A New Method of Optimum Reactive Power Allocation to Improve Network Voltage Profile

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Abstract

Voltage decrease increases transmission lines loading and power loss, besides causing generators VAR limit violations. This reduces generators active power generation capacity and transmission lines power handling capacity. Transmission lines overloading and contingencies severity highly increases in case of bad voltage profile, hence the bad voltage profile highly affects in power system security. It is a general trend to improve networks voltage profile by reactive power compensation but cost of reactive power compensation will be high if it is required to use them in all system bus-bars with under-voltage condition; hence it will reduce the cost if some bus-bars are selected to install the compensation devices. Compensation in those selected bus-bars improves the whole network voltage profile.

In this paper a new accurate and simple method for optimum reactive power allocation is presented to ensure a suitable voltage profile and alleviate generators VAR limit violations. The presented method uses an index which represents the mean value of voltage increase (MVVI) due to compensation MVAR allocation. The method gives the same results as other existing methods. The method has been applied to Sudan National Grid (NG) and gives good results in improving system voltage profile with minimum reactive power compensation.

1. Introduction

It is straight forward to control the load buses voltage magnitude by means of VAR sources or/and transformer taps adjusting. The dependence of the system voltage stability on reactive power distribution forms the basis for reactive power optimization [1]. According to the system loading, voltage magnitude are varies. The voltage magnitude decreases with system loading increase and vice-versa. In order to maintain the voltage within limits reactive power compensation by means of switching VAR sources are introduced. Load bus-bars voltage is calculated by performing load flow analysis using Newton-Raphson technique [2], [3], [4], [5]. The procedure of optimum reactive power allocation is incorporated in the program of load flow analysis using MATLAB.

A procedure is developed by [6] to allocate reactive power devices in a power system based on a set of indices that are on overall system conditions. Existing controllers are fully utilized before adding any new devices. The constraints include the limits on dependent variables (Reactive power of the generators and bus voltages) and independent variables (generator voltages and switch-able VAR sources). The purpose of optimum reactive power compensation study is to determine the minimum amount of reactive power required at selected buses to get a certain voltage profile. Many papers [6], [7], [8] have addressed this important issue. The common approach is to select locations at certain buses based on engineering judgment, and then try to minimize the number of locations and the amount of reactive power required at each. Voltages at some buses are more sensitive to reactive power variation than others. Besides that, allocating VAR sources at these buses highly affects other buses specially those which have direct connection to the bus where reactive power source is allocated. The purpose of optimum reactive power allocation is to determine the most suitable load buses where reactive power sources can be allocated to get a certain voltage profile with the minimum compensating reactive power compensation.

A new, simple and accurate method is presented and gains the same results of the available methods. The new method which is based on the Mean Value of Voltage Increase (MVVI) is superior to other existing methods for its simplicity as a mathematical formulation and its simplicity to be incorporated with newton-raphson load flow procedure. This method is based on the Jacobian matrix [9]. In this method voltage increase at all load buses is calculated for allocating a compensating reactive power (5 MVAR) at a load bus each time, then (MVVI) is calculated using (1). Mean value of load bus voltage increase due to a specified allocation gives an indication for the bus which has the greatest effect on the voltage of system load buses. While allocating the reactive power source at a particular bus, mean value of bus voltage increase is calculated. The process continues to obtain the mean value of voltage increase due to allocating the reactive power source at all load buses (one bus each time). Mean values are ranked beginning with the largest value. According to the mean value of voltage increase, decision of reactive power sources allocation can be made. The higher MVVI means the best allocation for the reactive power source.

There are two steps to determine the optimum reactive power compensation; those are first determining the optimum allocations for reactive power compensation and then determining the values of compensating VARs that should be place at the selected allocations [9].

2. The Mathematical Model of MVVI

It is generally considered that $\partial P/\partial V = 0$ and $\partial Q/\partial \theta = 0$ in a decoupled load flow algorithm. Then consider the reactive power equation:

$$[\Delta Q]=[\partial Q/\partial V][\Delta V] \tag{1}$$

From this equation the expression for change in voltage (ΔV) in terms of change in reactive power (ΔQ) is given by:

$$[\Delta V]=[J_V][\Delta Q] \tag{2}$$

Where:

$[J_V]$ is the inverse of $[\partial Q/\partial V]$

$[\partial Q]$ is the vector of control variable (Reactive Compensation) [9].

