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A Congestion Line Flow Control in Deregulated Power System

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Abstract: Under open access, market-driven transactions have become the new independent decision variables defining the behavior of the power system. The possibility of transmission lines getting over-loaded is relatively more under deregulated operation because different parts of the system are owned by separate companies and in part operated under varying service charges. This paper discusses a two-tier algorithm for correcting the lone overloads in conjunction with the conventional power-flow methods. The method uses line-flow sensitivities, which are computed by the East Decoupled Power-flow algorithm and can be adapted for on-line implementation.

Keywords: Deregulation, Line-flow control, Congestion management, Line-flow sensitivities.

1 Introduction

The ability to regulate power flow through certain paths in a network is of particular importance, especially in a deregulated electricity market. Existence of network constraints dictates that only a finite amount of power can be transferred between two points on the electric grid. In practice, it may not be possible to deliver all bilateral and multi-lateral contracts in full and to supply the pool demand at the lowest cost due to violation of operating constraints such as voltage limits and line congestion (line overloads). Congestion on a transmission system cannot be tolerated except for a very short duration since this may cause cascade outages with uncontrolled loss of load. Congestion also leads to market inefficiency. Congestion relief is sometimes achieved by methods such as re-dispatch of generation and curtailment of pool loads and/or by curtailment of bilateral contracts. Facts devices can be used effectively to control the power flow by changing their parameters to relieve congestion. Congestion does occur in both vertically bundled as well as in unbundled systems, but its management in the bundled system is relatively simple.

Over the past decade, researchers have focused considerable attention on this problem. S.N. Singh and A.K. David [1] developed mathematical models

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through line loss and line flow sensitivities for optimal location of FACTS devices with the objective of congestion management. S C Srivastava et al [2] developed a congestion management approach, where the entire system is divided heuristically, from the congestion point of view, into sensitive zones. This was achieved by computing active and reactive power distribution factors using the Newton's power flow algorithm. Gnanadas R et al [3] solved an optimal power flow problem with congestion constraints and using willingness-to-pay price factor. Verma K.S. and Gupta H.O. [4] a method for suitable location of UPFC through sensitivity of a performance index. Lo K.L., et al [5] used a fuzzy-logic based method to adjust the transmission line power-flow along with other variables like, line impedance, phase angle and transformer tap positions.

This paper proposes an iterative technique, through power flow distribution factors, to compute the changes necessary at the nodal injections to relieve a congested line from overload. The distribution factors are computed using the fast decoupled power-flow algorithm. Later, using the power injection model of UPFC, the parameters of complex voltage to be injected by UPFC to achieve the above correction is computed.

2 Problem Formulation

Conventional power-flow techniques solve the voltage state of the system. Given this state, every other dependent variable like power flow in lines, power loss in each of the lines and the total system loss can be known. The conventional power-flow problem is one of analysis, where the state vector $\boldsymbol{X}$ is computed by solving a set of equations:

$$\boldsymbol{F}(\boldsymbol{X}) = \boldsymbol{D}. \tag{1}$$

Here $\boldsymbol{X}$ is the voltage vector and $\boldsymbol{D}$ is a set of known power injections at the buses.

If some system operating variables, for example the line flows, are to be controlled and if these can be expressed as functions of the system state, then one can augment the above set of equations (1) and obtain the updated values of control variables at one go by solving simultaneously the following sets of equations:

$$\begin{aligned} \boldsymbol{F}(\boldsymbol{X},\boldsymbol{U}) &= \boldsymbol{D}, \\ \boldsymbol{H}(\boldsymbol{X},\boldsymbol{U}) &= \boldsymbol{W}, \end{aligned} \tag{2}$$

where $\boldsymbol{U}$ is a vector of control variables and $\boldsymbol{W}$ is a vector of controlled variables. In the present problem, the former can be taken from FACTS devices and the latter can be power flows in the specified lines. Using the Taylor's series expansion of each of the two equations in (2), the following linearized equations are obtained.

