Linear Sensitivity Analysis and Series Compensation for Transmission Congestion Management

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Abstract

Optimal utilization of transmission system without congestion in the network is most important as congestion can violet the security of the system. Sufficient amount of reactive power support needs to be provided in the system in order to maintain the power flow limits on transmission lines and voltage limits at bus bars. This Paper focuses on analysis of congestion occurrence with N-1 contingencies for line flow limits in case of line and generator outages using linear sensitivity factors and congestion management using series compensation. Generation shift factor and line outage distribution factor are used to find sensitive lines and series compensation in two stages are applied to the most sensitive lines to relieve congestion. Standard IEEE 6 bus test system is used to analyze contingencies and congestion mitigation. All the simulations are performed using power world simulator version 19.0. Mathematical calculations are also performed for the same 6-bus system for validation of results.

1 Introduction

1.1 Restructured power system and challenges

In the recent years, major changes have been introduced into the structure of electric power utilities all over the world. The reason for the introduction of such Major change in existing power utility structure is the scarcity of financial resources available with government and necessity of improving technical and commercial efficiency in the operation of the power system by means of deregulating and restructuring the power industry and opening it up to the private competition. A restructured power system allows the power supply to function competitively, as well as allowing consumers to choose suppliers of electric energy (M. Shahidehpour, 2000)Restructuring in electric power industry has caused an intensive usage of transmission grid.Also,lack of coordination between generation and transmission utilities or as a result of unexpected contingencies such as generation outages, sudden

increase of load demand, or failure of equipments, causes the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested (P.Bajpai, 2006)

Restructuring in power system has introduced many new technical challenges. Some of the technical challenges are operation of transmission system at optimum level by maintaining all system operational constraints,Ancillary Services Management, Optimal Bidding for a Gencos, Transmission Pricing, enhancement of available transfer capability, determination of total transfer capability, to satisfy most of bilateral transaction keeping in view economy, security and congestion management. Some of the Economical issues associated with deregulation are, active and reactive power spot price and wheeling charges (NERC, 1997) Power system all over the world has been forced to operate in almost their full capacities due to the economical, environmental, and political constraints whereas the almost of electric power that can be transmitted between two buses through a transmission grid is limited by technological and economical constraints. Power flow should not be allowed to increase a level where a random event could cause grid to collapse. Congestion is a situation where the demand for transmission capacity exceeds the transmission network capabilities, which might lead to a violation of network security limits. All the market players try to get the benefit of cheaper source and greater profit margins, which may lead to congestion of certain part of transmission grid. Congestion management is most priority management problem, which the system operator has to face very frequently.

1.2 Congestion Management Technique

Congestion Management of transmission network is to reduce the power flow in the congested lines by changing the power flow pattern. Primarily, this process of redispatch can be done by changing generation or modifying load, or both, without compromising the system security and quality of service. In a competitive environment, all the Generation Companies and Distribution Companies plan their transactions ahead of time. However, by the time of implementation of transactions, there may be congestion in some of the transmission lines. Hence, Independent system operator in a competitive electricity market is responsible for serving the necessary actions to ensure that no violations of the grid constraints occur (FERC, 1999) Congestion management approaches are based on issuing orders by the ISO to various parties to reschedule their contracts, re-dispatch generators, use various control devices or compensators, or shed loads in the extreme conditions when these measures are not able to manage the congestion. Basic approach is based on centralized optimization with some form of optimal power flow program or depending upon the control measures executed by the SO for congestion relief (R.D. Christie, 2000)

2 Linear Sensitivity Analysis

Several sensitivity factors Viz. Generalized generation distribution factor and generalized line outage distribution factors can be used to find congestion in a particular line. For the same contingencies has to be defined for the components of the system e.g. generators or transmission lines that are not in operation. This situation may arise in the system due to the violation of engineering constraints or maintenance schedule. The effect of this unavoidable situation may be quite severe as it can cause power flow congestion in the line. Transmission lines have thermal limit of carrying power and if the power flow exceeds that limit, which is quite expected during contingency, the line is said to be congested (Sen S., 2011). To avoid such congestion issues preliminary approach is presented of contingency analysis using linear sensitivity factors for realizing congestion in proposed system. Line and bus data of sample 6 bus system is taken from (Bruce, 1984)

