2.95×10^{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	3.81×10^{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	7.04×10^{15}	8	34	141.5	77	64.5	183.8 %
			33	34	69.6	52	17.6	133.8 %
19	35	1.84×10^{12}	8	34	123.3	77	46.3	160 %
			33	34	54.1	52	2.1	104 %
8	9	6.43×10^{11}	8	34	121.1	77	44.1	157.3 %
			32	34	60.5	52	8.5	116.3 %
19	33	2.81×10^{5}	8	34	94.9	77	17.9	123.2 %
12	23	3.45×10^{4}	10	21	230.9	194	36.9	119 %
			8	34	77.1	77	0.1	100.1 %
30	32	2.45×10^{4}	8	34	91.1	77	14.1	118.3 %
18	20	1.88×10^{4}	10	21	228.6	194	34.6	117.8 %
			8	34	78.2	77	1.2	101.6 %
9	10	1.27×10^{3}	10	21	218.5	194	24.5	112.6 %
9	11	8.88×10^{2}	10	21	217.2	194	23.2	112 %
			8	34	78.2	77	1.2	102 %
9	30	1.25×10^{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 %

3. Transmission Lines Overload Alleviation

The method developed by Mahdi El-Arini [2] is superior to other existing methods. The Jacobian matrix, sensitivity matrix and the lagrangian function are needed in almost all of the existing methods, but not in the proposed method. The reconstruction of Jacobian-like matrices and determination of their inverse at each new operating point during the optimization procedure are not required. The proposed method gives less computation time as compared to other existing methods.

In the proposed method the control variables are generators active power output. In many cases line overloads are completely alleviated by corrective generation rescheduling without load shedding. In some other cases system limitations oppose the solution in such a way that the new schedule of generation is out of generator limits. In some other cases the new generation schedule which alleviates the overload of the main overloaded lines creates new line overloads. In such cases, it is essential to shed the load at some buses directly fed from the generator which is out of limit and at buses directly fed through the overloaded lines.

4. The Mathematical Formulation

Transmission line overload is eliminated by the real power generation rescheduling and load shedding. The line overload alleviation problem can be formulated as an optimization problem. The objective is to seek the generation correction schedule and the load shedding which minimize the following objective scalar function for each overloaded line. This function is named the cost function [2].

$$C(x,u) = \sum \left(P_{ij}\max - P_{ij}\right)^2 \tag{1}$$

Subject to:

$$F(x,u) = 0 \tag{2}$$

$$G(x,u) \leq 0 \tag{3}$$

$$x_{\min} \leq x \leq x_{\max} \tag{4}$$

$$u_{\min} \leq u \leq u_{\max} \tag{5}$$

Where:

x : Vector of the state variables (Bus Voltage magnitudes and angles)
u : Vector of the control variables (Generation schedule).
$C(x,u)$: Sum of the square of the line active power overloads.
$F(x,u)$: Equality constraints (P&Q power flow equations).
$G(x,u)$: Inequality constraints (Line loading limits, Generation active and reactive and compensation reactive power limits and bus voltage limits).
$x_{\min}$ & $x_{\max}$: Minimum and maximum limits of the state variables.
P_{ij} : The active power flow through the line connected between buses i and j.

P_{ijMax} : The active power rating of the line connected between buses i and j.

$u_{\min}$ & $u_{\max}$: Minimum and maximum limits of control variables.

Electric high voltage networks are composed of mainly inductive branches. Thus the influence of bus voltage magnitude variation (*ΔV*) on the line active power flow variation (*ΔP*) and bus angle variation (*Δθ*) on the reactive power flow variation (*ΔQ*) remains small. Also in practical power systems lines can be overloaded while the bus voltages are not seriously affected. Then with enough reactive power reserve to maintain a normal voltage profile, the bus-bar voltage magnitudes may be considered constant and the phenomenon is considered in the decoupled load flow algorithm. A load flow solution is performed using the specified loads and generation. In this way base case values of generation, line flows and bus voltage magnitudes are obtained. The generation shift distribution factors are calculated using AC power flow. From the load flow and contingency analysis results, the set of the overloaded lines (O_L) is identified for lines in which $P_{ij} > P_{ijMax}$ [2].

$$h_L = \sum_{K=2}^{NG} a_{LK} * \Delta P_{gK} \tag{6}$$

In matrix form

$$[H] = [A]\lfloor \Delta P_g \rfloor \tag{7}$$

Where:

$[H]$: is the vector of the line power overload, h_L and its order is $N_{OL} \times 1$.

