Relieving Overload and Improving Voltage by the Network Contribution Factor (NCF) Method

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***Abstract*--This paper introduces new Network Contribution Factor (NCF) method for relieving overload and improving voltage by using the network contribution information and base load flow conditions. When line overload or low voltage occurs, irrespective if it is caused by disturbance, load increase, or wheeling, we first find the following network contribution factors: Flow Network Contribution Factor (FNCF) and Voltage Network Contribution Factor (VNCF). Then we choose the most contributing elements and change their parameters, either by line control (Thyristor Controlled Series Capacitor-TCSC, line switching, etc.) or bus control (shunt capacitor, Static Var Compensator-SVC, etc.). The variances of the line flow and bus voltage are calculated. The results are verified by power flow calculation. This method can quickly find the parameter contributing to the largest variance based on the network information and base load flow conditions. It can be used for re-dispatching load flow, solving congestion, relieving overload, improving voltage, controlling emergency, etc.**

***Index Terms*--Network Contribution Factor, Congestion Management, Overload, Voltage Control, Emergency Control, FACTS**

I. Introduction

One of the most challenging problems for a competitive power market is that congestion may occur frequently[1]. Following one or several disturbances, the over stressed system may have one or several lines overloaded or security flow-gate limits violated. If the overload can not be relieved quickly and appropriately, fault may occur (i.e., line sagged to trees) and more elements will be tripped. Also, a backup relay may operate due to the overload condition, leading to cascading outages and large area blackout as the final result [2,3,4]. In the complex and competitive power market, it is difficult for system operators to find effective means for relieving overload to make the maximum balance between the economy and security. There are examples of good and bad consequences of relieving overload during disturbances [5,6].

In general, compared with generator re-dispatching and load management, transmission network control is the fastest and cheapest control for relieving overload and controlling stability. Some research results were reported on using network switching for relieving overload condition [7,8]. The power flow sensitivity matrices are used to rank the candidate lines to be switched off to solve the voltage violation and overload problems [7]. The Z-matrix method is used to compare the changes in the Z elements due to one line being switched off [8]. The Optimal Power Flow (OPF) may be a good method in the regulated environment for dispatching the generation, adjusting the branch flow and relieving the overload [9]. But the OPF method is not as suitable as before in the competitive open access market.

This paper presents a novel and comprehensive method of using network contribution factors for the purpose of relieving overload, improving voltage, controlling emergency, etc. It gives useful control guidance for system operators and is easy to understand and implement. Based on network parameters and base flow bus voltages, for the line flow change, the Flow Network Contribution Factor (FNCF) for each line parameter variance (i.e., TCSC insertion or line switching) is estimated. For the bus voltage change, the Voltage Network Contribution Factor (VNCF) for each bus shunt element variance is obtained. Given certain amount of the line flow decrease or bus voltage increase, either FNCF or VNCF is used to get the necessary and optimal line or shunt parameter variance.

This paper introduces the mathematical formulation of the network contribution factor method. In Section II, both the line parameter variance and bus (shunt) parameter variance are considered. Numerical test results are presented in Section III. Conclusion and references are given in Section IV and V respectively.

II. Mathematical Formulation

From the fast decouple power flow, we know the approximate real power equation based on the simple fact that the line resistance is much smaller than the reactance, $r_i << x_i$

$$\frac{P}{E} = B^{'}\theta \tag{1}$$

where, P, E, θ are the node real power injection, magnitude and angle of the bus voltage respectively.

$$(B^{'})_{ij} = -b_{ij} \tag{2}$$

where b_{ij} is the series inductance of the line i-j

Given an n-bus-l-branch system, A is the node-branch incidence matrix, Y_p is the primitive branch admittance matrix, Y_{bs} is the node shunt capacitance matrix,

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$$Y_p = diag[y_1 \quad ... \quad y_l] \tag{3}$$

$$Y_{bs} = diag[y_{s1} \quad ... \quad y_{sn}] \tag{4}$$

$$A_{ij} = \begin{cases} 1 & \text{i is the sending node of branch j} \\ -1 & \text{i is the receiving node of branch j} \\ 0 & else \end{cases} \tag{5}$$