2.1 Mathematical calculation using sensitivity factors

The linear sensitivity factors estimate the Changes in different line flows for any particular outage condition without the need of full AC power flow solution. There are two types of sensitivity factors:
1. Generation outage sensitivity factor (GOSF)
2. Line outage sensitivity factor (LOSF)
Steps for GOSF calculations are:
Step-1: Formation of Ybus:

$$X12 = 0.20\,ohm;\ Y12 = \frac{1}{X12} = \frac{1}{0.2} = -j5\,mho$$

$$X14 = 0.20\,ohm;\ Y14 = \frac{1}{X14} = \frac{1}{0.2} = -j5\,mho$$

$$X15 = 0.30\,ohm;\ Y15 = \frac{1}{X15} = \frac{1}{0.3} = -j3.33\,mho$$

As Bus 1 is not connected with Bus 3 & 6.So, $Y13 = 0\,mho\ \&\ Y16 = 0\,mho$

Total Admittance at bus 1 is,

$$Y11 = Y12 + Y13 + Y14 + Y15 + Y16$$

$$Y11 = (-j5) + 0 + (-j5) + (-j3.33) + 0$$

$$Y11 = (-j13.33)\,mho$$

Similarly calculated for each bus and formulated Ybus as below,

$$Ybus = \begin{bmatrix} -j13.33 & j5.0 & 0 & j5.0 & j3.33 & 0 \\ j5.0 & -j27.33 & j4.0 & j10.0 & j3.33 & j5.0 \\ 0 & j4.0 & -j17.84 & 0 & j3.84 & j10 \\ j5.0 & j10.0 & 0 & -j17.5 & j2.5 & 0 \\ j3.33 & j3.33 & j3.84 & j2.5 & -j16.34 & j3.33 \\ 0 & j5.0 & j10 & 0 & j3.33 & -j18.33 \end{bmatrix}$$

Step-2: Formation of B' Matrix: 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.

$$B' = \begin{bmatrix} 27.33 & -4.0 & -10.0 & -3.33 & -5 \\ -4.0 & 17.84 & 0 & -3.84 & -10.0 \\ -10.0 & 0 & 17.5 & -2.5 & 0 \\ -3.33 & -3.84 & -2.5 & 16.34 & -3.33 \\ -5.0 & -10.0 & 0 & -3.33 & 18.33 \end{bmatrix}$$

Step-3: Formation of X Matrix: $X = [B']^{-1,}$ $\begin{bmatrix} 0.0941 & 0.0805 & 0.0630 & 0.643 & 0.0813 \\ 0.0805 & 0.1659 & 0.0590 & 0.0908 & 0.1290 \\ 0.0630 & 0.0590 & 0.1009 & 0.0542 & 0.0592 \\ 0.0643 & 0.0908 & 0.0542 & 0.1222 & 0.0893 \\ 0.0813 & 0.1290 & 0.0592 & 0.0893 & 0.1633 \end{bmatrix}$

Step-4: Calculating GOSF, $[\Delta\S] = [XF]\,[\Delta P]$, Where $[\Delta P] = \begin{bmatrix} -1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

1st element is consider as (-1) as bus1 is swing bus and 2nd element is consider as (-1) as calculation of GSF is for outage of generator Remaining element need to be considered as zero.

$$[\Delta\S] = \begin{bmatrix} 0 \\ 0.094125 \\ 0.080513 \\ 0.062977 \\ 0.064343 \\ 0.081285 \end{bmatrix} a_i^l = \frac{1}{X_l}\left[\Delta\S_{pm}^i - \Delta\S_{pn}^i\right], \Delta\S_{pm}^i = \text{mth element of } [\Delta\S], \Delta\S_{pn}^i = \text{nth element of } [\Delta\S]$$

