# Control of Market Power Using Demand Responsiveness in Congested Restructured Power System Networks

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***Abstract*—In this paper, an effective and realistic methodology has been devised for evaluation and control of market power in congested restructured power system networks. The evaluation of market power of any generator is based on optimization problem which determines the minimum amount of the real power need to be supplied by the generator for meeting the congested system constraints of restructured power system networks. The control of market power is achieved by the application of demand flexibility in the above said optimization problem. The optimization problem has been solved by considering the linear and non-linear modelling of the power system. The proposed methodology has been simulated on three bus and nine bus test systems under the various cases of congested transmission network with fixed and flexible demands. The simulated results reveal the effectiveness and practicability of the proposed approach.**

***Keywords: Locational Marginal Price, Market Clearing Price, Demand Response, Benefit Function, Social-Welfare Function.***

***Nomenclature:***

Parameters

| | |
|---|---|
| NG | Number of Generators |
| Yi, j | Element of bus admittance matrix |
| NL | Number of PQ buses |
| Pimax | Max Real Power Gen at ith bus |
| Pimin | Min Real Power Gen at ith bus |
| Qimax | Max Reactive Power Gen at ith bus |
| Qimin | Min Reactive Power Gen at ith bus |
| Vimax | Maximum voltage at ith bus |
| Vimin | Minimum voltage at ith bus |
| Pi, j max | Max Power flow limit between the buses i and j |
| bi j | Susceptance |

Variables

| | |
|---|---|
| P Gi | Real Power Gen at ith bus |
| Q Gi | Reactive Power at ith bus |
| PD, QD | Real and Reactive power demand |
| V | Bus voltage |
| $\delta$ | Angle associated with bus voltage V |

Functions

| | |
|---|---|
| C(PGi) | Fuel cost function |
| B(Pi) | Benefit function (BF) |

## I. Introduction

Restructuring in power system has introduced competition at generation point, thus causing generation, transmission, and distribution companies to work independently in electric industry. With continuous increment in electricity demand day-by-day, power sector is facing challenges to maintain the balance between generation and demand while satisfying both physical constraints (power flow equations) and engineering limits (voltage magnitude, line flow limits and power generation limits). In such an environment, system operator must manage transmission congestion and constraints [1]. Independent system operator (ISO) plays a major role in relieving the congestion. This task of management or relieving congestion is known as congestion management. For congestion management in transmission network, there are three different models namely optimal power flow model, price area congestion control model and U.S. transactions-based model are discussed in [2]. Analysis of active power flow has been done in [3], for which authors have obtained solution to optimal power flow.

Authors studied dynamic security constrained congestion management in an unbundled electric power system and a feasible approach had been developed for a system with a mix of pool & contract dispatches in [4]. For IEEE 30 bus test system, Sood et al. had proposed a generalized deregulated model to dispatch the pool combined with privately negotiated bilateral and multi-lateral contracts and then maximized the Social-welfare function [5]. Strategy for allocation of transmission losses among various market participants had been suggested in [6]. Authors presented for an OPF model for congestion management and minimizing load curtailment. The