$[A]$: is the matrix of generator shift distribution factors a_{LK} , its order is $N_{OL} \times N_G - 1$

$\lfloor \Delta P_g \rfloor$: is the vector of generation schedule correction with ΔP_{gK} elements.

$[H]$: is the vector of the amount of overload on each overloaded line, and is obtained using (8).

Let L be the number of the overloaded lines, then vector of lines amount of overload is

$$\begin{bmatrix} h_1 \\ h_2 \\ \cdots\cdot \\ h_L \end{bmatrix} = \begin{bmatrix} P_{1\max} \\ P_{2\max} \\ \cdots\cdots\cdot\cdot \\ P_{L\max} \end{bmatrix} - \begin{bmatrix} P_1 \\ P_2 \\ \cdots\cdot \\ P_L \end{bmatrix} \tag{8}$$

From (7)

$$\lfloor \Delta P_g \rfloor = \left[A^*\right][H] \tag{9}$$

Where $\left[A^*\right]$ is the pseudo-inverse of matrix $[A]$

After obtaining the correction vector $\lfloor \Delta P_g \rfloor$, the new generation schedule is calculated from

$$\lfloor P'_g \rfloor = \lfloor P_g \rfloor + \lfloor \Delta P_g \rfloor \tag{10}$$

Where:

$\lfloor P'_g \rfloor$: The vector of the new schedule generator active power output.

$\lfloor P_g \rfloor$: The vector of the old schedule generator active power output.

$\lfloor \Delta P_g \rfloor$: The vector of the active power generation correction.

5. DC Power Flow

Based on decupled power flow solution and considering the $(\Delta P - \Delta \theta)$ relation, the following can be obtained

$$\left[\frac{\Delta P}{|V|}\right] = [B'][\Delta \theta_1] \tag{11}$$

A further simplification of the power flow algorithm involves simply dropping the Q-V equation altogether [3]. This results in a completely linear non iterative power flow algorithm. In order to carry this out simply assumed that all $|V_i| = 1.0\, pu$, then (11) becomes

$$[\Delta P] = [B'][\Delta \theta] \tag{12}$$

The power flowing on each line using the DC power flow is then

$$P_{ik} = 1/X_{ik}\,(\theta_i - \theta_k) \tag{13}$$

6. Generation Shift Distribution Factors (GSDF's)

It is one of the linear sensitivity factors which show the approximate change in line flows for changes in generation on the network configuration and are derived from the DC load flow [3]. They can be used to determine the new generation schedule required to change line flows. GSDF's are therefore used to alleviate line active power overloads.

The Generation shift distribution factors are designated a_{Li} and have the following definition [2]

$$a_{Li} = \partial f_L / \partial P_{gi} \tag{14}$$

From DC power flow $f_L = 1/X_L\,(\theta_n - \theta_m)$ where L is a line with terminal buses *n* and *m*. Substituting (13) into (14) yield

$$a_{Li} = 1/X_L\,(X_{ni} - X_{mi}) \tag{15}$$

Where:

$X_{ni} = \partial \theta_n / \partial P_{gi}$ = the ni^{th} element in matrix [*X*].

$X_{mi} = \partial \theta_m / \partial P_{gi}$ = the mi^{th} element in matrix [*X*].

$X_L =$ Line reactance for line L connected between buses *n* and *m*.

Matrix $[X]$ is obtained as follows:

- Build matrix $[B']$ with dimension of $NB \times NB$ with its elements found as follows [1].

$$B'_{ij} = -1/X_{ij} \tag{16}$$

$$B'_{ii} = \sum 1/X_{ij} \,, j = 1 \ldots n, j \neq i \tag{17}$$

Where X_{ij} reactance of the line (or transformer) between buses i and j

- The slack (reference) bus is determined, and then row and column of the slack bus is eliminated leaving matrix $[B']$ above with dimension $(NB-1)\times(NB-1)$, where bus 1 is taken as the reference bus.
- The modified matrix above (of dimension $(NB-1)\times(NB-1)$) is inverted, the inverse represents matrix $[X]$.
- The reference bus row and column are again returned as zero elements to complete the dimension of matrix $[X]$ to be $NB \times NB$.