$\frac{1}{Xl}$ = Inverse of line reactance, as per the data given

Sample calculation for Bus-2 line 7 as given below:

$a_i^l = \frac{1}{X_l}\left[\Delta\S_{pm}^i - \Delta\S_{pn}^i\right]$, $a_2^7 = \frac{1}{0.2}[0.080513 - 0.128954]$, $a_2^7 = 5\,[0.048439]$, $a_2^7 = 0.31147$

Generation shift factor for Bus-2 and 3 are similarly calculated and shown in table no.1 as given below

Line No.	Buses m→n	Bus-1	Bus-2	Bus-3
1	1-2	0	-0.47062	-0.40256
2	1-4	0	-0.31489	-0.29487
3	1-5	0	-0.21448	-0.30256
4	2-3	0	0.05445	-0.34156
5	2-4	0	0.31147	0.21539
6	2-5	0	0.09927	-0.03418
7	2-6	0	0.06420	-0.24221
8	3-5	0	0.06219	0.28898
9	3-6	0	-0.00773	0.36949
10	4-5	0;	-0.00341	-0.07948
11	5-6	0	-0.05647	-0.12729

Table 1: Generation shift sensitivity factors (GSF)

Step-5: Calculating Line outage distribution factor:

$d_{l,k} = \frac{\Delta F_i}{F_k^0}$,

$d_{l,k}$ =Line outage distribution factor

where, Delta F_i = Change in MW flow of line l and F_k^0 = Intial power flow in line k (before outage)
Let line, l be connected between buses I and j.

Delta $f_i = \frac{1}{x_l}(\Delta\S_i - \Delta\S_j)$, Using both above Equation we get

$d_{l,k} = \frac{\text{Delta } F_i}{F_k^0}$, $d_{l,k} = \frac{\frac{1}{x_l}(\Delta\S_i - \Delta\S_j)}{P_{mn}} = \frac{1}{x_l}\left(\frac{\Delta\S_i}{P_{mn}} - \frac{\Delta\S_i}{P_{mn}}\right) = \frac{1}{x_l}(B_{mn}^i - B_{mn}^j)$

If i and j are not reference buses, then

$d_{l,k} = \frac{1}{x_l}\frac{((X_{im} - X_{in})x_k - (X_{jm} - X_{jn})x_k)}{X_k - (X_{mn} + X_{nn} - 2X_{mn})}$

Where, Line l is connected from bus i to j, Line k is connected from bus m to n. A sample calculation is shown below. Consider element d5, 4.This is the factor for line 5, when line 4 faces an outage. Here l = 5 and k = 4. Line is connected between 2 and 4 (i-j) and line 4 between 2 and 3 (m-n).
We use Eq. To get

$d_{l,k} = \frac{X_k}{x_l}\frac{(X_{im} - X_{in} - X_{jm} + X_{jn})}{X_k - (X_{mm} + X_{nn} - 2X_{mn})} d_{5,4} = \frac{x_4}{x_5} \times \frac{(X_{22} - X_{23} - X_{42} + X_{43})}{x_4 - (X_{22} + X_{33} - 2X_{23})}$

$$X_F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0941 & 0.0805 & 0.0630 & 0.643 & 0.0813 \\ 0 & 0.0805 & 0.1659 & 0.0590 & 0.0908 & 0.1290 \\ 0 & 0.0630 & 0.0590 & 0.1009 & 0.0542 & 0.0592 \\ 0 & 0.0643 & 0.0908 & 0.0542 & 0.1222 & 0.0893 \\ 0 & 0.0813 & 0.1290 & 0.0592 & 0.0893 & 0.1633 \end{bmatrix} d_{5,4} = \frac{0.25}{0.1} \times \frac{(0.0941 - 0.0630 - 0.0805 + 0.0590)}{0.25 - (0.0941 + 0.1659 - 2\times 0.0805)} = 0.159$$