Values of voltage increase in each of the load buses are obtained using (2), then mean of voltage increase as an indicator for the system voltage improvement due to an allocation is obtained using (3) [9].

$$MVVI = \frac{1}{NB}\sum_{i=1}^{NB}\Delta V_i \tag{3}$$

Where:

ΔV_i: Voltage increase at bus (i) due to capacitive reactive power allocation at bus (k).

Vector of $[\Delta V]$ is obtained using (2).

3. Determination the Value of Optimum Compensation

After determination of the optimum allocations using the above developed method, it is required to determine the values of compensating VARs that should be place at the selected allocations. The values of compensation VARs which provide a suitable voltage profile must be as small as possible. The procedure of determination of values of optimum reactive power compensation is as follows:

1. Apply as highest as possible of reactive power compensation at the bus with highest of *MVVI* that improves the voltage at this bus till its voltage reachs the lower permisible limits.
2. Then apply as highest as possible reactive power compensation at the bus with the second highest of *MVVI* which is ranked under that of step 1 to improve the voltage at this bus till its voltage reachs the lower permisible limit.
3. If voltage of the upper ranked buses violated their upper limit reduce their reactive power compensation.
4. During proceeding in the list of buses rank, if the voltage of the bus with a higher value of *MVVI* is suitable (bus 29 as example) leave this bus and apply as highest as possible reactive power compensation at the bus ranked under that bus (bus 26 as example) to improve the voltage at this bus till its voltage reachs the lower permisible limits.
5. Continue till all buses are within the permissible limits.

4. 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	---
2	1.0	180
3	1.0	180
4	1.0	14
5	1.0	360

