Generators and Loads Contribution Factors Based Congestion Management in Electricity Markets

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***Abstract*— In this paper, a scheme based on generators and loads real and reactive power flow contribution factors has been presented for congestion management in pool based electricity markets. The system operator (SO) can identify the generators and loads based on these contribution factors for rescheduling their real and reactive power generation and loads to manage congestion. The real and reactive power bid curves for both generators and loads have been incorporated in the optimization model to determine congestion cost. The impact of Thyristor Controlled Phase Angle Regulator has also been determined on the congestion cost. The study has been carried out on IEEE 57 bus test system.**

***Index Terms*— Transmission congestion management, Real and reactive contribution factors, and Power flow sensitivity**

I. INTRODUCTION

The system operator ensures open and non-discriminatory access to transmission system and manages the transactions to remove transmission line congestion and maintain the security of the system. These transactions are negotiated ahead of time and may violate the one or more physical operating limits causing congestion in the network [1-2]. A comprehensive bibliographical survey on various congestion management schemes has been presented in [3]. Various congestion management schemes based on price based, re-dispatch based, and sensitivity based methods have been presented in [4-10].

Flexible AC Transmission System (FACTS) controllers play an important role in increasing loadability and mitigating congestion in the network. The basic model for congestion management described in [11] is used in [12] incorporating the FACTS controllers for minimum curtailment of contracts. Reactive power management has been identified as one of the important ancillary services and its proper management can help to manage congestion [13]. In corrective action based congestion management methods, it is essential to accurately determine the contribution of each generator to each line flows. The generators whose contribution is considerable to the congested line may help to mitigate congestion more effectively than the other generators in the system. A number of power flow tracing based methods have appeared in the literature [14-16]. In [16] generators real power contribution factors were determined and its role in transmission pricing and congestion management was discussed.

In this paper, both the real and reactive power flow contribution factors for generators as well as loads has been proposed to identify the most appropriate generators and loads to participate in congestion management. Real and reactive quadratic bid curves of the generators and loads have been incorporated in an OPF formulation. The proposed method has been demonstrated on IEEE 57 bus test system.

II. MATHEMATICAL MODELING

The algorithm for calculating the contribution factors of each generator to the real power line flows has been proposed in [16]. In this paper work, the generators contribution to reactive power flows as well as loads contributions to real and reactive line flows has been proposed for determining the most appropriate generators as well as loads for congestion management.

A. Loads Contribution Factors

The approach has been extended for contribution factors of each generator and loads to both real and reactive power flows. These can be determined as given below:

(a) Perform the base case Newton-Raphson power flow.

(b) Compute the sensitivity Sij^k of the real and reactive power flow P_{ij} and Q_{ij} of a line connected between bus-i and bus-j to real and reactive power output $P_D{}^k$ and $Q_D{}^k$ of generator-k. The fast-forward/fast-backward substitution method allows an efficient computation of the sensitivity for real and reactive power flows:

$$S_{ijp}^{k}=\frac{dP_{ij}}{dP_D^k}=\frac{\partial P_{ij}}{\partial P_D^k}-\frac{\partial P_{ij}}{\partial \theta}\left(\frac{\partial g}{\partial \theta}\right)^{-1}\frac{\partial g}{\partial P_D^k} \quad (1)$$

$$S_{ijq}^{k}=\frac{dQ_{ij}}{dQ_D^k}=\frac{\partial Q_{ij}}{\partial Q_D^k}-\frac{\partial Q_{ij}}{\partial \theta}\left(\frac{\partial g}{\partial \theta}\right)^{-1}\frac{\partial g}{\partial Q_D^k} \quad (2)$$

$$S_{ijp}^{k}=N_{ijp}\left[J\right]^{-1}M_k \quad (3)$$

$$S_{ijq}^{k}=N_{ijq}\left[J\right]^{-1}M_k \quad (4)$$

where N_{ijp} and N_{ijq} are the sparse block vector with sub-vector [$-b_{ij}\ V_i\ V_j,\ 0\ldots0$] and [$b_{ij}\ V_i\ V_j,\ 0\ldots0$] and [$-g_{ij}\ V_i\ V_j,\ 0\ldots0$] and [$g_{ij}\ V_i\ V_j,\ 0\ldots0$] in the i^{th} and j^{th} position, respectively. M_k is the sparse block vector with sub-vector [1, 0] in the k^{th} position. [J] is the Jacobian power flow matrix. g is the power flow equation vector and θ is the voltage angle vector.