Bus admittance matrix can be obtained from:

$$Y = AY_pA^T + Y_{bs} \tag{6}$$

Assign $B^{'}$ as the negative value of the imaginary part of Y matrix,

$$B^{'} = -imag(Y) \tag{7}$$

For the real power flow,

$$P_{line} = -imag(Y_p)A^T(E\theta) \tag{8}$$

The approximate node injection can be composed from the line flows associated with this node,

$$P_{node} \cong AP_{line} = A(-imag(Y_p))A^T(E\theta) \tag{9}$$

A. Line Parameter Variance

For the parameter variance of line i, Δy_i, assume that the node injection P_{node} and bus voltage magnitude E do not change much, and the bus voltage angle θ varies $\Delta\theta$. Then assign

$$Y_1 = -imag(Y_p) \tag{10}$$

Since the node injection does not change, from (9) we get,

$$A(Y_1 + \Delta Y_1)A^T E(\theta + \Delta\theta) = AY_1A^T E\theta \tag{11}$$

thus

$$\Delta\theta = -(A(Y_1 + \Delta Y_1)A^T)^{-1}(A\Delta Y_1A^T)\theta \tag{12}$$

where $\Delta Y_1 = diag[0 \quad .. \quad \Delta y_i \quad .. \quad 0]$ (13)

From (8), we get the line flow change,

$$\Delta P_{line} = P_{line}^{new} - P_{line} = \Delta Y_1A^T(E\theta) - (Y_1 + \Delta Y_1)A^T(A(Y_1 + \Delta Y_1)A^T)^{-1}(A\Delta Y_1A^T)(E\theta) \tag{14}$$

since

$$\Delta Y_1A^T(E\theta) = \begin{bmatrix} 0 & .. & \sum_{j=1}^{n} A_{ji}E_j\theta_j & .. & 0 \end{bmatrix}^T \Delta y_i \tag{15}$$

$$(A\Delta Y_1A^T)(E\theta) = Ki\Delta y_i \tag{16}$$

where

$$Ki = \begin{bmatrix} A_{1i}\sum_{j=1}^{n}A_{ji}E_j\theta_j & .. & A_{ii}\sum_{j=1}^{n}A_{ji}E_j\theta_j & .. & A_{ni}\sum_{j=1}^{n}A_{ji}E_j\theta_j \end{bmatrix}^T \tag{17}$$

$$X_1 = (A(Y_1 + \Delta Y_1)A^T)^{-1} \tag{18}$$

$$X = (AY_1A^T)^{-1} \tag{19}$$

we can get the following line flow variance equations,

for line k, $k \neq i$,

$$\Delta P_{line-k} = -[A_{1k} \quad ... \quad A_{nk}]X_1Ki(y_k\Delta y_i) \tag{20}$$

for line k, $k = i$,

$$\Delta P_{line-i} = (\sum_{j=1}^{n}A_{ji}E_j\theta_j / y_i^{'} - [A_{1i} \quad ... \quad A_{ni}]X_1Ki)(y_i^{'}\Delta y_i) \tag{21}$$

where

$$y_i^{'} = y_i + \Delta y_i \tag{22}$$

The Flow Network Contribution Factor (FNCF) N_f can be defined as follows,

for line k, $k \neq i$

$$N_{f,k} = -[A_{1k} \quad ... \quad A_{nk}]X_1Ki \tag{23}$$

for line k, $k = i$

$$N_{f,k} = \sum_{j=1}^{n}A_{ji}E_j\theta_j / y_i^{'} - [A_{1i} \quad ... \quad A_{ni}]X_1Ki \tag{24}$$

In general, bus impedance matrix (imaginary part) X_1 doesn't change much from the original matrix X due to the line parameter variance Δy_i. If we assume $X_1 \cong X$, the Flow Network Contribution Factor N_f will be constant except for line i.