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importance of congestion management had been discussed in reference [7], which identified the congestion management as one of the key issues to maintain security and reliability of transmission networks. For elimination of congestion, an approach based on locational marginal price had been reported in [8]. In [9], the profits of GENCOS in a perfectly competitive and oligopolistic pool electricity market with bidding strategy had been studied and analyzed. DCOPF model had been used to determine LMPs. With the help of OPF tool, ISO can match supply & demand bids and can estimate the nodal prices. Authors introduced a new parameter termed as willingness to-pay-to-avoid-curtailments. Sood et al. [10] had obtained cost effective power generation and then mitigated congestion in de-regulated power system with incorporation of both conventional and renewable energy sources. Researchers, who were working on congestion management, had suggested that there are two approaches that can alleviate congestion. These two approaches are generation side and demand-side approaches. In [11-12], researchers had concentrated on demand - side approach considering this approach more effective in improving security and reliability in operation of power system. Due to difficulty in overcoming transmission congestion, load control methods are used by the researchers in new era of smart grid regimes. Haque et al. in 2019 discussed about direct and in-direct load control methods in low voltage network for relieving congestion [13]. After the electric power industry started a process of transition and restructuring, the concept of market power had gained its importance. Operational and physical constraints of the network had been identified as major threats to the market by GENCOs. In [14], author reviewed about concept of market power in competitive environment. It had been mentioned that a utility possessing market power could increase market price of good more than its marginal cost. In perfect competitive environment, market participants could not have any market power. Khajeh et al. proposed different indices of market power for separating two strategies naming physical holding and financial holding in [15]. Authors solved linear optimization problem considering transmission constraints and calculated proposed indices naming ex - ante modified TCRSI, ex-ante physical withholding index and ex - ante financial holding index.

The objective of this paper is to illustrate the impact of demand flexibility on control of market power in congested restructured power system network. For that, market power has been calculated for both fixed and flexible demands. It has been observed that by making demand flexible in congested restructured power system network, market power of generators can be controlled. The market power has been evaluated using optimization problem while taking minimization of supply from a particular generator as an objective function. Function 'fmincon' has been used in MATLAB environment for solving minimization problem. In addition, OPF problem has been solved taking social welfare function as objective function.

The rest of paper is organized as follows: Section 2 gives mathematical model of OPF in electricity market. The detailing about linear formulations of OPF problem is given in section 2.1. To determine market power, steps are provided in section 2.2. Solution methodology of the problem is included in section 3 and discussion of results has been given in section 4. Finally, section 5 concludes this paper.

## II. Mathematical Model of OPF in Electricity Market

Congestion management can be achieved by maximization of social welfare function. Social welfare function consists of two parts. One part is associated with customers (as benefit function) and second part is linked with generation companies (cost function of real power generation). Social welfare function is a difference of benefit function and cost function. It is the measure by customer's willingness to pay for its demand and cost of unit of energy.

$$\text{Benefit function} = \sum_{i=1}^{N} B(P_i) \tag{1}$$

Social Welfare Function is given as in equation (2)

$$\text{Max}\ \{\text{BF} - \text{C}(\text{P}_\text{G})\} \quad or \quad \text{Min}\{C(P_G) - BF\} \tag{2}$$

The objective function for simple OPF problem is considered as the minimization function of cost of the generation.

$$C(\text{P}_{\text{Gi}}) = \sum_{\text{i}=1}^{\text{N}_\text{G}} (\alpha_\text{i} + \beta_\text{i} \text{P}_{\text{Gi}} + \gamma_\text{i} \text{P}_{\text{Gi}}^2) \tag{3}$$

subjected to the constraints as given in equations (4) - (9).

$$\text{P}_i - P_{Di} = \sum_j |V_i||V_j| Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{4}$$

$$\text{Q}_i - Q_{Di} = \sum_j |V_i||V_j| Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{5}$$

For i=1, 2, ……, NL. Inequality constraints are as follows:

Generating limits:

$$\text{P}_\text{i}^{\text{min}} \le \text{P}_\text{i} \le \text{P}_\text{i}^{\text{max}} \qquad \forall \text{i} \in \tag{6}$$

$$Q_i^{min} \leq Q_i \leq Q_i^{max} \qquad \forall i \in N_G \tag{7}$$

Bus Voltage Limits:

$$|V|_i^{min} \leq |V_i| \leq |V|_i^{max} \qquad \forall i \in \tag{8}$$

Power Flow Limits:

$$P_{ij} \leq P_{ij}^{max} \qquad \forall Y_{ij} \neq 0 \tag{9}$$

The OPF problem determines a minimum cost operating point that satisfies both physical constraints (i.e., the power flow equations) and engineering limits (e.g., voltage magnitude limits, line flow limits, and power generation limits). The full non-linear OPF problem is referred to as the alternating current optimal power flow (ACOPF) and a commonly used linearized version is called the direct current optimal power flow (DCOPF).