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(c) The contribution factor of load at slack bus to real power flow of line *i-j* is:

$$CF_{ijp} = \left(\frac{(P_{ij} - \sum_{k=2}^{NG} S_{ijp}^k P_D^k) P_D^1}{\sum_{k=1}^{NG} P_D^k} \right) \quad (5)$$

In a similar manner, the contribution factors of slack bus load to reactive power flow of line *i-j* can be written as:

$$CF_{ijq} = \left(\frac{(Q_{ij} - \sum_{k=2}^{NG} S_{ijq}^k Q_D^k) Q_D^1}{\sum_{k=1}^{NG} Q_D^k} \right) \quad (6)$$

(d) The contribution factor of the m^{th} load (except slack bus load) to the real and reactive power flow of line *i-j* is

$$CF_{ijp}^m = \frac{\left(P_{ij} - \sum_{k=2}^{NG} S_{ijp}^k P_D^k + S_{ijp}^m \sum_{k=1}^{NG} P_D^k \right) P_D^m}{\sum_{k=1}^{NG} P_D^k} \quad (7)$$

$$CF_{ijq}^m = \frac{\left(Q_{ij} - \sum_{k=2}^{NG} S_{ijq}^k Q_D^k + S_{ijq}^m \sum_{k=1}^{NG} Q_D^k \right) Q_D^m}{\sum_{k=1}^{NG} Q_D^k} \quad (8)$$

These contribution factors will help the SO to identify the generators as well as loads to participate in congestion management. The quadratic bids for real and reactive power of generators have been taken in OPF simulation.

B. General OPF Formulation

The congestion management has been formulated as a non-linear programming problem solved using the GAMS/CONOPT solver [17].

Objective function: (Case 1)

$$Min \sum_{i=1}^{n} \left[\begin{array}{l} Cpg^+(\Delta P_G i^+) + Cpg^-(\Delta P_G i^-) \\ + Cqg^+(\Delta Q_G i^+) + Cqg^-(\Delta Q_G i^-) \end{array} \right] \quad (9)$$

The incremental and decremental bids for generator real and reactive power has been represented by quadratic cost curves with cost coefficients as:

$$Cpg^+(\Delta P_G i^+) = a1 + b1 * \Delta P_G i^+ + c1 * (\Delta P_G i^+)^2 \quad (10)$$

$$Cpg^-(\Delta P_G i^-) = a1 + b1 * \Delta P_G i^- + c1 * (\Delta P_G i^-)^2 \quad (11)$$

$$Cqg^+(\Delta Q_G i^+) = (Cpg\sqrt{(\Delta P_G i^+)^2 + (\Delta Q_G i^+)^2} - Cpg^+(\Delta P_G i^+) \quad (12)$$

$$Cqg^-(\Delta Q_G i^-) = (Cpg\sqrt{(\Delta P_G i^-)^2 + (\Delta Q_G i^-)^2} - Cpg^-(\Delta P_G i^-) \quad (13)$$

Equality constraints: Real and reactive power flow equations with base load, inc/dec loads as:

$$P_G - Pi^0 - \Delta Pi^+ + \Delta Pi^- - P(v,\delta) = 0 \quad (14)$$

$$Q_G - Qi^0 - \Delta Qi^+ + \Delta Qi^- - Q(v,\delta) = 0 \quad (15)$$

$P(v,\theta), Q(v,\theta)$ are the load flow equations given as:

$$P_i = P_{gi} + P_{DGi} - P_{di} = \sum_{j=1}^{N_b} V_i V_j \left[\begin{array}{l} G_{ij}\cos(\delta_i - \delta_j) \\ + B_{ij}\sin(\delta_i - \delta_j) \end{array} \right] \quad (16)$$

$\forall\, i = 1,2,\ldots N_b$

$$Q_i = Q_{gi} + Q_{DGi} - Q_{di} = \sum_{j=1}^{N_b} V_i V_j \left[\begin{array}{l} G_{ij}\sin(\delta_i - \delta_j) \\ - B_{ij}\cos(\delta_i - \delta_j) \end{array} \right] \quad (17)$$

$\forall\, i = 1,2,\ldots N_b$

where

P_i real power injection at bus-*i*; Q_i reactive power injection at bus-*i*; P_{gi}, Q_{gi} real and reactive power generation at bus-*i*; P_{di}, Q_{di}real and reactive power demand at bus-*i*; *V*ivoltage magnitude at bus-*i*; $\delta_i$load angle at bus-*i*; $Y_{ij} = G_{ij} + B_{ij}$ *i-j*th element of Y-bus matrix; N_b Number of buses.