$$\begin{pmatrix} \dfrac{\partial \boldsymbol{F}}{\partial \boldsymbol{X}} & \dfrac{\partial \boldsymbol{F}}{\partial \boldsymbol{U}} \\ \dfrac{\partial \boldsymbol{H}}{\partial \boldsymbol{X}} & \dfrac{\partial \boldsymbol{H}}{\partial \boldsymbol{U}} \end{pmatrix} \begin{pmatrix} \Delta \boldsymbol{D} \\ \Delta \boldsymbol{U} \end{pmatrix} = \begin{pmatrix} \Delta \boldsymbol{D} \\ \Delta \boldsymbol{W} \end{pmatrix}. \tag{3}$$

It is to be noted that, while $[\partial \boldsymbol{F} / \partial \boldsymbol{X}]$ is the Jacobian of the usual power-flow equations, the one in equation (3) is enlarged to include the control variables. Simultaneous solution of state and control variables, using the equation (3), can be computationally inefficient, for, we are not making use of the solution of the power-flow equations available with the professional packages. In (2), decoupling of (3) was suggested where the state and the control variables are computed alternatively. The decoupling is done by computing for $[\Delta \boldsymbol{X}]$ from first of the two matrix equation (3) at a converged load-flow (here $[\Delta \boldsymbol{D}] = 0$) and substituting the computed $[\Delta \boldsymbol{X}]$ in the second equation to obtain $[\Delta \boldsymbol{U}]$ as a function of $[\Delta \boldsymbol{W}]$; thus getting a two-tier algorithm, the first to compute the state and the second to compute the control variables. In the second stage, the control and the controlled variables are related through a sensitivity matrix $[\boldsymbol{S}]$ as

$$[\Delta \boldsymbol{U}] = [\boldsymbol{S}][\Delta \boldsymbol{W}], \tag{4}$$

where $[\boldsymbol{S}]$ is given by

$$\boldsymbol{S} = \left[\frac{\partial \boldsymbol{H}}{\partial \boldsymbol{U}} - \frac{\partial \boldsymbol{H}}{\partial \boldsymbol{X}} \frac{\partial \boldsymbol{F}^{-1}}{\partial \boldsymbol{X}} \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{U}} \right]^{-1}.$$

This two-tier algorithm, through the above S matrix can be computationally cumbersome. In addition, the convergence depends on the system loads. Hence the need for using some other sensitivities, like participation factors, to control the power flow in the lines. The control device considered is UPFC. The power injection model of UPFC is used to relate the computed power injections with the injected complex voltage. The participation factors are derived from the fast-decoupled load flow algorithm.

3 Lineflow-Sensitivity Factors

The authors of reference [2] computed the real and reactive power flow sensitivities with the Newton's power flow algorithm. These are P_{ij} / P_k and Q_{ij} / Q_k, where P_{ij} and Q_{ij} are the real and reactive power flows in line i - j and P_k and Q_k are the power injections at the bus.

Assuming that the power flows in a line are dependent on the voltage and angles and the voltage magnitudes on either side of the line, we can write the power flows as:

$$P_{ij}, Q_{ij} = f\left(\delta_i, \delta_j, |V_i|, |V_j|\right), \tag{5}$$

$$\begin{aligned} \Delta P_{ij} &= \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j = a_{ij}\Delta\delta_i + b_{ij}\Delta\delta_j, \\ \Delta Q_{ij} &= \frac{\partial Q_{ij}}{\partial |V_i|}\Delta |V_i| + \frac{\partial Q_{ij}}{\partial |V_j|}\Delta |V_j| = a'_{ij}\Delta |V_i| + b'_{ij}\Delta |V_j|, \end{aligned} \tag{6}$$

where $\Delta\delta_i$, $\Delta\delta_j$, $\Delta|V_i|$ and $\Delta|V_j|$ can be replaced by nodal power injections using the static load flow equations. Here, fast decoupled power flow algorithm is used.

$$\begin{aligned} (\Delta\delta) &= \left(\boldsymbol{B}'^{-1}\right)\left(\frac{\Delta P}{V}\right), \\ (\Delta V) &= \left(\boldsymbol{B}''^{-1}\right)\left(\frac{\Delta Q}{V}\right), \end{aligned} \tag{7}$$

$$(\Delta\delta_i) = \left(B_i'^{-1}\right)\left(\frac{\Delta P}{V}\right), \tag{8}$$

where $B_i'^{-1}$ is the i-th row of $\boldsymbol{B}'^{-1}$ matrix.