### A. Formulation of the Linearized Optimal Power Flow Problem

A linear optimal power flow problem approximates the non-linear OPF under several simplifying conditions such as i) High voltage transmission lines can be considered as lossless lines which means line resistance can be ignored ii) Bus voltage angle differences are very small, and bus voltage magnitudes are approximately 1.0 pu which means reactive power is eliminated as a variable in the transmission network modeling.

After applying these assumptions, the reactive power flow is considered as zero on each line and the real power flow in line is simplified using equation (10).

$$P_{ij} = b_{ij}(\delta_i - \delta_j) \tag{10}$$

### B. Determination of Market Power

In restructured power system network, competitions play an important role. To have fair competition, market power is required to be controlled in congested system conditions. Otherwise, if firm has a chance to exercise market power, the competition turns to be unfair. For achieving control of market power, first step is to evaluate the market power of each generator of the considered system. Market power can be obtained using minimization of the supply from the generators considering one at a time as shown in equation (11).

$$\text{Objective Function} = \text{Min} \quad P_i \tag{11}$$

subjected to the constraints as given in equations (4) - (9).

For observation of effect of flexibility in demand, two cases for market power have been considered. In case1, demand has been taken as fixed under congested system conditions. While in case2, flexible demand under congested conditions has been considered.

## III. Solution Methodology

The optimal power flow problem has been solved using 'fmincon' in-built function. Decision variables are taken as real power generation, demand, voltage magnitude and voltage angles depending upon the case. Linear / non-linear equality and in equality constraints have been considered as per the requirement of problem. Fig. 1 shows the steps involved in solving the OPF problem.

The concept of obtaining market power of the generators given in [15] has been used in this paper. According to which it is required to check whether system has a capacity to meet all demands without taking any supply from a considered firm or not. When the system can meet all demands without taking supply from a specific firm, then market power of that firm/generator is zero. The mathematical model for finding market power has been developed and solved as a linear programming problem whose objective function is to minimize the supply from given generator while meeting all equality and in-equality constraints.

## IV. Results and Analysis

### A. Different Cases of 3 bus 3 Lines System

The data used for solving OPF problem has been taken from [16]. Four cases of linear OPF for given 3 bus system 3 lines system (as shown in Fig. 2) have been solved as below:

*Case 1:* demand at bus 3 is fixed at 30 MW under non congested conditions.

*Case 2:* demand at bus 3 is flexible under non congested conditions.

*Case 3:* demand at bus 3 is fixed at 30 MW under congestion.

Case 4: demand at bus 3 is flexible under congestion.

The solution of OPF is presented in Table 1.

Table 1 shows that when system is free from congestion and demand is fixed the LMP = MCP = 37.57$/MWh and if this demand is made flexible then MCP is reduced to 33$/MWh. When demand is fixed under congested system conditions, then MCP = 47.86$/MWh which is higher than the LMP (45.15$/MWh) at demand side. Whereas if demand is flexible under congested system conditions, then market is cleared at comparatively lesser price 33.5$/MWh.

### B. Different Cases of 9 bus 9 Lines System

The data required to solve OPF problem of 9 bus 9 lines system is taken from case 9 of the MATPOWER software [17]. Two cases for 9 bus 9 lines system (as shown in Fig. 3) have been solved as below:



