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Transmission Congestion Management Considering Voltage Security Using Bender Decomposition

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Abstract— This project work is aimed to ensure the system stable under N-1 contingency conditions. Eigen values were calculated and the rank of system buses based on their contribution to voltage instability of system under all possible contingencies. Then based on the ranking, the most suitable bus is selected for applying the Tie-Lines with switches to ensure that system is securable at any contingency condition. The IEEE 30-bus test system is used for N-1 contingency analysis. In order to relieve congestion without violating voltage security the optimal power flow problem with AC constraints are solved by using Bender decomposition method. . It is also shown that Transmission Switching(TS) based on DC optimal power flow (DCOPF) formulation as used in the literature may jeopardize system security and in some cases result in voltage collapse due to the shortcomings in its simplified models.

***Key words* - Benders decomposition, optimal power flow (OPF) and N- 1 contingency, Transmission congestion, Transmission switching (TS).**

I. INTRODUCTION

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the system. When a power system is subjected to a sudden increase of reactive power demand following a system contingency, the additional demand is met by the reactive power reverses and the system settles to a stable voltage level. However, it is possible, because of a combination of events and system conditions that the additional reactive power demand may lead to voltage collapse, causing a major breakdown of part or all the system. Voltage instability within the power system has serious consequences including voltage collapse and system blackout.

As one of the important and suitable solutions for congestion management, optimal network reconfiguration has been employed by operators to improve operating conditions. Generally, two types of switches are used for this purpose; sectionalizing switches and tie switches, which are normally closed or normally open, respectively. From time to time, the network operators change the state of these switches in order to enhance system security. The network switching can be classified into two main categories: 1) opening or closing branches and 2) substation switching.

The proposed approach is based on DC Optimal Power Flow (DCOPF) which utilizes TS in order to remove congestion. They have also used TS to relieve congestion with contingency analysis where problem is formulated as a Mixed Integer Programming and solved based on DCOPF.

II.CONGESTION MANAGEMENT

A. *Transmission Congestion*

Transmission congestion can be defined as the condition where desired transmission line-flows exceed reliability limits. Congestion management can be defined as the actions taken to avoid or relieve congestion. More broadly, congestion management can be considered any systematic approach used in scheduling and matching generation and loads in order to manage congestion. Transmission line congestion can be reduced by using Tie lines devices by controlling the power flow. The power industry was much easier without transmission limits.

B. *Contingency*

In power system the term Contingencies referring to disturbances such as transmission element outages or generator outages may cause sudden and large changes in both the configuration and the state of the system.

Contingencies may result in severe violations of the operating constraints. Consequently, planning for contingencies forms an important aspect of secure operation.

1 .N-1 Contingency Criteria

The power systems have been expected to remain operational following a single contingency, the widely known (N-1) criterion. A contingency, as defined by North American Electric Reliability Council (NERC), is the unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, or switch. Systems are designed to withstand one contingency, i.e., (N-1) criterion. Unfortunately, some events trigger others and cascading failures might occur. Therefore, not all contingencies are equal, and the number of components in a given system makes it prohibitive to evaluate all (single) contingencies. The system is considered (N-1) secure when a single contingency will not cause any system limits to be violated. Some power systems are designed to withstand specific (N-2) and (N-3) contingencies.

III.PROBLEM FORMULATION BASED ON BENDER DECOMPOSITION

Benders decomposition is a solution method for solving certain large-scale optimization problems. Instead of considering all decision variables and constraints of a large-scale problem simultaneously, Unlike the traditional approach, these algorithms divide the decision making process into two stages. The main purpose of this method is to minimize the Transmission congestion generation with regards to physical system constrains such as line thermal and bus voltage limits. For example, the bus angles across the system have to be maintained between upper and lower limits or bus voltages across the system should not exceed certain levels.

The existing methods have not examined the impact of switching on important system variables such as bus voltages and transmission losses. But in this method it alleviates congestion and takes into consideration the impacts of switching on mentioned variables. In each search trial of the proposed procedure switching is performed and this cycle will continue until no further optimal TS can be found.

