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TRANSMISSION CONGESTION MANAGEMENT USING LINEAR SENSITIVITY FACTORS FOR ELECTRICAL POWER SYSTEM

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ABSTRACT

Transmission congestion is the one of the important phenomenon for electricity market as it directly increase the electricity cost and affects system's security. Congestion can be occurred due to violations of operating limits. The management of congestion is very critical function for the system operator. Various congestion management techniques are used for transmission congestion management. This paper presents the analysis of transmission congestion using linear sensitivity factors for the various contingencies of line outage and generation outage. The generation shift factors and line outage distribution factors are used to find most sensitive lines. The congestion in most sensitive line can be removed by series compensation using FACTS devices. The analysis of occurrence and removal of congestion is performed on standard 6 bus system using MATLAB programming.

Keywords- Congestion, Congestion management, deregulation, contingency, linear sensitivity factors

I. INTRODUCTION

The electricity is one of our basic needs today. The demand of electricity increases day by day as population increases. The power system has to expand the existing capacity of generation or to construct new power system. The building of new power system is very costlier option, so the enhancement of existing system is the alternative option. The power system operates near its critical operating limits to satisfy the increasing load demand. These operating limits may be thermal limit, stability limit, voltage limit, transformer ratting etc. The system operator monitors the power system violations of the limits for the secure operation. We can say that the transmission congestion occurs, when the limits are violated due to sudden increase in load demand, generation outage or transmission line outage etc. The system security and stability are affected due to congestion. The electricity cost also increases due to congestion. So transmission congestion is one of the important phenomenons of electricity market. The congestion management is very important and crucial task of system operator.

The electric utilities are restructuring all over the world. Restructuring means converting the vertically integrated market into unbundled system [6]. Due to deregulated environment, the electricity market becomes competitive and customers of electricity have choice to buy electricity from the cheaper generation. Transmission congestion is directly related to electricity market. It does occur in both vertically integrated market and deregulated market. But the management of congestion in vertically integrated market is quite simple as generation and transmission systems are controlled by one utility. The management in deregulated market is complex as the generation and transmission systems are separated and not controlled by one utility. Due to lack of coordination between generation and transmission, all desired transactions are not possible to dispatch and transmission congestion occurs. Also congestion cost would increase which may be unwanted burden to the society.

II. CONGESTION MANAGEMENT

There are many rules and guidelines are defined for controlling transmission network with maintaining system security and reliability for congestion management [2]. The rules should be such that they maximize the market efficiency for short and long term periods. The congestion management schemes should be transparent and robust. The available transfer capacity [2] is calculated by system operator to get idea to determine if the transmission network could accommodate the transaction or not. The capacity is then allocated according to capability. In congestion Management of transmission network the power flow in the congested lines is reduced by changing the power flow pattern. It can be done by changing the generation or load or by both with system security and reliability. In deregulated environment, the power market becomes competitive and all generation and distribution companies decide their transactions ahead of time. But at the time of implementation of transactions, the congestion may occur in some of the transmission lines. So the independent system operator has to eliminate that congestion. There are various congestion management schemes that are used all over the world. The methods can be classified as cost free methods and non-cost free methods. The outaging of congested lines, operation of transformer taps, operation of series FACTS devices are the cost free methods in which only technical constraints are considered and market economy is not considered. The generation re-dispatching and load curtailment are the non-cost free methods which involves market economy.

In congestion management, the main objective is to allocate the efficient transfer capacity with maintaining system security [1]. The independent system operator continuously updates the available transfer capacity and check of the required capacity of various regions. After that the capacity is allocated based on explicit auctioning or implicit auctioning. After capacity allocation, the congestion is forecasted. If the congestion will occur after capacity allocation then the capacity alleviation methods are used to relieve congestion. The type of contract, first come first serve, pro rata method, auctioning methods are the capacity allocation methods while rescheduling of generation, counter trading, load curtailment methods are the capacity alleviation methods.

The FACTS devices can be used for the congestion management as they have many advantages [3]. FACTS devices can improve the system performance by reducing the flow of the loaded line and also increase the system stability by reducing the system losses. Various FACTS devices like thyrister controlled series capacitors (TCSC), thyrister controlled phase shifters (TCPS), unified power flow controllers (UPFC) are used in series with the most congested line. The FACTS devices can also enhance the available transfer capacity. The optimal location of the device and optimal size, modelling and cost of devices are various factors related to FACTS devices for congestion management.