We can easily get the line flow variance,

$\Delta P_{line-k} = N_{f,k}y_k\Delta y_i$, k=1,…,l (25)

From (25) we can see that the line flow variances are related to three components: the Flow Network Contribution Factor N_f, this line's series inductance and admittance variance of the line i. For each line parameter change, we can get all other line flow variances easily. Vice versa, we can calculate the line parameter variance based on the exact line flow change we want. This gives us a good guidance to issue network control to re-dispatch the line flows:

Step 1, use the base network X matrix to get N_f and ΔP_{line-k}, so the positive or negative contribution of each line parameter change to the line flow of interest is easily known.

Step 2, choose the most contributable line, change its parameter, get the actual N_f and ΔP_{line-k} by using the real X_1 and $y_i^{'}$, thus get the desired overload relieving.

Step 3, run power flow program to verify the result.

For the line switching, just simply assign $\Delta y_i = -y_i$, $\Delta P_{line-i} = -P_{line-i}$. For other line flow changes, for a small size system, switching off an in-service line may make a big variance of X, so we use real X_1 and $y_i^{'}$ to get the actual N_f and ΔP_{line-k}. For a large size system, switching off one or several lines may not change X as much, so we still use the three steps above.

The above method can give quick guidance for selection of the parameter to change and the exact parameter variance. The power flow calculation can verify it to get an accurate control.

B. Bus Parameter Variance

When shunt capacitor bank or SVC is being switched on/off at a bus, the capacitance variance at bus i is Δy_{bs}. For real power flow:

$$P_{line} = Y_1A^T(E\theta) \tag{26}$$

$$P_{node} = B^{'}(E\theta) \tag{27}$$

from (26) and (27) we can get

$$E\theta = (B^{'})^{-1}P_{node} \tag{28}$$

$$\Delta P_{line} = Y_1 A^T((B'_{new})^{-1} - (B'_{old})^{-1})P_{node} \quad (29)$$

Since Y_1, A and P_{node} are constant, B' does not change much. The line real power flow will change, but not much, for the variance of bus capacitance.

However, based on reactive power equation of the fast decoupled method, the reactive power Q and bus voltage E will change,

$$\frac{Q}{E} = B''E \quad (30)$$

$$\frac{\Delta Q}{E} = B''\Delta E \quad (31)$$

$$\Delta E = (B'')^{-1}\frac{\Delta Q}{E} = (B'')^{-1}\begin{bmatrix} 0 \\ .. \\ \Delta y_{bs} \\ .. \\ 0 \end{bmatrix} E = X_2 \begin{bmatrix} 0 \\ .. \\ \Delta y_{bs} \\ .. \\ 0 \end{bmatrix} E \quad (32)$$

For the n-bus network with m PQ buses, B'' is $m \times m$ admittance matrix, X_2 is the inverse of B''.

If we assume B'' doesn't vary much, we can get the bus voltage magnitude variance

$$\Delta E_j = (X_{2,ji}E_j)\Delta y_{bs} \quad \text{j=1,…,m} \quad (33)$$

The Voltage Network Contribution Factor (VNCF) N_v can be defined as follows,

$$N_{v,j} = X_{2,ji}E_j \text{, j=1,…,m} \quad (34)$$

III. Numerical Results

Take an example of the WSCC 9-bus system given in Fig. 1.

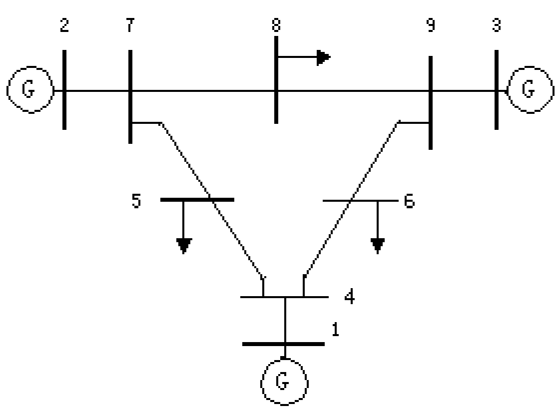

Fig. 1. WSCC 9-bus system

Table I gives the base flow condition of each line in p.u.. Table II presents the FNCF (Flow Network Contribution Factor) results if a TCSC with 50% compensation capacity is inserted at each of the lines 4-5, 4-6, 5-7, 6-9, 7-8 and 8-9 respectively. FNCF gives the guidance for the line flow adjustment.