Line-outage distribution factors of all the other lines are similarly calculated and shown in table 2

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l/k	k=1	k=2	k=3	4	5	6	7	8	9	10	11
l=1	0	635	543	-112	-503	-210	-122	-137	14	10	132
l=2	595	0	457	-33	612	-61	-35	-40	4	-327	39
l=3	405	365	0	146	-109	272	-158	177	-17	317	-170
l=4	-103	-32	178	0	124	226	-466	-400	-525	171	132
l=5	-588	765	-170	159	0	297	172	193	-19	-673	-186
l=6	-188	-59	325	221	226	0	239	269	-26	311	-258
l=7	-121	-38	210	507	146	267	0	-199	584	201	443
l=8	-118	-37	204	-375	142	258	-172	0	475	195	-425
l=9	15	5	-25	-624	-17	-32	638	601	0	-24	557
l=10	7	-235	287	126	-387	235	137	153	-15	0	-147
l=11	107	34	-184	117	-128	-265	362	-401	416	-177	0

Table 2 **Line outage distribution factor (LODF)**

3   Simulation and results

Similar sample 6 bus system is used to perform contingency analysis using sensitivity factors. Fig no.1 shows GSF/TLR sensitivity analysis with the outage of a generator no.3 using PWS (PWS, 2013)and table 3 shows the generation shift factors for the same.
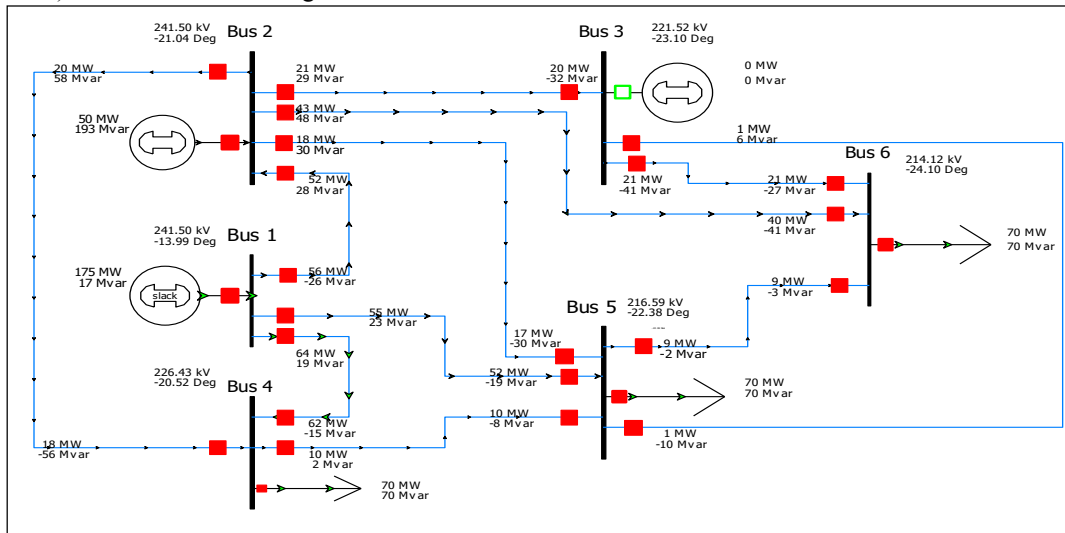

Figure 1: Simulation circuit of sample 6 bus system for GSF/TLR analysis for outage of generator 3