A. LOAD FLOW ANALYSIS

The load flow analysis is performed before and after line outages of a given system. Therefore the Eigen values are calculated using the Jacobin matrix of Newton–Raphson method. The voltage equation is expressed as

$$\begin{bmatrix} \Delta p \\ \Delta Q \end{bmatrix} \quad \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \qquad (1)$$

ΔP = Incremental change in bus real power

ΔQ = Incremental change in bus reactive power injection

$\Delta\theta$ = Incremental change in bus voltage angle

ΔV = Incremental change in bus voltage magnitude

To express the relation between ΔQ and ΔV for a small change in real power, $\Delta p = 0$ can be assumed. This yield:

$$\Delta V = (J_{QV} - J_{Q\theta} \,.\, J_{P\theta}^{-1} \,.\, J_{PV}) \,.\, \Delta V \qquad (2)$$

Rearranging (2), we have

$$\Delta V = J_R^{-1} \Delta Q \qquad (3)$$

Where,

$$J_R=(J_{QV}-J_{Q\theta}\cdot J_{P\theta}^{-1}\cdot J_{PV}) \qquad (4)$$

J_R is called the reduced jacobian matrix of the system. It relates the bus voltage magnitude and reactive power $J_R$injection.

$$\text{Let}\quad J_R=\pounds\lambda\eta \qquad (5)$$

Where,

$\pounds$, λ and η are right Eigen vector, left Eigen vector and diagonal Eigen value matrix of J_R respectively.

$$\Delta V=\pounds\lambda^{-1}\eta\Delta Q \qquad (6)$$

$$V=\lambda^{-1}q \qquad (7)$$

Where,

$V=\eta\Delta V$ is the vector of modal voltage variations and

$q=\eta\,\Delta Q$ is the vector of modal reactive power variation

$$\pounds^{-1}=\eta \qquad (8)$$

Equation (7) represents uncoupled first order equations. Thus for the i^{th} mode:

$$V_i=(1/\sigma_i)\ q_i \qquad (9)$$

If $\sigma_i>0$, the i^{th} modal voltage and the i^{th} modal reactive power variations are along the same direction, indicating that the system is voltage stable. If $\sigma_i<0$, the i^{th} modal voltage and the i^{th}modal reactive power variation are along opposite direction, indicating that the system is voltage unstable.

The magnitude of each modal voltage variation equals the inverse of σ_i times the magnitude of the modal reactive power variation. In this sense, the magnitude of σ_i determines the degree of stability of the i^{th} modal voltage. The smaller the magnitude of positiveσ_i, the closer the i^{th} modal voltage is to be unstable.

When $\sigma_i=0$, the i^{th} modal voltage collapses because any change in that modal reactive power causes infinite change in the modal voltage. The effect or participation of system buses in voltage instability and critical modes near the point of collapse can be also determined using modal analysis. Relative participation of k^{th}bus to i^{th}mode is expressed by bus participation factor as follows:

$$P_{ki}=\pounds_{ki}\eta_{ik} \qquad (10)$$

Where, $\pounds_i$and $\eta_i$are k^{th} element of the right and left eigen vectors corresponding to i^{th}eigen value of $J_R$respectively.

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B. STAGES IN BENDERS DECOMPOSITION

There are two optimal stages in Bender Decomposition Method. In first-stage is solved for a subset of variables, and the values of the remaining variables are determined by a second-stage calculation given the values of the first-stage variables. If the second stage problem determines that the proposed first-stage decisions are infeasible, then one or more constraints are generated and added to the first stage, which is then re-solved In this manner, a series of small problems are solved instead of a single large problem, which can be justified by the increased computational resource requirements associated with solving larger problems. The first stage contains Participation in all Critical Modes before Transmission switching and the second stage contains Total Participation in all Critical Modes before and after Transmission Switching.

1. First Stage - PCM Calculation:

Voltage instability could be identified if the smallest Eigen values of power system steady state reduced Jacobin matrix are negative or very close to zero. Under these conditions, it is necessary to increase the magnitude of critical modes until the system security is ensured and voltage stability is achieved.

This can be done by providing adequate reactive power support to the system. The term critical mode is used to identify all Eigen values whose magnitudes are smaller than a prescribed critical value(σ_Critical).The critical modes are determined based on modal analysis of system reduced jacobian matrix under contingency conditions and the effectiveness of buses on these critical modes is recognized by their participation factors.

Therefore, in this method, the objective is to determine system buses that have the most effect on critical mode. In this approach, a probabilistic index is defined which evaluates the relative participation of each bus in voltage instability caused by all the critical modes corresponding to that contingency

$$\mathrm{PCM_i} = \sum_{j=1}^{m} \mathrm{P_{outage}}(k) \times \frac{\mathrm{p_{ij}}}{\sigma_i} \qquad (11)$$

Where,

PCM_i: Contribution of bus i to voltage instability caused by critical modes under k^{th} contingency state.