TABLE I
BASE FLOW OF THE WSCC 9-BUS SYSTEM
(100MVA BASE, VALUE: P.U.)

Line	Line Flow	Magnitude
1-4	0.7164 + 0.2548i	0.7604
2-7	1.6300 - 0.0126i	1.6300
3-9	0.8500 - 0.1291i	0.8597
4-5	0.4081 + 0.3106i	0.5128
4-6	0.3062 + 0.0889i	0.3189
5-7	-0.8547 - 0.0193i	0.8549
6-9	-0.6014+ 0.0195i	0.6017
7-8	0.7614 + 0.0503i	0.7631
8-9	-0.2414 - 0.1388i	0.2785

Note: The assumed line flow direction is from the beginning node to the ending node. Negative values of real power flow of line 5-7, 6-9 and 8-9 indicate that the actual flow directions are opposite to the assumed directions.

A. *Cases of the Line Parameter Variance*

Case 1 Insertion of TCSC at a line

If we assume that the line flow limit of line 5-7 is 0.8 p.u., we can see that it is overloaded at the base flow condition. Consider insertion of Thyristor Controlled Series Capacitor (TCSC) at each line (assume we have a TCSC at each line) to adjust the line flow.

TABLE II
FLOW NETWORK CONTRIBUTION FACTOR (VALUE: 1E-3)
(50% COMPENSATION OF A TCSC AT EACH LINE)

Line	4-5	4-6	5-7	6-9	7-8	8-9
4-5 flow	0.0928	-0.1519	-1.5	1.2	0.2593	-0.1573
4-6 flow	0.1757	0.1142	1.7	-1.3	-0.2846	0.1701
5-7 flow	0.3145	-0.3026	-1.7	2.4	0.4759	-0.2951
6-9 flow	-0.3433	0.3113	3.2	1.5	-0.5234	0.3058
7-8 flow	0.1444	-0.1371	-1.3	1.1	0.1236	0.1249
8-9 flow	0.2045	-0.1912	-1.9	1.4	0.2914	-0.0972

For line 5-7 flow, since its actual direction is opposite to the assumed direction, positive value of the FNCF is needed to decrease the flow. From Table II, we can see that the biggest positive value of FNCF for line 5-7 flow is insertion of TCSC at line 6-9. Therefore, insertion of TCSC at line 6-9 will contribute the most to relieving the overload on line 5-7.

Table III gives the flow changes and errors by inserting TCSC with 50% compensation capacity at line 6-9. Column 2 is the line flow change based on the Network Contribution Factor from matrix X. Column 4 is the line flow change based on the real Network Contribution Factor from matrix X_1. Column 6 is the power flow result. Columns 3, 5 are errors compared with the power flow result.

TABLE III
LINE FLOW CHANGE FOR THE LINE 6-9 PARAMETER VARIANCE
(CHANGE, FLOW VALUE: P.U., ERROR: %)

Line	Change	Error	Change	Error	Power flow
4-5	0.0784	5.21	0.0836	-0.99	0.0828
4-6	-0.0733	19.64	-0.0851	6.69	-0.0912
5-7	0.0761	10.08	0.0853	-8.3	0.0846
6-9	-0.0884	0.6	-0.0883	-0.113	-0.0884
7-8	0.0786	8.86	0.0838	2.88	0.0863
8-9	0.0766	10.85	0.0815	5.16	0.0859

From Table III, we can see that the line flow change obtained by the Network Contribution Factor method is very close to the power flow result. By this method, we can quickly find the necessary parameter change to relieve the overload, and avoid the many trials of power flow calculation.

