International Journal of
Electrical Engineering and Futuristic Technology
A Peer Reviewed Journal

A D PUBLICATION

IJEEFT 01 (2017) 031-038

Linear Sensitivity Indices And Series Compensation For Transmission Congestion Management In Power System

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A B S T R A C T : The transmission congestion is one of the major problems in deregulated electricity market. The transmission network is unable to accommodate the desired transactions due to violation of operating limits of power system. So transmission congestion is occurred. It affects system security and electricity cost. To maintain the power flow limits in the transmission lines, sufficient amount of reactive power supports are needed. This paper describes the congestion due to N-1 contingencies for line outage and generator outage. The analysis is done based on linear sensitivity factors that are line outage distribution factors and generator shift factors. The series compensation is provided to the most sensitive lines. The results are carried out on 6 bus system using MATLAB programming.

Keywords: Congestion management, linear sensitivity index, series compensation, FACTS

1. Introduction

The electricity market becomes competitive nowadays due to deregulation [3]. The electricity demand increases as population increases. In competitive electricity market, it is important to have knowledge about the amount of power transfer from point to point or from generators to loads in a power system at this moment and in the future from the viewpoint of system operation and planning. Due to increase in load demand, the critical operating limits are reached, and due to violation of operating limits the congestion occurs. One of the important functions of system operator is to manage the congestion as congestion affects the system security and economy of power system. The outages of any generators, outage of any lines or sudden increase in load demand are the various reasons for congestion occurrence. So it is important to maintain the system security and the cost of energy should be less as possible. The power system should operate reliably to continually supply the energy to the consumers. For the security point of view, the violations to power system limits are monitored continuously by the system operator.

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Journal access: www.adpublication.org

The electricity market is directly affected by transmission congestion. Congestion does occur in both vertically integrated market and unbundled deregulated market. The congestion is managed easily in vertically bundled market as only one utility is there for transmission and generation system. congestion management in deregulated environment is complex.

2. Congestion Management Methods

There are various methods in the literature for the congestion management [6]. There are two types of methods for congestion management that are market based methods and non-market based methods. The market based methods are the methods having technical constraints only, market economy is not considered. These methods are out-aging of the most congested line, operation of transformer taps or phase shifters or operation of series FACTS devices. The type is market based methods in which rescheduling of generation and load curtailment are included. The term which is related to congestion management is ATC (Available Transfer Capacity) [2]. It is the additional transfer capacity remaining after committed uses for future demand of load. Firstly the system operator calculates the ATC and one could know that if there is enough transfer capacity for transaction or not. To manage congestion, the power flow pattern change to reduce the flow of the congested line in power system. Accordingly the generation or load or both changes with maintaining security and stability of system.It can be done by changing the generation or load or by both with system security and reliability.

3. FACTS devices and congestion management

One of the methods to relieve congestion is use of FACTS devices [1]. FACTS devices have many advantages. By using FACTS devices, the system performance improves and the flow of overloaded line reduces. FACTS devices increase the system stability by reducing the system losses. First of all, the line flows of various lines are checked for various contingencies. For any outage of line or generator, if the line flow exceeds its thermal limit then the congestion occurs. For various line contingencies and generator outages, the most sensitive line to the outage is found out using various sensitivity factors that are line outage distribution factors, generation shift factors or performance index etc. Various FACTS devices like thyrister controlled series capacitors (TCSC), thyrister controlled phase shifters (TCPS), unified power flow controllers (UPFC) are placed in series with the most congested line so that the reactance of line reduces as the capacity of that line enhances and flow of line becomes within their limits [9,10]. The ATC is also increased with FACTS devices. The optimal location of the device and optimal size are the important factors with FACTS devices in congestion management [1].

4. Linear sensitivity indices

The system operator has to continuously check the limits of power system in real time operation for security [7]. There are various possible outages of lines and generators for secure operation of power system. It is not possible to consider all outages and violation of limits are not solved quickly. The solution to that problem is linear sensitivity index that gives the results very quickly. The linear sensitivity indices defined as he appropriate change in power flow for any change in power generation or power change in any other line [5].

These sensitivity factors give idea about the sensitivity of the line and overloading of particular line for various possible outages. Two types of sensitivity indices are used for power system security studies.

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

DC load flow is used to derive these sensitivity factors and approximate but quick solution for change in power flow in the power system is found out [8].