Inequality constraints:

Incremental generation real and reactive power limit

$$0 \le \Delta Pi^+ \le Pi^{\max} - Pi^0 \quad , 0 \le \Delta Pi^- \le Pi^0 - Pi^{\min} \quad (18)$$

$$0 \le \Delta Qi^+ \le Qi^{\max} - Qi^0 \quad , 0 \le \Delta Qi^- \le Qi^0 - Qi^{\min} \quad (19)$$

Line flow limit, Voltage limit, and angle limit

$$S_i^{\min} \le S_{ij} \le S_i^{\max}, V_i^{\min} \le V_i \le V_i^{\max} \quad (20)$$

$$\theta_i^{\min} \le \theta_i \le \theta_i^{\max} \quad (21)$$

Objective function: (Case 2)

$$Min \sum_{i=1}^{n} \left[\begin{array}{l} Cpd^+(\Delta P_D i^+) + Cpd^-(\Delta P_D i^-) \\ + Cqd^+(\Delta Q_D i^+) + Cqd^-(\Delta Q_D i^-) \end{array} \right] \quad (22)$$

$$Cpd^+(\Delta P_D i^+) = a2 + b2 * \Delta P_D i^+ + c2 * (\Delta P_D i^+)^2 \quad (23)$$

$$Cpd^-(\Delta P_D i^-) = a2 + b2 * \Delta P_D i^- + c2 * (\Delta P_D i^-)^2 \quad (24)$$

$$Cqd^+(\Delta Q_D i^+) = (Cpd\sqrt{(\Delta P_D i^+)^2 + (\Delta Q_D i^+)^2} - Cpd^+(\Delta P_D i^+) \quad (25)$$

$$Cqd^-(\Delta Q_D i^-) = (Cpd\sqrt{(\Delta P_D i^-)^2 + (\Delta Q_D i^-)^2} - Cpd^-(\Delta P_D i^-) \quad (26)$$

The all equality and inequality constraints are same as for the scheme with generation rescheduling. The power flow equations can be modified in the presence of TACPR [17].

III. System Studies

The congestion has been simulated by increasing the load in steps and finding the line with a flow near to its line rating. For the test system; line 1 has been found to be congested. The results have been obtained for two cases:

Case 1: Congestion management with Generation Rescheduling

Case 2: Congestion Management with Load Curtailment

(A) Results for IEEE 57 Bus test System for both cases

Based on the contribution factors, generators G2 and G9 for case 1 have been selected to reschedule their real power. The generation for base case, change in the generation, new generation schedule, and minimum and maximum limits has been shown in the Fig. 1. It is observed form the figure that the generator G2 and G9 reschedule their generation by increasing and decreasing their generation level within the specified limits.

For case2, based on the contribution factors of loads on the congested line, real loads L12 and L32 and reactive loads 2 and L27 have been selected for congestion management. The real and reactive load curtailment is shown in the Fig.2. As observed from Fig. 2, L12 decrement its load and L32 increase its load.

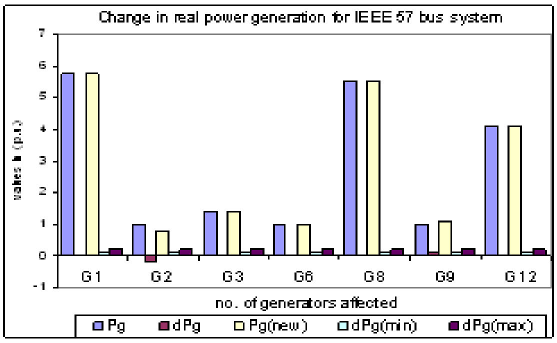

Fig. 1: Change in real power generation (case1)

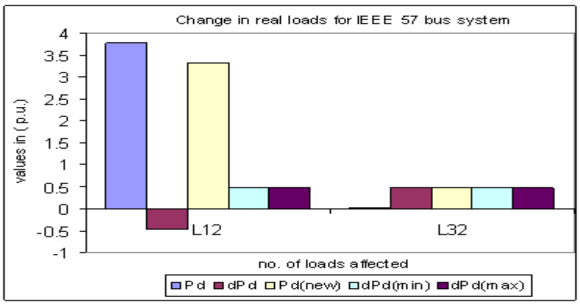

Fig.2: Change in real loads (Case 2)

(B) Results for IEEE 57 Bus test System with TCPAR[18]

The results obtained for generation rescheduling for case1 in the presence of TCPAR has been shown in the Figs. 3. The generator G2 and G9 participating in the congestion management scheme are subjected to lower values of real and reactive power rescheduling to manage congestion in the presence of TCPAR.