Bus No	1>>2	1>>4	1>>5	2>>3	2>>4	2>>5	2>>6	3>>5	3>>6	4>>5	5>>6
Bus 1	0	0	0	0	0	0	0	0	0	0	0
Bus 2	-470	-314	-214	54	311	99	64	62	-7	-3	-56
Bus 3	-402	-294	-302	-341	215	-34	-242	289	369	-79	-127
Bus 4	-314	-504	-180	16	-379	29	18.9	18	-2	116	-16
Bus 5	-321	-271	-407	-105	101	-192	-124	-120	15	-169	109.6
Bus 6	-406	-296	-297	-190	220	-26	-410	152	-343	-75.2	-246.7

x 10^{-3}   **Table 3** Simulation results for GSF for outage of gen-3

Line outage distribution factor sensitivity analysis is similarly performed on same system to analyze all possible contingencies and finally most sensitive lines considering total MVA flows. Fig 2 shows LODF analysis for outage of line 1and table 4 represents simulation results of LODF for outage of all 11 lines one by one.
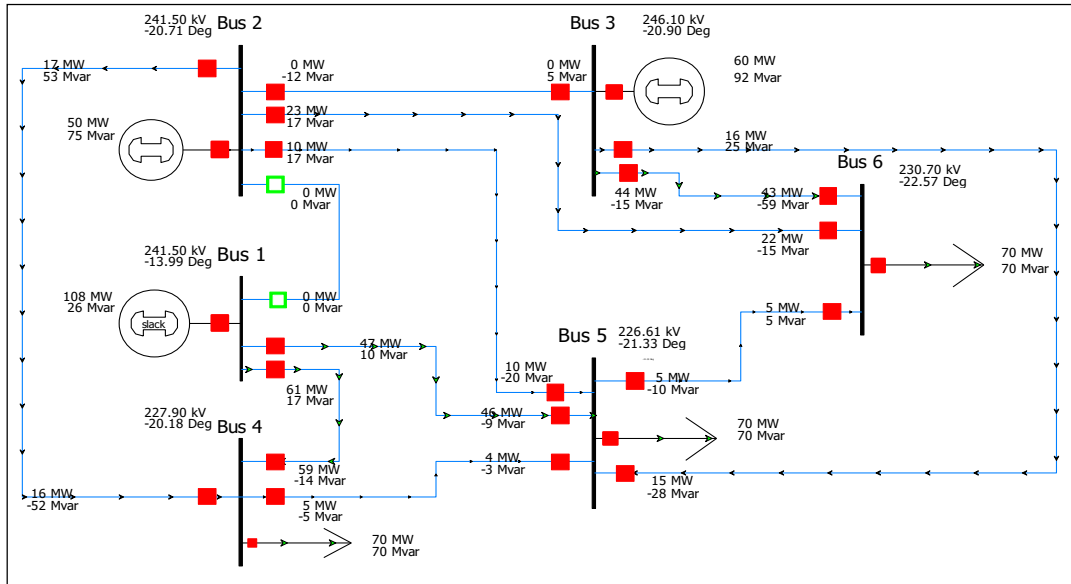

Figure 2: Simulation circuit of 6-bus sample system for LODF (outage of 1-2)

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

Table 4 Simulation results for LODF sensitivity analysis

Series compensation is provided on the most sensitive lines based on contingency analysis. Fig 3 shows simulation circuit with compensation stage 1 in which even in case of outage of line number 1 (1-2), all other line flows are within their limits. Similarly, all possible contingencies are analyzed and represented in table no.5 with compensation.
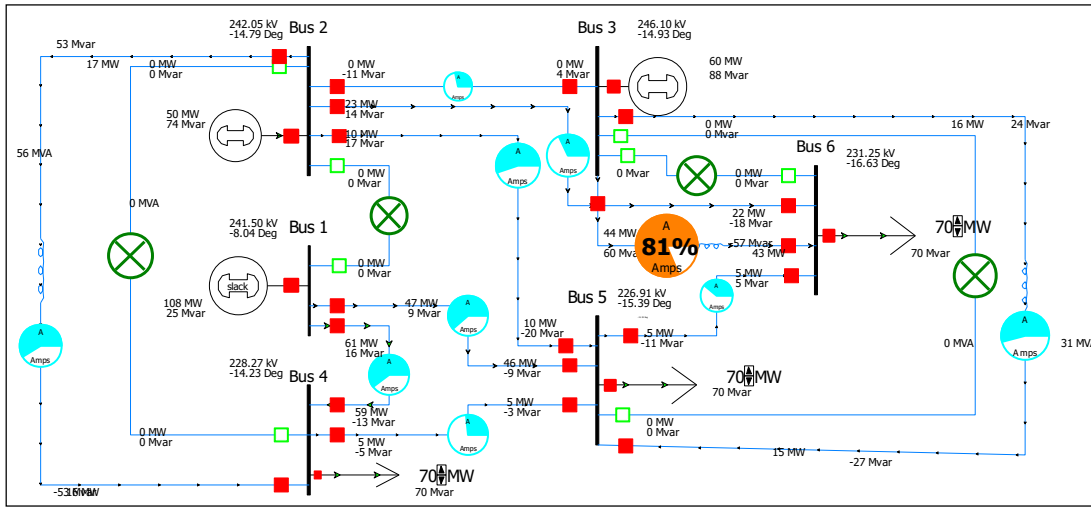
Figure 3: Simulation circuit with compensation (outage of 1-2)