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,

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

Where, *l* = line index

i =bus index

Δfl = change in megawatt power flow on line *l*

ΔPi = change in generation at bus *i*

Xni = n^{th} element of reactance matrix from θ vector

Xmi = m^{th} element of reactance matrix from θ 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,

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

Where, Δfl = change in MW flow on line l

fk° = original flow on line k before it was outaged.

These sensitivity factors are used to find out the most sensitivity line regarding various contingencies. The lines having the highest value of sensitivity are the most sensitive lines. So the congestion is occurred due to overloading of particular line. To remove this congestion and to reduce the flow of overloaded line, the series compensation is provided to that overloaded line, so that the reactance of that line decreases and the capacity of that line increases and the flow becomes within their operating limits [4].

Steps for congestion management using series compensation and linear sensitivity factors:

1. Read system data input
2. Perform load flow using NR method (Normal case)
3. Calculation of sensitivity indices (Generation shift factor and line outage distribution factors) to find out the most sensitive line.
4. Perform load flow using NR method for various contingencies, i.e. Generator outage, line outage
5. Series compensation is provided to the most sensitive line using series capacitor or FACTS Device.
6. Perform load flow after series compensation.

5. Simulations and results

The sample 6 bus system is used for the simulation work and taken from the reference [7]. 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. Fig.1 shows the sample 6 bus system which has 3 generator buses and 3 load buses.

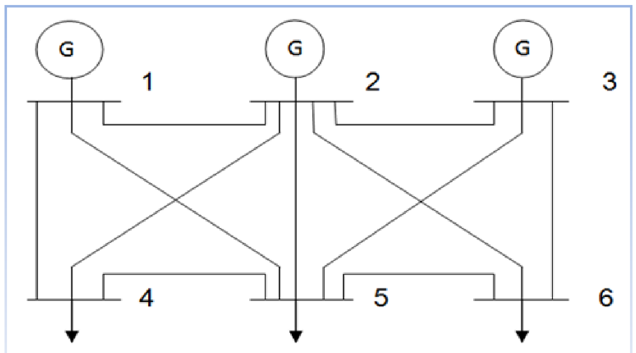

Fig.1: Sample 6 bus system

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

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:

Step 1: Reactance matrix X (sensitivity matrix)

Table 3: 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 2: Generation shift distribution factor $ali = \frac{\Delta fl}{\Delta Pi} = \frac{1}{xl}(Xni - Xmi)$

From Table 4, we can say that for outage of generator 2 and outage of generator 3, line 1 (1-2) and line 2 (1-4) are the most sensitive lines.

Table 4: Generation shift factors

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

Step 3: Line outage distribution factors $dl, k = \frac{\Delta fl}{fk^{\circ}} = \frac{\frac{xk}{xl}(Xin - Xjn - Xim + Xjm)}{xk - (Xnn - Xmm - 2Xnm)}$

From table 5, we can see that for the outage of line 1(1-2), line 2 (1-4) is the most congested line as the sensitivity factor of that line is highest. Also for outage of line 7 (2-6), the most congested line is line 9 (3-6). Similarly, the other lines with their sensitivity are shown in Table 5.

Table 5: Line outage distribution factors

Line	1 (1-2)	2 (1-4)	3 (1-5)	4 (2-3)	5 (2-4)	6 (2-5)	7 (2-6)	8 (3-5)	9 (3-6)	10 (4-5)	11 (5-6)
1 (1-2)	0.0000	0.6353	**0.5427**	-0.1127	-0.5031	-0.2103	-0.1221	-0.1369	0.0135	0.0096	0.1316
2 (1-4)	**0.5948**	0.0000	0.4573	-0.0331	**0.6121**	-0.0618	-0.0359	-0.0403	0.0040	-0.3269	0.0387
3 (1-5)	0.4052	0.3647	0.0000	0.1458	-0.1090	0.2721	0.1580	0.1772	-0.0174	0.3174	-0.1703
4 (2-3)	-0.1029	-0.0323	0.1783	0.0000	0.1242	0.2262	0.4662	-0.3995	-0.5253	0.1706	0.1320
5 (2-4)	-0.5884	**0.7647**	-0.1708	0.1591	0.0000	**0.2969**	0.1724	0.1933	-0.0190	**-0.6731**	-0.1858
6 (2-5)	-0.1875	-0.0589	0.3250	0.2209	0.2264	0.0000	0.2394	0.2685	-0.0264	0.3110	-0.2580
7 (2-6)	-0.1213	-0.0381	0.2102	0.5073	0.1464	0.2667	0.0000	-0.1992	**0.5842**	0.2011	0.4433
8 (3-5)	-0.1175	-0.0369	0.2036	-0.3755	0.1418	0.2583	-0.1720	0.0000	0.4747	0.1948	-0.4246
9 (3-6)	0.0146	0.0046	-0.0253	**-0.6245**	-0.0176	-0.0321	**0.6382**	**0.6005**	0.0000	-0.0242	**0.5567**
10 (4-5)	0.0065	-0.2353	0.2865	0.1259	-0.3879	0.2350	0.1365	0.1530	-0.0150	0.0000	-0.1471
11 (5-6)	0.1067	0.0335	-0.1849	0.1172	-0.1288	-0.2646	0.3618	-0.4013	0.4158	-0.1769	0.0000