III. LINEAR SENSITIVITY ANALYASIS

In the real time operation, system operator monitors the system for security. There are thousands of possible outages are monitored for secure operation. The study of violation of operating limits and possible outages is very difficult to solve as the results should be provided quickly. The linear sensitivity factors are used to calculate the possible outages quickly. The appropriate change in power flow for any change in power injection on network configuration is defined as linear sensitivity factor [4].

The sensitivity factors are used to find out the sensitivity of the line and overloading of particular line regarding to outages. There are two types of sensitivity factors used for power system security studies.

1. Generator shift distribution factors (GSDF)
2. Line outage distribution factors (LODF)

These sensitivity factors can be derived from the DC load flow method and gives approximate but quick solution for change in power flow in the power system.

The generation shift distribution factors defined as the change in power flow on line *l* due to change in power generation ΔP_i occurs at bus *i*. Mathematically,

$$ali = \frac{\Delta fl}{\Delta Pi}$$

Where, *l* = line index

i =bus index

$\Delta fl =$ change in megawatt power flow on line *l*

$\Delta Pi =$ change in generation at bus *i*

The sensitivity matrix [X] is formulated using the DC load flow equation $\theta = [X]P$

So, the generation shift factor

$$ali = \frac{\Delta fl}{\Delta Pi} = \frac{1}{xl}(Xni - Xmi)$$

Where, *xl* = line reactance of line *l*

Xni = n^th^ element of reactance matrix from $\Delta\,\theta$ vector

Xmi = m^th^ element of reactance matrix from $\Delta\,\theta$ vector

The line outage distribution factor can be defined as the change in power flow on line l due to change in power flow of any line k. Mathematically,

$$dl,k = \frac{\Delta fl}{fk^{\cdot}}$$

Where, Δfl = change in MW flow on line l

$fk^{\cdot}$ = original flow on line k before it was outaged.

From DC load flow,

$$dl,k = \frac{\Delta fl}{fk^{\cdot}} = \frac{\frac{xk}{xl}(Xin - Xjn - Xim + Xjm)}{xk - (Xnn - Xmm - 2Xnm)}$$

IV. SIMULATIONS AND RESULTS

The sample 6 bus system is used for the simulation work and taken from the reference [4]. The bus data and line data are shown in table 1 and table 2 respectively. For the sensitivity calculations the MATLAB programming is used. The power flow and losses are calculated using NR power flow method.

Table 1: Bus data for sample 6 bus system

Bus no.	Bus type	Voltage (p.u.)	Angle (degree)	Pgen (MW)	Pload (MW)	Qload (MVAR)
1	Swing	1.05	0	0	0	0
2	Generator	1.05	-3.7	50	0	0
3	Generator	1.07	-4.3	60	0	0
4	Load	0.9896	-4.2	0	70	70
5	Load	0.9857	-5.3	0	70	70
6	Load	1.0044	-5.9	0	70	70

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Table 2: Line data for sample 6 bus system

Line No.	Buses	Resistance(R) (p.u.)	Reactance(X) (p.u.)	Half susptance (Bc/2)	Thermal limit (MVA)
1	1-2	0.1	0.2	0.02	40
2	1-4	0.05	0.2	0.02	60
3	1-5	0.08	0.3	0.03	50
4	2-3	0.05	0.25	0.03	40
5	2-4	0.05	0.1	0.01	70
6	2-5	0.01	0.3	0.02	30
7	2-6	0.07	0.2	0.025	90
8	3-5	0.12	0.26	0.025	70
9	3-6	0.02	0.10	0.01	80
10	4-5	0.20	0.40	0.04	20
11	5-6	0.10	0.30	0.03	40

Calculation steps for sensitivity indices:

Step 1: Formulation of admittance matrix Ybus.

Table 3: Bus admittance matrix for 6 bus sample system Ybus

-13.33i	5i	0	5i	3.33i	0
5i	-27.33i	4i	10i	3.33i	5i
0	4i	-17.84i	0	3.84i	10i
5i	10i	0	-17.5i	2.5i	0
3.33i	3.33i	3.84i	2.5i	-16.34i	3.33i
0	5i	10i	0	3.33i	-18.33i

Step 2: Formulation of susptance matrix B'

We will form B' by removing the first row & column corresponding to swing bus and then taking the negative of the imaginary part of Ybus.