Case 2 Line Switching

In reality, TCSC is not installed everywhere in the network. To get an easy control of the line parameter, due to the economic and technological considerations, line switching may be more applicable for the system operators.

Table IV and Table V are given to show the line flow results of switching the line 8-9 and line 5-7 respectively.

TABLE IV. LINE FLOW CHANGES FOR LINE 8-9, 5-7 DISCONNECTED
(VALUE: P.U.)

Flow	Line 8-9 off			Line 5-7 off		
4-5	0.2339	0.2414	0.2361	0.8009	0.8326	0.8518
4-6	-0.2263	-0.2404	-0.2296	-0.7974	-0.8596	-0.7767
5-7	0.2225	0.2379	0.2403	0.8547	0.8547	0.8547
6-9	-0.2145	-0.2329	-0.2354	-0.7927	-0.8801	-0.8117
7-8	0.2193	0.2257	0.2434	0.7975	0.8289	0.8576
8-9	0.2414	0.2414	0.2414	0.8242	0.8584	0.8469

Columns 2,3,4 are line flow changes when line 8-9 is switched off by Flow Network Contribution Factors (obtained from matrix X and X_1) method and power flow method respectively. Columns 5,6,7 are similar except for line 5-7 being switched off.

We can see from Table IV that for the line switching control, the results of the Flow Network Contribution Factor method are very accurate since they are very close to those of the power flow method. Since the line 5-7 carries a big flow, when this line is off, there is a big flow transfer to other lines, so other lines may be heavily loaded, as described in Table V. Thus, the line switching control to relieve overload has to be carefully used because it may result in overloading of other lines.

TABLE V
LINE FLOWS WITH LINES DISCONNECTED (VALUE: P.U.)

Flow	Original	8-9 off	5-7 off
4-5	0.4081	0.8856	1.2599
4-6	0.3062	-0.1638	-0.4705
5-7	-0.8547	-0.3765	0
6-9	-0.6014	-1.0697	-1.4131
7-8	0.7614	1.2305	1.6190
8-9	-0.2414	0	0.6055

B. Bus Parameter Variance

We consider the bus parameter variance, caused by switching on 0.5 p.u. (in base MVA capacity) shunt capacitance at bus 5.

TABLE VI
BUS VOLTAGE MAGNITUDE VARIANCE (VALUE: P.U.)

Voltage	Method 1	Method 2	Method 3
Bus 4	0.0156	0.0163	0.0176
Bus 5	0.0433	0.0453	0.0469
Bus 6	0.0121	0.0126	0.0140
Bus 7	0.0101	0.0106	0.0117
Bus 8	0.0079	0.0082	0.0093
Bus 9	0.0044	0.0046	0.0053

Method 1 uses the original matrix B'' to get the voltage variance. Method 2 uses the new matrix B'' after switching on the shunt capacitor. Method 3 is the power flow method. We can see that their bus voltage variances are very close. The Voltage Network Contribution Factor (VNCF) method can get voltage improvement with good accuracy.

For the real line flow, switching the shunt capacitor at the bus does not cause a major change. We can see this from Table VII.

TABLE VII
LINE FLOW VARIANCE (VALUE: P.U.)

Line	Method 1	Method 2
4-5	0.0106	-0.0040
4-6	-0.0077	0.0032
5-7	-0.0095	-0.0035
6-9	-0.0031	0.0032
7-8	-0.0054	-0.0035
8-9	-0.0022	-0.0034

Method 1 is the Network Contribution Factor method. Method 2 is the power flow method. We can see that the shunt capacitance variance does not contribute much to real flow change of the line. It contributes to the variances of the bus voltage and reactive power injection.

IV. CONCLUSION

This paper introduces a novel and comprehensive method by using Network Contribution Factors. With the aid of the FNCF and VNCF, necessary line parameter variance and bus parameter variance can be calculated to adjust the line flow and bus voltage without many trials of running the power flow program. It can be used for re-dispatching load flow, managing congestion, relieving overload, improving voltage, controlling emergency, etc. The method is simple, fast and accurate.

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