Substituting in equations (6):

$$\begin{aligned} \Delta P_{ij} &= a_{ij}\left(B_i'^{-1}\right)\left(\frac{\Delta P}{V}\right) + b_{ij}\left(B_j'^{-1}\right)\left(\frac{\Delta P}{V}\right), \\ \Delta Q_{ij} &= a'_{ij}\left(B_i'^{-1}\right)\left(\frac{\Delta Q}{V}\right) + b'_{ij}\left(B_j'^{-1}\right)\left(\frac{\Delta Q}{V}\right). \end{aligned} \tag{9}$$

The above infers that sensitivity factors PSF and QSF can be calculated.

$$\begin{aligned} \mathrm{PSF}_{ij}^{k} &= \frac{\Delta P_{ij}}{\Delta P_k} = a_{ij}\frac{g_{ik}}{V_k} + b_{ij}\frac{h_{ik}}{V_k}, \\ \mathrm{QSF}_{ij}^{k} &= \frac{\Delta Q_{ij}}{\Delta Q_k} = a'_{ij}\frac{g'_{ik}}{V_k} + b'_{ij}\frac{h'_{ik}}{V_k}. \end{aligned} \tag{10}$$

where B_i' and B_i'' are the i-th rows of $\boldsymbol{B}'$ and $\boldsymbol{B}''$ matrices.

The incremental line-flow sensitivity factors, as computed above, are valid around some neighborhood of the given operating point. When the load level changes by significant amount, these factors are recomputed.

4 Line-Flow Adjustments

The line overload in a congested line can be adjusted by the sensitivities as follows. Let ΔP be the mismatch between the desired flow in a line and the calculated flow.

$$\Delta p_{ij} = \Delta p_{ij\,\text{des}} - \Delta p_{ij\,\text{cal}} . \tag{11}$$

Then the incremental real power injection at the k-th bus necessary to correct this mismatch is

$$\Delta P_k = \text{PSF} \times \Delta P_{ij}, \qquad \Delta Q_k = \text{QSF} \times \Delta Q_{ij} . \tag{12}$$

5 Results of Simulation

The use of the power flow sensitivity factors in line overload elevation is tested on IEEE-30 bus system. The following cases are considered for solution through math lab software.

Case 1: line flow is controlled in the line in which the UPFC is located. Two lines are considered for study.

Case 2: line flow is controlled in the line with UPFC is placed in some other line.

In either case, the power injections are necessary to control the line flows in stipulated lines are computed using the line flow sensitivity factors, PSF and QSF. Using the power injection model of UPFC, the complex voltage (polar form) which is to be injected by UPFC in order to correct the given line flow mismatch is subsequently computed.

Case 1.1:

UPFC placed in line 1-3 and power controlled in line 1-3:

$P_{1-3\,\text{cal}} = 83.220605$, $P_{1-3\,\text{desired}} = 87.00$;

$Q_{1-3\,\text{cal}} = 5.126813$, $Q_{1-3\,\text{desired}} = 7.00$.

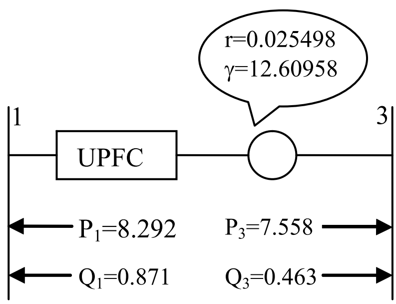

Fig. 1 – *Power flow control* Case 1.1.

Table 1
Convergence of flows in line 1-3 (Case 1.1).