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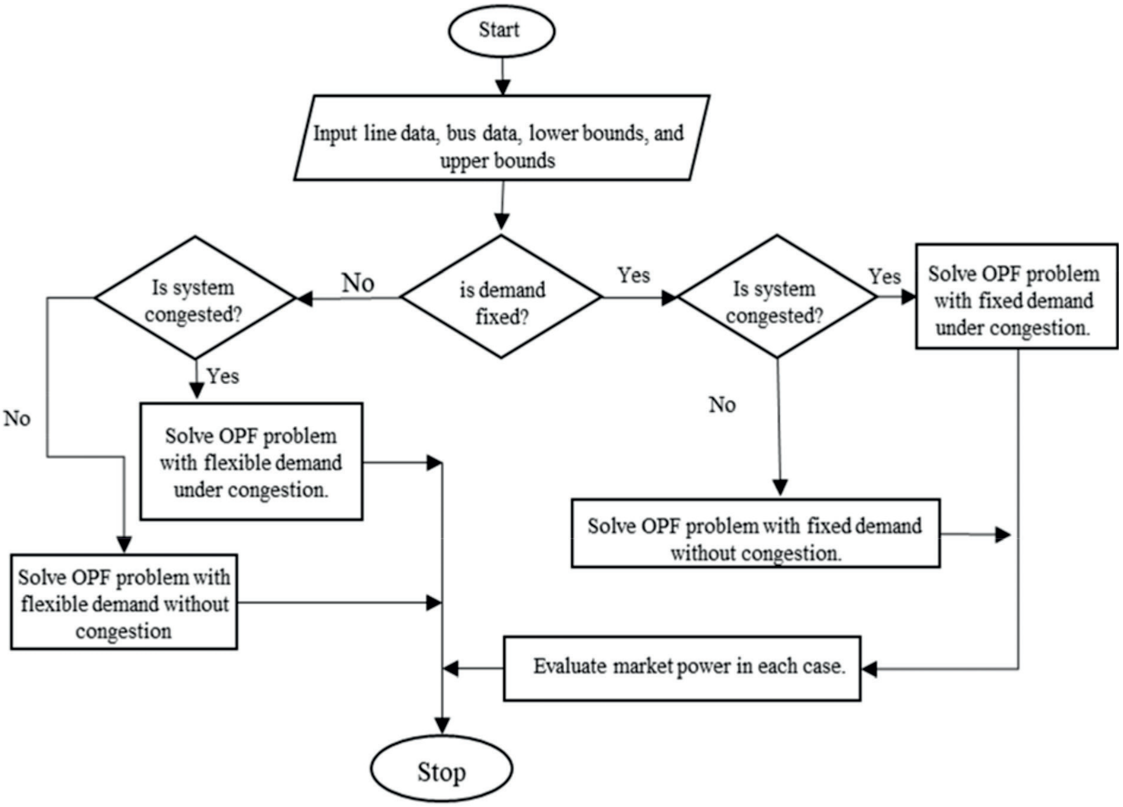


Fig. 1: Flow-Chart Depicting Solution Methodology

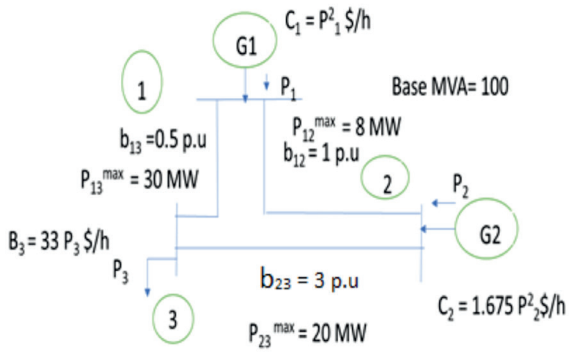


Fig. 2: Single Line Diagram of 3 Bus 3 Lines System [16]

Table 1: Results of Linear OPF for 3 Bus 3 Lines System

| Case | At bus1 (gen) in (MW) | At bus 2 (gen) in (MW) | At bus 3 (demand in (MW) | LMP for 3 buses ($/ MWh) | | | MCP ($/ MWh) | Market power for generators in (MW) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Bus 1 | Bus 2 | Bus 3 | | 1 | 2 |
| 1 | 18.79 | 11.21 | 30 | 37.57 | 37.57 | 37.57 | 37.57 | 0 | 0 |
| 2 | 16.5 | 9.85 | 26.35 | 33 | 33 | 33 | 33 | 0 | 0 |
| 3 | 15.7 | 14.29 | 30 | 31.43 | 47.86 | 45.15 | 47.86 | 0 | 14.29 |
| 4 | 15 | 14.29 | 25 | 30 | 33.5 | 33 | 33.5 | 0 | 0 |

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*Case 1:* demand at buses 5, 7 and 9 are fixed at 30, 90 and 50 MW, respectively with congestion.