$\mathrm{P_{outage}}$(k): likelihood of k^{th} contingency occurring corresponding to outage of line k;

m: number of critical Eigen values in k^{th} contingency;

p_{ij}: Participation factor of bus i to critical Eigen value j;

σ_i : Critical Eigen value j.

2. Second Stage- TPCM Calculation

The Total Participation in all Critical Modes (TPCM) for each bus considering all possible contingencies can be calculated by following equation:

$$\mathrm{TPCM_i} = \sum_{K=1}^{L} \sum_{j=1}^{m} \mathrm{P_{outage}}(k) \times \frac{\mathrm{p_{ij}}}{\sigma_j} \qquad (12)$$

Where.

$\mathrm{TPCM_i}$ is the total participation of bus i in all critical modes under all possible contingencies.

L is the number of possible contingencies.

TPCM demonstrates the relative contribution of each bus to system voltage instability under all possible system states. According to (12), the bus which has a larger participation factor in critical modes is more effective in voltage instability. TPCM values are calculated for every bus using (12).

The bus with the largest TPCM is considered as the best location for Transmission Switching. Because according to definition of TPCM, that bus is more effective in more probable contingencies or is more effective in more critical modes.

IV. FINDING LOCATION TO ADD TIE LINES BETWEEN 30 BUS SYSTEMS

Transmission switching can improve the economic benefits of a power system through changing its topology during operations. However, the switching operation itself represents a step change in power system which is, to some extent, similar to a contingency that can bring disturbances into systems. This paper proposes a new model for static-security-constrained transmission switching.

If all the Eigen values are positive, the system voltage is stable. If at least one Eigen value is equal to zero, negative and less than half then the system voltage is unstable. If the system is unstable then have to analyze the TPCM values for identifying buses which have critical modes. Some lines were identified as candidate lines for switching to remove congestion. After identifying, the Tie-Lines were connected between the respective buses with switches. Transmission switching is performed for voltage security.

A. Priority List for Transmission Switching

By using the TS based on the Bender Decomposition method, one can find the candidate lines that have to be opened to relieve congestion. The system operator would also require a priority list for these lines since line switching's in a real power system have to be performed one at a time and not simultaneously.

In this method an option is proposed to find a priority list for opening identified lines. Therefore, the bender decomposition method is also formulated by limiting the number of switching actions. The stable condition is obtained with less number of Tie-lines this procedure is repeated until congestion is fully or partially removed while for each switching actions, N-1 criteria and voltage security criteria are respected as well.

V. NUMERICAL SIMULATIONS AND RESULTS

This chapter presents the results of IEEE 30 bus test system and the Eigen values are calculated under normal and N-1 line outage condition Values. The following tables in this chapter represent the simulated results. From Table I it is observed that the minimum Eigen values in line 36,38,39,40.

The TCPM are calculated for each bus to know about the buses which have more participants in IEEE30 bus system. From Table II it is observed that, the bus 25, 26, 27,28,29,30 has highest TCPM value compared to other buses which were mentioned in bold. So the Tie-line with switches has been installed between the buses (25-30), (26-29), (25-29) to ensure the voltage security under contingency condition. After adding Tie lines The Eigen values has been increased and the system become stable. It is observed from the Table III the Eigen values are increased for the buses 25, 26, 29, 30 which were mentioned in bold. This ensures that IEEE 30bus system is securable at any N-1 contingency conditions. It also reduces the Transmission congestion by adding less number of Transmissions switching between the buses.

TABLE I. Calculated Eigen Values After N-1 Line Outage Condition

S.No.	Line outages	Eigen values
1	**1-2**	**0.5080**
2	**1-3**	**0.5056**
22	**16-17**	**0.5008**
23	**15-18**	**0.4910**

3	2- 4	0.5057
4	3- 4	0.5061
5	2- 5	0.5084
6	2- 6	0.5052
7	4- 6	0.5088
8	5- 7	0.5066
9	6- 7	0.5087
10	6- 8	0.4836
11	6- 9	0.4975
12	6-10	0.4901
13	9-11	0.0000
14	9-10	0.4067
16	4-12	0.5030
17	12-13	0.4709
18	12-14	0.5025
19	12-15	0.4709
20	12-16	0.4905
21	14-15	0.5077
24	18-19	0.5062
26	10-20	0.5096
27	10-17	0.5086
28	10-21	0.4844
29	10-22	0.4844
30	21-23	0.5025
31	15-23	0.4915
32	22-24	0.4724
33	23-24	0.4668
34	24-25	0.3476
35	25-26	0.0000
36	25-27	0.2939
37	28-27	0.4939
38	27-29	0.2702
39	27-30	0.2134
40	29-30	0.2744
41	8-28	0.4906