Table 4: B' matrix for 6 bus system

27.33	-4	-10	-3.33	-5
-4	17.84	0	-3.84	-10
-10	0	17.5	-2.5	0
-3.33	-3.84	-2.5	16.34	-3.33
-5	-10	0	-3.33	18.33

Step 3: Formulation of reactance matrix $X' = [B']^{-1}$

Table 5: Reactance matrix of 6 bus system

0	0	0	0	0	0
0	0.0941	0.0805	0.0630	0.0643	0.0813
0	0.0805	0.1659	0.0590	0.0908	0.1290
0	0.0630	0.0590	0.1009	0.0542	0.0592
0	0.0643	0.0908	0.0542	0.1222	0.0893
0	0.0813	0.1290	0.0592	0.0893	0.1633

Step 4: Calculations of generation shift distribution factor using $ali = \frac{\Delta fl}{\Delta Pi} = \frac{1}{xl}(Xni - Xmi)$

Manual calculations of Generation Outage (Gen 3):

Base-case flow on line 2-6 = 26.2 MW

Base-case generation on bus 3 = 60 MW

Generation shift distribution factor = $a(2-6)3 = \frac{1}{x2-6}(X23 - X63)$ = (1/0.2) (0.08051-0.12895) = -0.2422

The flow on line 2-6 after generation outage = 26.2 + (-0.2422) (60) = 40.6 MW

Table 6: Generation shift distribution factors during normal condition

Line no	Bus 1	Bus 2	Bus 3
1	0	-0.4706	-0.4026
2	0	-0.3149	-0.2949
3	0	-0.2145	-0.3026
4	0	0.0544	-0.3416
5	0	0.3115	0.2154
6	0	0.0993	-0.0342
7	0	0.0642	-0.2422
8	0	0.0622	0.2890
9	0	-0.0077	0.3695
10	0	-0.0034	-0.07995
11	0	-0.0564	-0.1273

Step 5: Calculations of line outage distribution factor using $dl,k = \frac{\Delta fl}{fk^{\circ}} = \frac{\frac{xk}{xl}(Xin - Xjn - Xim + Xjm)}{xk - (Xnn - Xmm - 2Xnm)}$

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Manual calculations of Line outage (line 3-5):

Base-case flow on line 3-5 = 19.1

Base-case flow on line 1-5 = 35.6 MW

Line outage distribution factor = $d1-5{,}3-5 = \frac{\frac{x3-5}{x1-5}(X15-X55-X13+X53)}{x3-5-(X55-X33-2X53)}$ =(0.26/0.3)(0-0.12215-0+0.09077)/(0.26)-(0.12215+0.1659-2(0.09077)) =0.18

The flow on line 1-5 after the outage = 35.6 + (0.18) (19.1) = 39.038 MW

Table 7: Line outage distribution factors for all lines during normal condition

Line no	1	2	3	4	5	6	7	8	9	10	11
1	0	0.6353	0.5427	-0.1127	-0.5031	-0.2103	-0.1221	-0.1369	0.0135	0.0096	0.1316
2	0.5948	0	0.4573	-0.0331	0.6121	-0.0618	-0.0359	-0.0403	0.0040	-0.3269	0.0387
3	0.4052	0.3647	0	0.1458	-0.1090	0.2721	0.1580	0.1772	-0.0174	0.3174	-0.1703
4	-0.1029	-0.0323	0.1783	0	0.1242	0.2262	0.4662	-0.3995	-0.5253	0.1706	0.1320
5	-0.5884	0.7647	-0.1708	0.1591	0	0.2969	0.1724	0.1933	-0.0190	-0.6731	-0.1858
6	-0.1875	-0.0589	0.3250	0.2209	0.2264	0	0.2394	0.2685	-0.0264	0.3110	-0.2580
7	-0.1213	-0.0381	0.2102	0.5073	0.1464	0.2667	0	-0.1992	0.5842	0.2011	0.4433
8	-0.1175	-0.0369	0.2036	-0.3755	0.1418	0.2583	-0.1720	0	0.4747	0.1948	-0.4246
9	0.0146	0.0046	-0.0253	-0.6245	-0.0176	-0.0321	0.6382	0.6005	0	-0.0242	0.5567
10	0.0065	-0.2353	0.2865	0.1259	-0.3879	0.2350	0.1365	0.1530	-0.0150	0	-0.1471
11	0.1067	0.0335	-0.1849	0.1172	-0.1288	-0.2346	0.3618	-0.4013	0.4158	-0.1769	0

Now the contingency is applied to 6 bus system to produce congestion in the system. Here outage of generator 3 gives the results of generator shift factors as shown in Table 8 below.