Values of GSDF's are calculated according to the active power flow direction obtained from the AC load flow results. Values of GSDF's are calculated using (15) and are given in Table (5).

Table (5) Values of GSDF's of the overloaded lines

Transmission Line		G5	G7	G18	G19	In case of
From	To					
19	35	0.006	0.086	0.003	- 0.700	All outages
19	33	0.006	0.089	0.006	0.300	All outages
7	35	0.067	0.255	0.07	- 0.600	All outages
10	21	0.316	0.214	-0.166	0.198	All outages
30	32	0.0034	-0.098	0.010	-0.102	All outages
8	34	0.198	0.497	0.204	O.278	All outages
32	34	-0.008	0.098	-0.011	0.1	All outages
33	34	- 0.006	- 0.089	-0.003	-0.304	Lines 7-35 and 19-35 outages
33	34	0.006	0.089	0.007	0.304	Lines 7-8 outage

7. Application of the Method in the National Grid

There are five power stations in the Sudanese National Grid. In each station, there is a set of generators. Excluding the slack bus-bar, the set of control variables contains the active power output of four stations. $\lfloor P_{g5} \; P_{g7} \; P_{g18} \; P_{g19} \rfloor_t$. The method of transmission lines overload alleviation is programmed with the load flow analysis using Newton-Raphson [4]-[7] using MATLAB. The vector of the new active power generation schedule that alleviates line overloads is obtained using (18)

$$\begin{bmatrix} P'_{g5} \\ P'_{g7} \\ P'_{g18} \\ P'_{g19} \end{bmatrix} = \begin{bmatrix} P_{g5} \\ P_{g7} \\ P_{g18} \\ P_{g19} \end{bmatrix} + \begin{bmatrix} \Delta P_{g5} \\ \Delta P_{g7} \\ \Delta P_{g18} \\ \Delta P_{g19} \end{bmatrix} \tag{18}$$

Where vector of correction $\lfloor \Delta P_g \rfloor$ is obtained as follows:

$$\begin{bmatrix} \Delta P_{g5} \\ \Delta P_{g7} \\ \Delta P_{g18} \\ \Delta P_{g19} \end{bmatrix} = \left[A^*\right]\left[H\right] \tag{19}$$

Where $\left[A^*\right]$ is a vector of dimension ($4 \times N_{OL}$). It represents the pseudo-inverse of matrix $\left[A\right]$ and, $\left[H\right]$ is the vector of the amounts of line overloads. The dimension of matrix $\left[H\right]$ is ($N_{OL} \times 1$).

8. Results of Line Overload Alleviation

The most network weakness is line (8-34), 16 different outages lead to this line overload. From the results of contingency analysis, one of the outages which lead to lines (8-34) and (32-34) overload is the outage of line (8-9). The vector [H] and matrix [A^*] for these lines are calculated below and the results of line overload alleviation are given in Table (6). Figure (2) shows the curves of APLPI against the exponent (*m*) before and after the transmission line overload alleviation.

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} P_{1\max} \\ P_{2\max} \end{bmatrix} - \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \text{ That is } \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} 77 \\ 52 \end{bmatrix} - \begin{bmatrix} 121.1 \\ 60.5 \end{bmatrix} = \begin{bmatrix} -44.1 \\ -8.5 \end{bmatrix}$$

$$\left[A^*\right] = \begin{bmatrix} 1.6454 & -6.4472 \\ 0.9920 & 1.3091 \\ 1.7685 & -7.0511 \\ -0.6459 & 7.4256 \end{bmatrix}$$