Step: 4 NR load flow is performed for various N-1 contingencies that are line outages and generator outages

Here, the NR load flow gives the power flows of each line and MVA flows which is shown in Table 6 and 7 respectively. The red colour values shows that the line exceeds its operating limit and the overloading of that line should be removed by series compensation.

Table 6: MW power flow during various contingencies

LINE NO	1-2 30	1-4 50	1-5 40	2-3 20	2-4 40	2-5 20	2-6 30	3-5 20	3-6 60	4-5 20	5-6 30
Normal case	**28.690**	**43.585**	**35.601**	**2.930**	**33.091**	**15.515**	**26.249**	**19.117**	**43.773**	**4.083**	**1.614**
1-2	-	60.696	47.459	-0.180	17.077	10.017	22.933	15.775	44.013	4.507	4.640
1-4	60.643	-	53.555	1.794	68.440	12.602	24.443	17.667	44.050	-6.196	3.264
1-5	50.393	61.496	-	9.800	26.310	27.481	34.372	27.011	42.728	14.292	-4.833
2-3	28.360	43.472	36.040	-	33.512	16.161	27.803	18.109	**41.891**	4.390	1.973
2-4	13.746	63.862	32.841	8.023	-	23.771	31.741	24.822	43.128	-10.153	-2.913
2-5	26.250	43.090	39.658	6.631	**37.890**	-	30.970	23.606	42.991	8.105	-1.949
2-6	25.982	42.884	39.894	15.681	37.500	22.058	-	14.662	60.903	7.639	10.980
3-5	26.772	43.208	38.531	-5.096	37.266	20.927	22.886	-	**54.868**	7.572	-5.704
3-6	33.637	45.730	36.095	-19.045	31.451	14.908	55.273	40.578	-	4.403	20.436
4-5	29.074	42.124	37.044	3.726	**30.528**	16.778	27.114	20.029	43.652	-	0.926
5-6	29.193	43.851	35.146	30340	32.920	15.066	26.930	18.689	**44.609**	4.107	-
G2	53.03	64.61	51.64	6.07	14.40	11.51	26.74	11.82	39.14	5.21	5.98
G3	59.78	63.49	55.70	21.78	19.44	43.16	-0.55	21.67	10.12	8.57	21.01

For outage of line 1 (1-2), the flow of line 2 (1-4) is 60.696 MW which exceeds its limit of 50 MW. Also MVA flow is 62.943 MVA which exceeds the limit of 60 MVA. For outage of generator G3, the flow of line 2(1-4) is 63.49 MW exceeds the limit of 60 MW. Similarly, for all other N-1 contingencies of line outages and generator outages, the MW flows and MVA flows are shown in Table 6 and Table 7 respectively.