Table 8: Results of generation shift factors due to outage of generator 3

Bus no	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
1	0	0	0	0	0	0	0	0	0	0	0
2	**-0.4706**	**-0.3149**	**-0.2145**	**0.0544**	**0.3115**	**0.0993**	**0.0642**	**0.0622**	**-0.0077**	**-0.0034**	**-0.0565**
3	**-0.4026**	**-0.2949**	**-0.3026**	**-0.3416**	**0.2154**	**-0.0342**	**-0.2422**	**0.2890**	**0.3695**	**-0.0795**	**-0.1273**
4	-0.3149	-0.5044	-0.1807	0.0160	-0.3790	0.0292	0.0189	0.0183	-0.0023	0.1166	-0.0166
5	-0.3217	-0.2711	-0.4072	-0.1057	0.1013	-0.1927	-0.1246	-0.1207	0.0150	-0.1698	0.1096
6	-0.4064	-0.2960	-0.2976	-0.1907	0.2208	-0.0266	-0.4100	0.1526	-0.3433	-0.0752	-0.2467

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Now, line outage distribution factors for any line outages can be similarly performed for various contingencies of line outages. The results are shown in table 9. Here for the outage of line 1-2, the most sensitive line is line 1-4 as it has highest value of LODF. Similarly for all other line outages, the most sensitive line can be found out.

Table 9: Results of line outage distribution factors for various line outages

Line no	1-2 out	1-4 out	1-5 out	2-3 out	2-4 out	2-5 out	2-6 out	3-5 out	3-6 out	4-5 out	5-6 out
1(1-2)	0	-63.5	**-54.3**	11.3	**50.3**	21.0	12.2	13.7	-1.3	-1	-13.2
2(1-4)	**-59.5**	0	-45.7	3.3	-61.2	6.2	3.6	4	-0.4	32.7	-3.9
3(1-5)	-40.5	-36.5	0	-14.6	10.9	-27.2	-15.8	-17.7	1.7	-31.7	17
4(2-3)	10.3	3.2	-17.8	0	-12.4	-22.6	-46.6	40	52.5	-17.1	-13.2
5(2-4)	58.8	**-76.5**	17.1	-15.9	0	**-29.7**	-17.2	-19.3	1.9	**67.3**	18.6
6(2-5)	18.8	5.9	-32.5	-22.1	-22.6	0	-23.9	**-26.8**	2.6	-31.1	25.8
7(2-6)	12.1	3.8	-21	-50.7	-14.6	-26.7	0	19.9	**-58.4**	-20.1	-44.3
8(3-5)	11.7	3.7	-20.4	37.5	-14.2	-25.8	17.2	0	-47.5	-19.5	42.5
9(3-6)	-1.5	-0.5	2.5	**62.5**	1.8	3.2	**-63.8**	**-60**	0	2.4	**-55.7**
10(4-5)	-0.6	23.5	-28.6	-12.6	38.8	-23.5	-13.6	-15.3	1.5	0	14.7
11(5-6)	-10.7	-3.4	18.5	-11.7	12.9	23.5	-36.2	40.1	-41.6	17.7	0

Table 10: Power flow results for various conditions

Line no	Active power (MW) flow			Reactive power (MVAR) flow			MVA flow		
	Normal	Gen 3 out	Line 3-5 out	Normal	Gen 3 out	Line 3-5 out	Normal	Gen 3 out	Line 3-5 out
1	28.646	55.161	26.728	-15.4	-10.728	-14.585	32.524	56.194	30.449
2	43.609	**62.771**	**43.230**	19.797	28.531	22.385	47.892	**68.951**	48.682
3	35.578	54.806	38.509	11.223	22.458	21.602	37.306	59.229	44.154
4	2.931	23.629	-5.095	-12.269	0.951	-10.671	12.614	23.648	11.827
5	33.047	19.538	37.222	44.328	41.935	47.391	55.291	46.263	60.261
6	15.518	17.661	20.929	15.316	17.854	24.687	21.80	25.113	32.365
7	26.249	41.508	22.885	12.389	22.073	16.193	29.026	47.012	28.035
8	19.115	1.657	-	23.132	18.124	-	30.008	18.200	-
9	43.775	21.696	54.869	60.703	**49.399**	**64.529**	74.840	53.953	**84.703**
10	4.096	8.979	7.586	-4.827	-2.597	0.092	6.330	9.347	7.586
11	1.612	9.071	-5.707	-9.636	-5.757	-15.221	9.770	10.743	16.256