Then the correction $\lfloor \Delta P_g \rfloor$ is calculated

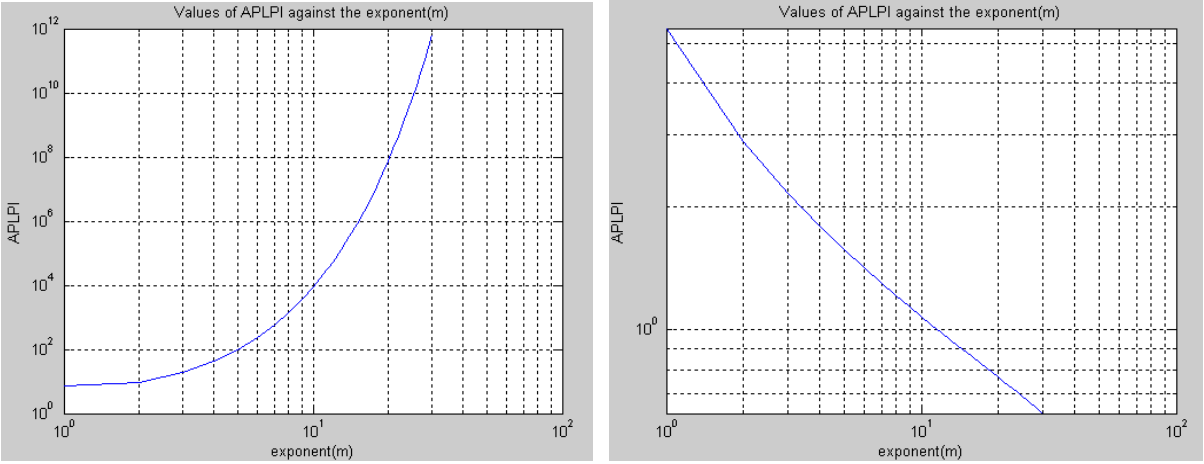
$$\begin{bmatrix} \Delta P_{g5} \\ \Delta P_{g7} \\ \Delta P_{g18} \\ \Delta P_{g19} \end{bmatrix} = \begin{bmatrix} 1.6454 & -6.4472 \\ 0.9920 & 1.3091 \\ 1.7685 & -7.0511 \\ -0.6459 & 7.4256 \end{bmatrix} \begin{bmatrix} -44.1 \\ -8.5 \end{bmatrix} = \begin{bmatrix} -17.7606 \\ -54.8730 \\ -18.0584 \\ -34.6318 \end{bmatrix}$$

Then the new generation schedule is given by

$$\begin{bmatrix} P'_{g5} \\ P'_{g7} \\ P'_{g18} \\ P'_{g19} \end{bmatrix} = \begin{bmatrix} 360 \\ 180 \\ 180 \\ 14 \end{bmatrix} + \begin{bmatrix} -17.7606 \\ -54.8730 \\ -18.0584 \\ -34.6318 \end{bmatrix} = \begin{bmatrix} 342.24 \\ 125.13 \\ 161.9 \\ 0 \end{bmatrix}$$

Table (6) Results of Transmission Lines Loading and APLPI before and after correction

Outaged Element		Case	APLPI (m=30)	Overloaded Elements		Actual Flow (MW)	P_{max} (MW)	Amount of Overload	% Line Loading
From	To			From	To				
8	9	Old Scheduling	6.43×10^{11}	8	34	121.1	77	44.1	157.3 %
				32	34	60.5	52	8.5	116.3 %
		New Scheduling	0.0478	8	34	60.75	77	---	78.9 %
				32	34	36.7	52	---	70.6%



(2-a) (2-b)

Figures (2) Values of APLPI against the exponent (m) before and after correction

9. Discussion of the Results

The new generation schedule is applied to the generation stations; the last station reaches its lowest limit by applying a fraction of the correction. The overload of both lines (8-34) and (32-34) is alleviated in one iteration without load shedding. Table (6) shows the results and Figure (3) shows values of APLPI against the exponent (*m*) before and after correction

10. Conclusion

In this paper, transmission lines overload alleviation is performed for Sudan National Grid. The results shown that alleviation of line's (8-34) overload in case of line (8-9) outage is solved by generation rescheduling without load shedding. The solution completed in one iteration, the APLPI dropped from (6.43×10^{11}) to (0.0478) and the amount of loading reduced highly from (157.3%) to (78.9) % for line (8-34) and from (116.3%) to (70.6%) for line (32-34).

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