TABLE II. **Calculation of TPCM values**

S.No.	Bus.No.	TPCM
1	1	0.0000
2	2	0.0000
3	3	0.0006
4	4	0.0009
5	5	0.0000
6	6	0.0009
7	7	0.0004
16	16	0.0235
17	17	0.0322
18	18	0.0634
19	19	0.0722
20	20	0.0644
21	21	0.0423
22	22	0.0561

8	8	0.0000
9	9	0.0090
10	10	0.0326
11	11	0.0000
12	12	0.0093
13	13	0.0000
14	14	0.0226
15	15	0.0288

23	23	0.0442
24	24	0.0797
25	25	0.1862
26	26	0.2918
27	27	0.1846
28	28	0.0047
29	29	0.3585
30	30	0.3901

TABLE III. Calculation of Eigen Values After and Before Installation of Tie Lines

S.No	Line outage	Eigen values	Eigen values
1	1-2	0.5080	0.5305
2	1-3	0.5056	0.5276
3	2- 4	0.5057	0.5277
4	3- 4	0.5061	0.5282
5	2- 5	0.5084	0.5309
6	2- 6	0.5052	0.5272
7	4- 6	0.5088	0.5316
8	5- 7	0.5066	0.5286
9	6- 7	0.5087	0.5309
10	6- 8	0.4836	0.5031
11	6- 9	0.4975	0.5157
12	6-10	0.4901	0.5072
13	9-11	0.0000	0.0000
14	9-10	0.4067	0.4125
16	4-12	0.5030	0.5221
17	12-13	0.4709	0.0000

18	**12-14**	**0.5025**	**0.5229**
19	**12-15**	**0.4709**	**0.4845**
20	**12-16**	**0.4905**	**0.5082**
21	**14-15**	**0.5077**	**0.5297**
22	**16-17**	**0.5008**	**0.5213**
23	**15-18**	**0.4910**	**0.5071**
24	**18-19**	**0.5062**	**0.5277**
25	**19-20**	**0.2696**	**0.5318**
26	**10-20**	**0.5096**	**0.5141**

S.No	Line outage	Eigen values	Eigen values
28	**10-21**	**0.4844**	**0.5015**
29	**10-22**	**0.4844**	**0.4553**
30	**21-23**	**0.5025**	**0.5230**
31	**15-23**	**0.4915**	**0.5106**
32	**22-24**	**0.4724**	**0.4896**
33	**23-24**	**0.4668**	**0.4831**
34	**24-25**	**0.3476**	**0.3548**
35	**25-26**	**0.0000**	**0.0000**
36	**25-27**	**0.2939**	**0.5163**
37	**28-27**	**0.4939**	**0.5270**
38	**27-29**	**0.2702**	**0.5045**
39	**27-30**	**0.2134**	**0.5130**
40	**29-30**	**0.2744**	**0.5322**
41	**8-28**	**0.4906**	**0.5432**

VI. CONCLUSION

The feasibility of the TS has been tested in the IEEE 30 bus test system. In this system, there are 6 generators along Hence, these generators are economical generation units and it is desirable to fully dispatch without violating any security criteria. The load Flow analysis is performed and Eigen values are calculated for before and after line outages. For installing Tie lines Bender decomposition Method is formulated. Using TPCM values

Tie lines are connected between the buses .In order to relieve congestion; the TS problem has been utilized based on DCOPF with AC constraints. In some cases, maybe more than one TS action is required for transmission congestion relief. Therefore, a methodology is also proposed to find a priority list providing a guideline for operators in taking switching actions. The results of TS with AC constraints is also compared to those of TS based on DCOPF showing that DCOPF is inadequate and may give results that can jeopardize system security or in some cases may lead to voltage collapse. The effect of voltage bands on TS with AC constraints is also discussed; with tighter voltage bands, the number of TS actions that respect voltage security would decrease and consequently TS cannot completely remove congestion. After adding Tie lines, power flow of system is in stable condition. It is concluded that the test systems were not violate voltage security.

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