Similarly, the real power loads rescheduling with TCPAR for Case 2 is shown in Figs. 4. It is observed from Fig. that loads are subjected to lower values of curtailment in the presence of TCPAR. The congestion costs obtained for both the cases without and with TCPAR have been determined and are shown in Figs. 5 and 6. Comparing the congestion cost as shown in the Figs. 5 and 6, without and with TCPAR, it is observed that the congestion cost for both cases with TCPAR has been found to be lower as compared to the congestion costs obtained without the presence of TCPAR. The reductions in the congestion costs are obtained as the generators as well as loads are subjected to lower value of rescheduling in the presence of TCPAR. Comparing the congestion costs for Case 2 and Case 1, it is observed from the Figs. 9 and 10 that the congestion cost is found to be comparatively higher for load curtailment case as congestion cost found in case of generation rescheduling without and with TCPAR as loads are subjected to higher values of rescheduling than the generators.

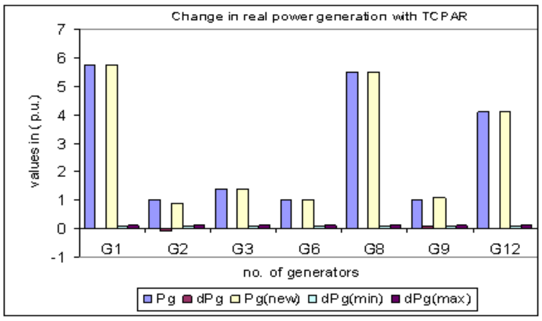

Fig.3: Change in real power generation with TCPAR (Case 1)

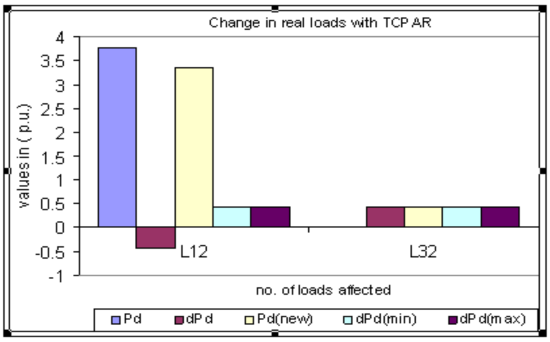

Fig.4: Change in real load with TCPAR (Case 2)

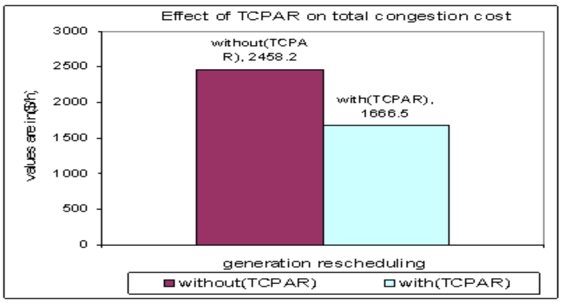

Fig. 5: Effect of TCPAR on total congestion cost (Case1)

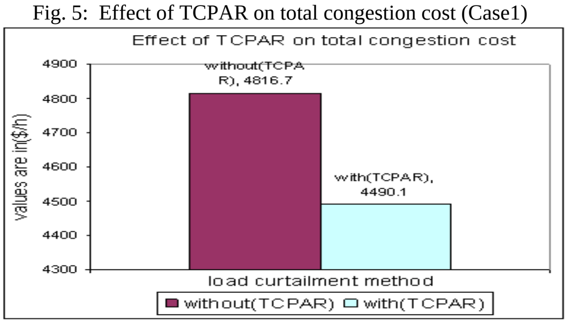

Fig. 6: Effect of TCPAR on total congestion cost (case2)

IV. Conclusions

The following observations have been obtained:

(i) The system operator can identify most appropriate generators and loads for their rescheduling and curtailment for congestion management based on these contribution factors.

(ii) The congestion cost is found to be more for load curtailment based approach than generator rescheduling based approach.

(iii) The congestion cost reduces in the presence of TCPAR for both generator rescheduling and load curtailment based methods.

The contribution factors based approach is simple as these factors can be calculated well in advance with only single load flow solution and most appropriate generators and loads can be selected based on their contributions to the congested lines for congestion management.

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