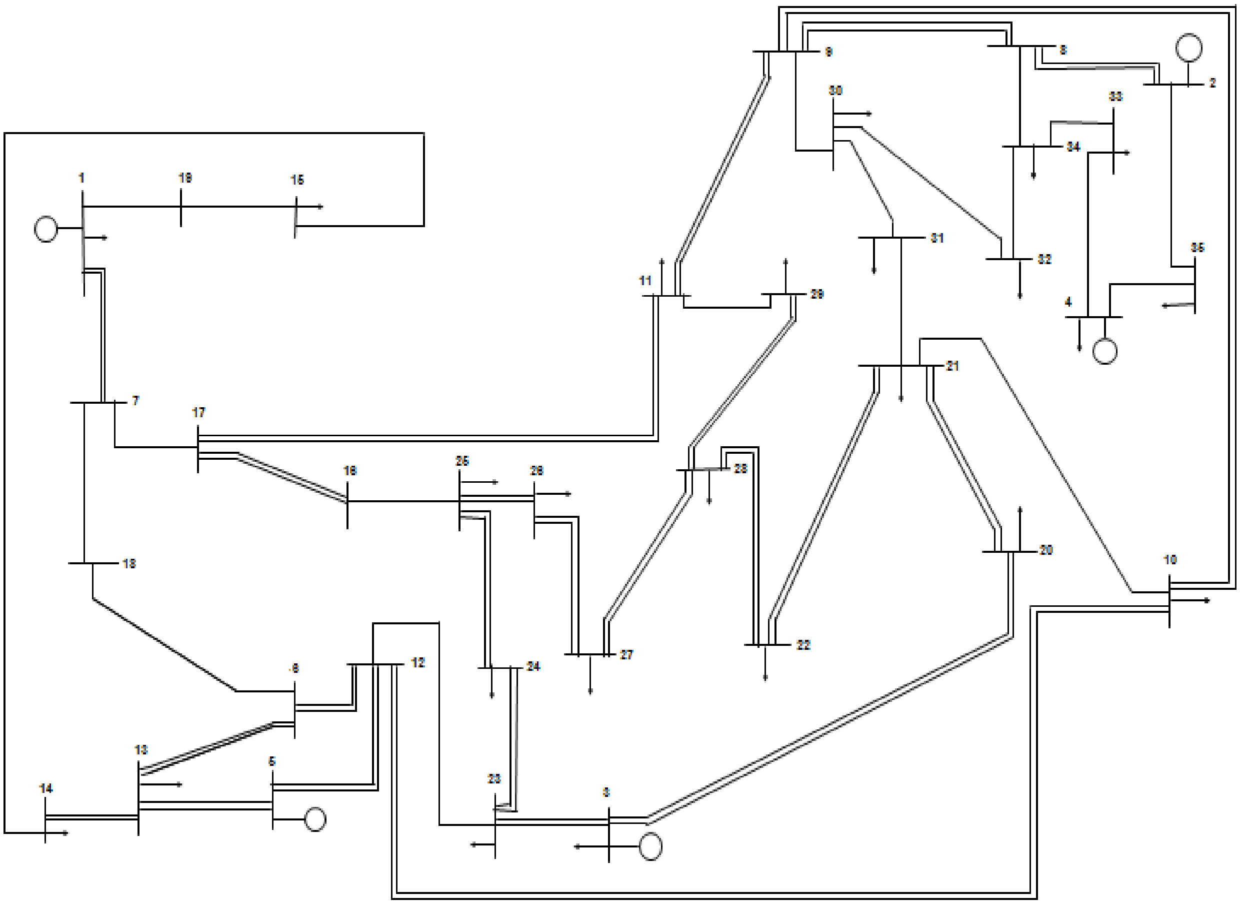

Figure (1) Sudan National Grid

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

5. Results and Discussion

The method is applied to Sudan National Grid, the optimum allocations have been determined, Figure (2) shows the curve of MVVI against load buses where compensation with a value of 5 MVAR has been performed.

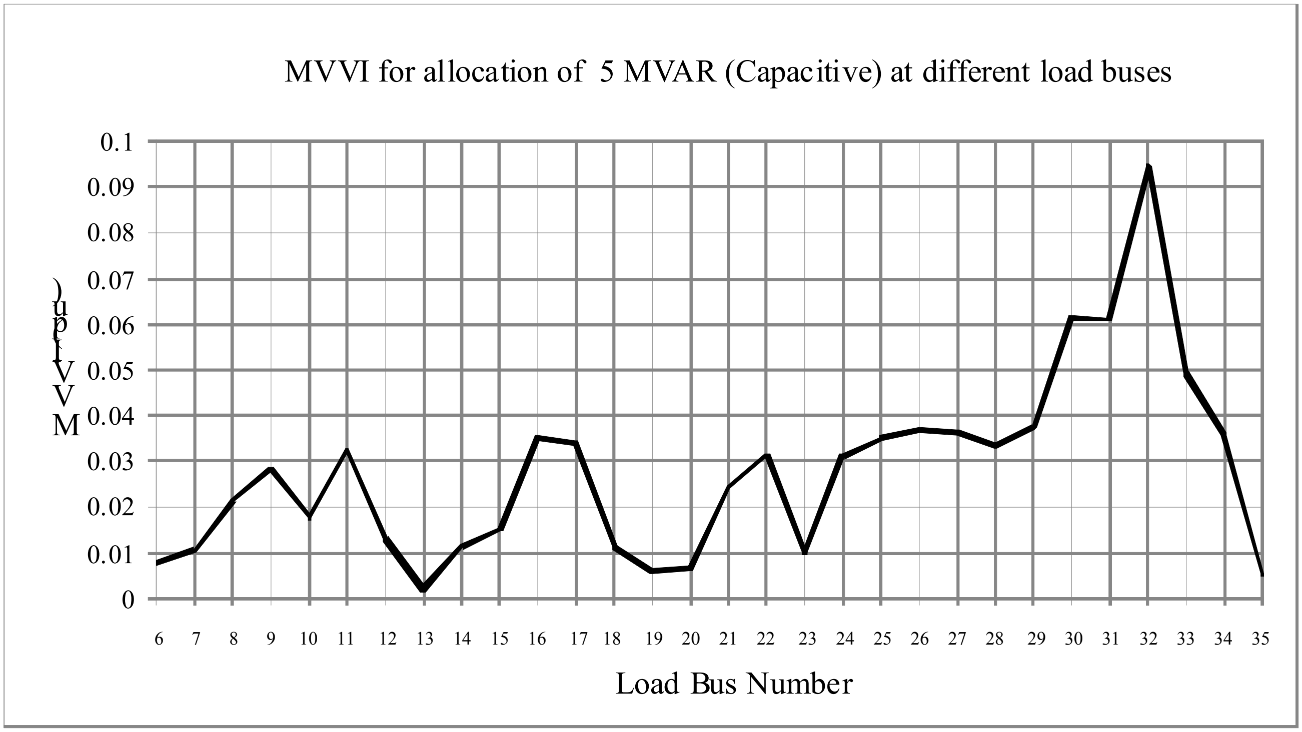

Figure (2) the curve of MVVI against load buses

Bus- bars have been ranked starting with the bus-bar of the highest MVVI as shown in Table (4). Table (5) shows values of compensation MVAR that improves the network voltage profile, besides the buses where the compensation devices should be installed. Noted that it is just required to compensate at 6 allocations this will highly reduce the cost of compensating devices including the capacitor banks and switching and protection devices. Table (6) shows values of load busbars voltage before and after applying the capacitive compensation at the upper ranked load busbars show step by step till voltage of the entire load buses is within the accepted limits. Low voltages are shown in bold.