Iterat. No.	Real Power –flow mismatch	Reactive Power- flow mismatch
0	3.779395	1.873187
1	1.972834	0.590715
2	0.070365	0.070365
3	0.013151	0.028974
4	0.001367	0.009064

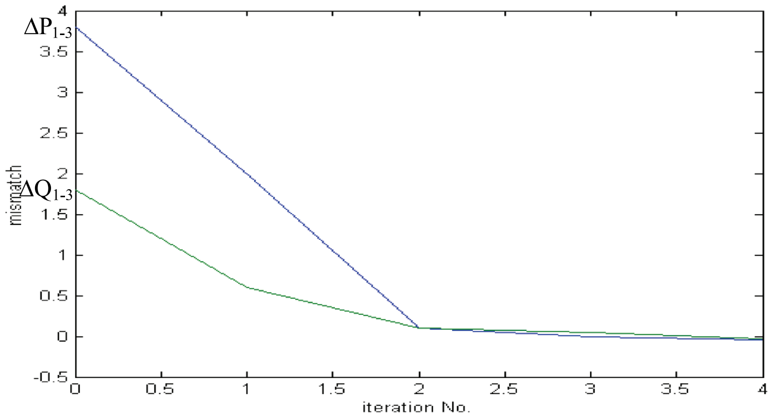

Fig. 2 – *Nature of convergence of flows in line* 1-3.

Case 1.2:

UPFC placed in line 6-10 and power controlled in line 6-10:

$P_{6-10\,\mathrm{cal}} = 15.8230$, $P_{6-10\,\mathrm{desired}} = 18.00$;

$Q_{6-10\,\mathrm{cal}} = 0.65630$, $Q_{6-10\,\mathrm{desired}} = 2.00$.

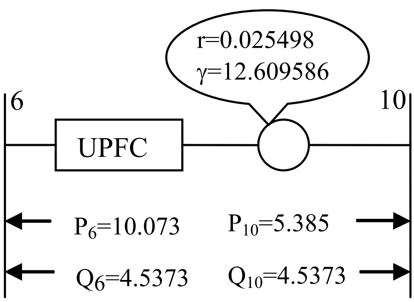

Fig. 3 – *Power flow control* (Case 1.2).

Table 2
Convergence of flows in line 6-10 (Case 1.2).

Iteration No.	Real Power mismatch	Reactive Power mismatch
0	2.177252	1.347467
1	1.323738	0.735697
2	0.737689	0.281170
3	0.142380	0.081262
4	0.036607	0.024350
5	0.005461	0.005020

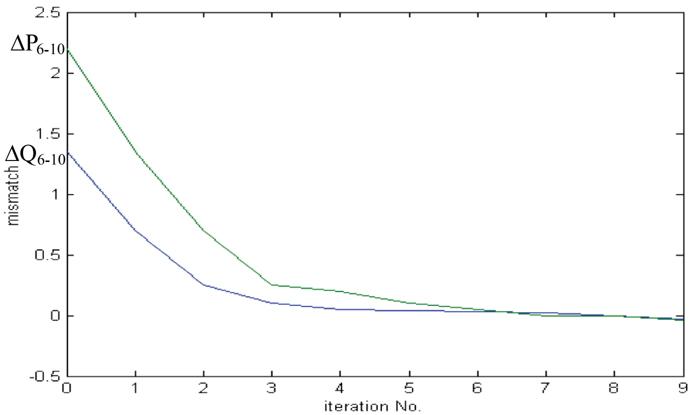

Fig 4 – *Nature of convergence of flows in line* 6-10 (Case 1.2).

Case 2.1:

UPFC placed in line 10-22 and power controlled in line 1-3:

$P_{1-3\text{cal}} = 83.220605$, $P_{1-3\text{desired}} = 80.00$;

$Q_{1-3\text{cal}} = 5.126813$, $Q_{1-3\text{desired}} = 3.00$.

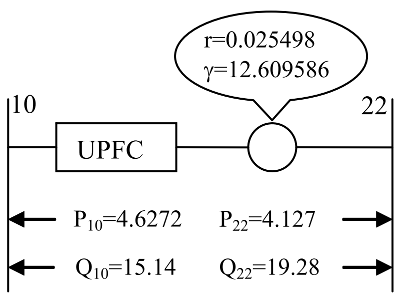

Fig. 5 – *Power flow control in line* 1-3 *with* UPFC *in line* 10-22 (Case 2.1)

Table 3
Convergence of line flows (Case 2.1).