Contingency		1>>2	1>>4	1>>5	2>>3	2>>4	2>>5	2>>6	3>>5	3>>6	4>>5	5>>6
Normal												
Power flow		32.58	48	37.33	12.59	56.71	21.83	29.02	31.71	74.85	6.41	9.8
1	1>>2	-	62.74	48.31	10.68	59.09	22.54	28.78	30.99	74.1	6.54	11.55
2	1>>4	65.1	-	53.61	23.52	92.04	15.57	23.78	50.47	86.54	14.34	14.25
3	1>>5	53.33	65.92	-	21.84	53.98	33.03	35.19	43.22	83.84	14.42	15.20
4	2>>3	30.69	48.95	38.04	-	54.39	22.58	30.25	32.48	76.62	6.96	10.00
5	2>>4	28.98	90.87	36.16	9.95	-	36.15	41.05	34.06	67.29	19.72	12.81
6	2>>5	32.18	47.32	43.47	11.54	63.66	-	35.82	38.14	75.93	10.01	14.54
7	2>>6	35.41	37.88	38.53	29.13	87.06	17.25	-	50.33	90.86	13.4	19.09
8	3>>5	28.72	50.32	45.02	15.23	58.96	31.27	27.97	-	87.88	7.46	16.65
9	3>>6	34.73	60.14	46.89	32.24	45.78	23.7	81.07	54.67	-	7.56	28.03
10	4>>5	32.47	47.69	39.08	13.97	57.53	24.31	30.54	33.12	76.2	-	10.37
11	5>>6	32.79	48.67	37.89	13.41	57.16	24.91	29.87	34.05	73.65	5.87	-
12	G1	55.2	69.32	49.11	33.01	35.74	11.73	23.86	43.7	90.8	8.66	12.02
13	G2	68.35	90.91	79.63	33.33	28.78	27.01	58.84	2.84	34.29	13.26	11.93

Table 5 Simulation results with compensation stage 1

For stage 2 compensation variable capacitor is connected with the same lines as shown in fig 3 and change in total MVA flow obtained for each outage are tabulated in table no.6

Sr No.	Outages	Change in total MVA flow	Sr No.	Outages	Change in total MVA flow
1	Normal system flow	361	8	Line out 7	419
2	Line out 1	355	9	Line out 8	369
3	Line out 2	439	10	Line out 9	415
4	Line out 3	420	11	Line out 10	365
5	Line out 4	351	12	Line out 11	358
6	Line out 5	377	13	G2 Out	433
7	Line out 6	373	14	G3 Out	449

Table 6 Simulation results with compensation stage 2

4 Conclusion

In this paper using linear sensitivity factors all the possible contingencies were analyzed and most sensitive lines were found out those contributes in causing congestion in system. Static capacitors were connected in series on sensitive lines which results in reduction of MVA flows of lines during all contingencies and hence mitigation in congestion. Compared to static capacitors, Variable capacitors can provide more tuned compensation to the system.

5 Acknowledgment

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