Table 7: MVA flow with various contingencies

LINE NO	1-2 40	1-4 60	1-5 50	2-3 40	2-4 70	2-5 30	2-6 90	3-5 70	3-6 80	4-5 20	5-6 40
Normal flow	**32.570**	**48.005**	**37.338**	**12.614**	**56.710**	**21.827**	**29.030**	**30.042**	**74.857**	**6.411**	**9.797**
1-2	-	**62.943**	48.381	11.670	55.165	19.777	26.543	29.221	74.860	6.599	11.573
1-4	**61.132**	-	57.604	15.621	**96.536**	19.195	26.498	31.181	78.421	11.213	10.536
1-5	52.292	**67.156**	-	13.389	53.818	35.763	38.160	39.040	75.953	14.343	13.868
2-3	32.214	47.915	37.735	-	56.807	22.159	30.288	29.766	**74.185**	6.722	9.924
2-4	16.329	**92.489**	37.017	15.448	-	30.018	34.079	36.700	77.371	18.415	12.331
2-5	29.931	48.592	44.506	10.992	61.366	-	35.244	36.807	**75.126**	8.171	13.640
2-6	29.641	47.942	42.774	16.842	59.595	28.700	-	26.698	**97.430**	8.480	11.889
3-5	30.496	48.812	44.196	11.828	61.656	32.402	28.043	-	**84.724**	7.572	16.288
3-6	33.761	58.279	45.403	30.039	47.935	23.545	**81.525**	53.278	-	4.433	26.817
4-5	32.986	47.309	39.016	12.965	**58.291**	23.339	29.861	31.449	75.428	-	10.380
5-6	33.114	48.478	37.839	12.790	57.659	23.634	29.074	32.481	**73.209**	5.273	-
G2	**68.10**	**85.90**	64.10	15.90	24.00	13.70	28.30	21.80	72.90	6.10	7.10
G3	**68.40**	**91.00**	79.60	32.80	27.00	58.80	0.90	34.30	10.80	9.90	28.70

Step:5 Series compensation is provided using TCSC to the most sensitive lines for various outages

From Table 8, it is conclude that, line 1-4 and 3-6 are the most sensitive lines and series compensation is required to remove congestion on those lines. After providing series compensation, the flow of line becomes within their operating limits as capacity of tha line increases as shown in Table 9.

Table 8: Series compensation to the most sensitive lines for various outages

Out line/ gen	Compensation to line	MW	MVA
1-2	30% to 1-4	66.882	69.127
1-4	30% to 2-4	72.577	98.723
1-5	30% to 1-4	70.271	74.462
2-4	40% to 1-4	70.536	96.394
2-6	20% to 3-6	63.616	98.577
3-5	10% to 3-6	56.370	87.245
3-6	10% to 2-6	57.516	83.157
G2	30% to 1-4	70.991	72.848
G3	20% to 1-4	63.264	65.334

Table 9: MVA Flows with Series Compensation

LINE NO	1-2 85.7	1-4 100	1-5 85.7	2-3 40	2-4 85.7	2-5 30	2-6 100	3-5 88	3-6 100	4-5 20	5-6 40
1-2	-	**69.127**	42.362	11.901	51.719	20.123	27.308	29.220	74.751	8.216	10.752
1-4	**61.956**	-	56.442	15.364	98.723	17.843	25.583	30.022	77.964	8.294	10.422
1-5	43.825	**74.462**	-	13.124	51.216	35.142	37.703	38.576	75.659	15.657	13.790
2-3	32.214	47.915	37.735	-	56.807	22.159	30.288	29.766	74.185	6.722	9.924
2-4	12.476	**96.394**	33.034	14.826	-	27.962	33.020	34.658	76.473	13.112	11.109
2-5	29.931	48.592	44.506	10.992	61.366	-	35.244	36.807	75.126	8.171	13.640
2-6	29.818	48.024	42.662	16.522	59.722	28.813	-	23.307	**98.577**	8.189	9.903
3-5	30.581	48.778	43.889	11.557	61.460	31.981	26.205	-	**87.245**	7.432	17.150
3-6	46.313	70.991	43.438	30.298	47.480	22.579	**83.157**	52.346	-	4.002	24.047
4-5	32.986	47.309	39.016	12.965	58.291	23.339	29.861	31.449	75.428	-	10.380
5-6	33.114	48.478	37.839	12.790	57.659	23.634	29.074	32.481	73.209	5.273	-
G2	51.473	**72.848**	44.522	11.751	52.711	19.795	26.823	29.099	74.764	8.405	11.161
G3	60.313	**65.334**	56.167	29.951	54.933	22.590	41.915	31.020	70.584	10.537	15.009

Conclusion

The transmission congestion is very critical problem to deregulated electricity market. Using linear sensitivity factors (GSDF and LODF), we can find the most sensitive line for various contingencies. The series compensation is provided to the most sensitive lines using TSCS and the flows of the overloaded lines are within their limits after compensation. For compensation various FACTS devices can also be used with the most sensitive line as FACTS devices have many advantages.

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