Table (4) Different compensating allocations ranked starting with the bus of highest MVVI

Rank	Load Bus	MVVI
1	32	0.0946
2	30	0.0615
3	31	0.0611
4	33	0.0491
5	29	0.0374
6	26	0.0368
7	27	0.0364
8	34	0.0358
9	16	0.0353
10	25	0.0349
11	17	0.0342
12	28	0.0332
13	11	0.0323
14	22	0.0313
15	24	0.0312
16	9	0.0284
17	21	0.0244
18	8	0.0215
19	10	0.0178
20	15	0.0150
21	12	0.0130
22	14	0.0114
23	18	0.0112
24	7	0.0106
25	23	0.0102
26	6	0.0079
27	20	0.0064
28	19	0.0062
29	35	0.0054
30	13	0.0019

Table (5) values of the required compensation MVAR and their allocation

Rank	MVVI (pu)	Load Bus	Compensation MVAR
1	0.0946	32	100 MVAR
2	0.0615	30	50 MVAR
3	0.0611	31	50 MVAR
4	0.0491	33	90 MVAR
5	0.0374	29	------------
6	0.0368	26	100 MVAR
7	0.0364	27	------------
8	0.0358	34	50 MVAR
No. of compensated buses = 6			Total MVAR = 440

Table (6) Load Bus-bars Voltages Before and After Compensation

Load Bus Number	Voltage (pu) Without Compensation	Voltage (pu) After (100 MVAR) Compensation At bus 32	Voltage (pu) After (50 MVAR) Compensation At each of bus 30 and bus 31	Voltage (pu) After (90 MVAR) Compensation At bus 33	Voltage (pu) After (100 MVAR) Compensation At bus 26	Voltage (pu) After (50 MVAR) Compensation At bus 34
6	1.004	1.006	1.007	1.008	1.009	1.010
7	1.014	1.015	1.016	1.017	1.018	1.018
8	0.998	1.011	1.016	1.026	1.028	1.038
9	0.992	1.000	1.008	1.011	1.017	1.020
10	1.006	1.010	1.015	1.016	1.020	1.021
11	0.981	0.987	0.996	0.998	1.005	1.008
12	1.007	1.009	1.012	1.013	1.016	1.017
13	1.002	1.002	1.003	1.003	1.003	1.003
14	1.029	1.029	1.030	1.030	1.030	1.030
15	1.043	1.044	1.044	1.044	1.044	1.044
16	0.984	0.989	0.996	0.997	1.008	1.009
17	0.983	0.988	0.995	0.997	1.006	1.007
18	1.015	1.016	1.017	1.018	1.019	1.019
19	0.991	0.991	0.991	0.991	0.991	0.991
20	0.981	0.982	0.984	0.984	0.986	0.986
21	**0.936**	**0.941**	**0.949**	0.950	0.958	0.959
22	**0.932**	**0.936**	**0.944**	**0.945**	0.957	0.958
23	0.972	0.973	0.974	0.975	0.979	0.979
24	**0.930**	**0.933**	**0.938**	**0.939**	0.956	0.957
25	**0.922**	**0.925**	**0.931**	**0.932**	0.952	0.953
26	**0.921**	**0.925**	**0.931**	**0.932**	0.958	0.959
27	**0.924**	**0.928**	**0.935**	**0.936**	0.956	0.957
28	**0.932**	**0.936**	**0.944**	**0.945**	0.958	0.959
29	0.971	0.976	0.984	0.985	0.997	0.998
30	**0.888**	**0.923**	0.990	0.994	1.000	1.003
31	**0.890**	**0.921**	0.988	0.992	0.997	1.001
32	**0.813**	0.962	0.993	1.009	1.013	1.027
33	**0.876**	**0.896**	**0.900**	0.987	0.989	1.003
34	**0.864**	**0.894**	**0.901**	**0.927**	**0.928**	0.952
35	0.981	0.980	0.980	0.980	0.980	0.979

6. Conclusion

In this paper, the network voltage profile has been improved by the minimum compensation to reduce the reactive power compensation cost. The mean value of voltage increase (MVVI) index has been calculated for allocation of a constant value of capacitive reactive power (5 MVAR) at a load bus each time, and all load buses have been ranked starting with the bus of highest value of (MVVI). The results obtained are highly reduced the cost of reactive power compensation.

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