Table 10 shows the power flow results using NR method and change in power flow for normal condition, during outage of generator 3 and during outage of line 3-5. So we can say that the change in power flow can be determined by linear sensitivity factors.

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Table 11: MVA flows for all lines with various contingencies

Contingency (Outage)	1-2	1-4	1-5	2-3	2-4	2-5	2-6	3-5	3-6	4-5	5-6	Total MVA
Normal case MVA	32.524	47.890	37.306	12.614	55.291	21.803	29.026	30.008	74.840	6.330	9.770	357.4
1 (1-2)	-	62.860	48.330	11.671	53.505	19.748	26.541	29.185	74.843	6.524	11.543	344.75
2 (1-4)	**61.077**	-	57.564	15.621	**95.223**	19.161	26.492	31.135	78.398	11.093	10.502	406.23
3 (1-5)	53.587	65.744	-	13.427	54.900	**35.705**	38.049	39.016	75.823	14.412	14.011	404.67
4 (2-3)	32.167	47.801	37.703	-	55.396	22.136	30.284	29.731	74.168	6.644	9.896	345.93
5 (2-4)	16.329	**92.489**	37.017	14.369	-	30.018	34.079	36.700	77.371	**18.415**	12.331	369.12
6 (2-5)	29.882	48.467	44.467	10.992	59.989	-	35.237	36.764	75.104	8.174	13.606	361.88
7 (2-6)	29.595	47.820	42.740	16.840	58.237	28.678	-	26.661	**97.407**	8.445	11.877	368.3
8 (3-5)	30.449	48.682	44.154	11.827	60.261	32.365	28.035	-	84.703	7.586	16.256	364.32
9 (3-6)	33.721	58.101	45.865	**30.039**	46.709	23.518	81.505	**53.250**	-	4.435	**26.830**	403.97
10(4-5)	32.936	47.163	38.996	12.968	56.723	23.344	29.865	31.451	75.428	-	10.378	359.25
11(5-6)	33.066	48.361	37.804	12.790	56.222	23.601	29.074	32.438	73.210	5.214	-	351.78
12 (G2)	54.129	69.316	51.676	15.089	37.873	15.639	24.996	27.239	76.756	5.943	8.690	387.35
13 (G3)	56.194	68.951	**59.229**	23.648	46.263	25.113	**47.012**	18.200	53.953	9.347	10.743	**418.65**

Table 11 shows the MVA flows for all the lines with various contingencies of line outages and generation outages. The flows in Table 11 having darkened value give the highest flow of the line with particular outage of line or generation outage. Some of the lines exceed its thermal limits. The total MVA flow values are also changes with various contingencies. These lines are said to be the most sensitive lines and are congested. For outage of line 1-2, the line 1-4 becomes the most sensitive line as the power flow in line 1-4 exceeds its limit having the highest value of 61.077. For outage of generator 3, line 1-5 becomes most congested having the value of 59.229. Similarly, for any other outages the most sensitive line can be found out as shown in Table 11. The congestion in these lines should be removed by series compensation or using any of FACTS devices.

V. CONCLUSION

The transmission congestion is very critical problem to deregulated electricity market. The linear sensitivity indices and contingency analysis is useful to find out the most congested line and most sensitive line. In this paper, various contingencies are applied and the system is analysed for power flow of each line using linear sensitivity factors to find out the most sensitive lines which cause congestion in the system. The congestion management techniques like series compensation using FACTS devices should be applied to sensitive lines to reduce the MVA flow within the limits. Hence, congestion can be mitigated.

VI. FUTURE SCOPE

After finding the most sensitive line using linear sensitivity factors, the congestion can be removed by using the FACTS devices or series compensation for 6 bus sample system. Then the contingency analysis can be done for large system to find out most sensitive lines. The optimal location for the compensator should be provided to remove congestion.

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