Iteration No.	Real Power mismatch	Reactive Power mismatch
0	3.220605	2.126813
1	1.094109	1.677376
2	0.192226	0.698510
3	0.019109	0.516199
4	0.085754	0.376675
5	0.054225	0.277729
6	0.044228	0.203178
7	0.030124	0.149509
8	0.023362	0.109548
9	0.016476	0.080521

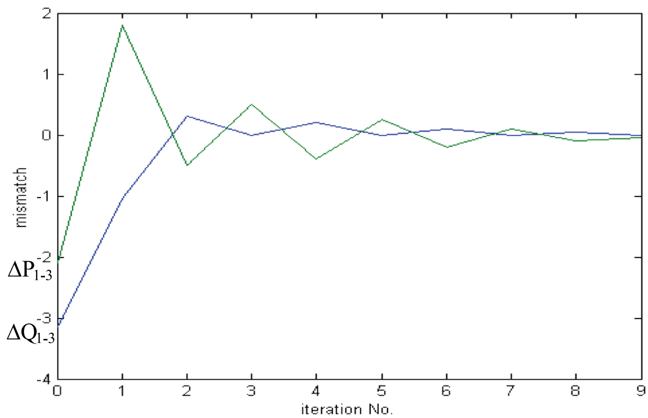

Fig. 6 – *Nature of convergence of flows in line* 1-3 (Case 2.1).

Case 2.2:

UPFC placed in line 25-27 and power controlled in line 1-3:

$P_{1-3\text{cal}} = 83.220605$, $P_{1-3\text{desired}} = 80.00$;

$Q_{1-3\text{cal}} = 5.126813$, $Q_{1-3\text{desired}} = 3.00$.

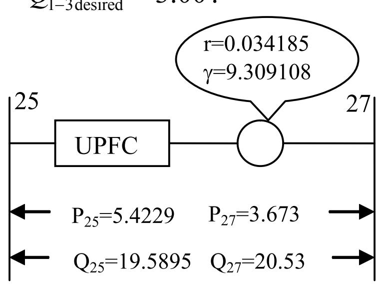

Fig. 7 –*Power flow control in line 1-3 with UPFC in line* 25-27 (Case 2.2).

Table 4
Convergence of line flows (Case 2.2).

Iteration No.	Real Power mismatch	Reactive Power mismatch
0	3.220605	2.126813
1	0.898608	1.077683
2	0.316900	0.608329
3	0.091099	0.516199
4	0.076354	0.213424
5	0.044547	0.128646
6	0.026944	0.077891

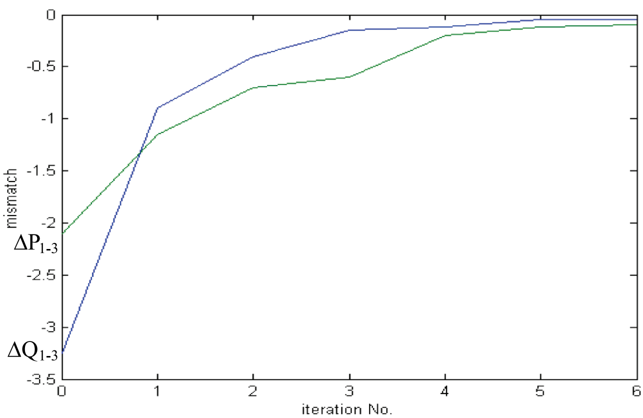

Fig. 8 – *Nature of convergence of flows in line* 1-3 (Case 2.2).

6 Conclusion

A line flow overload alleviation algorithm is presented using the line-flow sensitivity factors; these factors are computed by the static power flow equations solved with fast-decoupled power-flow algorithm. The power-injection model of the UPFC needs the computation of incremental power injections at nodes to affect the necessary change in the power flows in the lines. These are computed in this paper using the power-flow sensitivity factors. There is a need to re-compute the sensitivities when the line overload occurs at a load level very different from base case because of the non-linear relation between the line-flows and the power injections. As expected, the number of iterations needed for convergence in line-flow is larger when the UPFC is located in a line other than the one where the flow is corrected. However, in all the cases studied, the convergence is fast and no acceleration factors are necessary. The algorithm presented here can be easily adapted to real-time control.

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