*Case 2:* demand at buses 5,7 and 9 is flexible and respective demand bids are taken as 15, 17 and 15 $/ MWh with system under congestion.

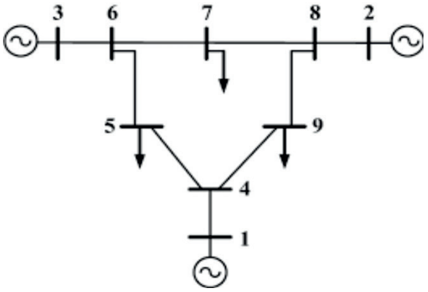


Fig. 3: Single Line Diagram of 9 Bus 9 Lines System [17]

For case1, column I and II of Table 2 present the optimum results of OPF. For case2, column I, II and III of Table 3 present the optimum results of OPF.

Table 2: Results of Non-Linear OPF for 9 Bus 9 Lines System for Case1 (Fixed Demand and Congestion)

| I<br>Real Power (MW) | II<br>Demand (MW) | III<br>Market Power (MW) |
|---|---|---|
| $P_{G1}$ = 54.55 | $P_{D5}$ = 30 | Gen1 = 80 |
| $P_{G2}$ = 92.94 | $P_{D7}$ = 90 | Gen2 = 27.18 |
| $P_{G3}$ = 65.31 | $P_{D9}$ = 50 | Gen3 = 49.70 |

Table 3: Results of Non-Linear OPF for 9 Bus 9 Lines System for Case2 (Flexible Demand with Congestion)

| I<br>Demand Bids | II<br>Real Power (MW) | III<br>Demand (MW) | IV<br>Market Power (MW) |
|---|---|---|---|
| $B_5$ =15 $P_5$ | $P_{G1}$ = 54.55 | $P_{D5}$ = 30 | Gen1=10 |
| $B_7$ =17 $P_7$ | $P_G2$ = 92.94 | $P_{D7}$ = 123.75 | Gen2=10 |
| $B_9$ =15 $P_9$ | $P_{G3}$ = 56.26 | $P_{D9}$ =50 | Gen3=10 |

For case1, fixed demand is met with generations shown in column I of Table 2. Table 3 shows that customer at bus 7 has bided more price so demand met at bus 7 is higher as compared to case1. From here, it can be established that when demand is made flexible, demand met depends upon customer's willingness to pay.

### *C. Solution for Market Power*

For market power, when supply from generator is minimized one at a time then the value of generation obtained gives the market power of that generator. As shown in Table 1, market power of both generators for all four cases has been calculated. It is observed that generators have market power under congested system conditions. Then to control this market power, demand is made flexible under congested conditions. As a result of demand responsiveness, market power of generator 1 is reduced to 0 MW from 14.29 MW.

From column III of Table 2, it is observed that the values of market power with fixed demand (case1) for 9 bus 9 lines system as 80, 27.18 and 49.70 MWs respectively at generators 1, 2 & 3. Then on making demand flexible under congested system conditions (case2), the values of market power are reduced to 10 MW at all three generators as shown in column IV of Table 3. From these results, it can be concluded that market power can be controlled using demand responsiveness.

## IV. Conclusion

This paper provides an overview of solving optimal power flow problem. The solution of OPF problem under non congested conditions reveals that when demand is fixed then MCP is higher as compared to LMP, whereas if demand is made flexible, then MCP price is same as the LMP. Further, customer pays more for fixed demand in comparison to flexible demand under congestion. Subsequently, role of the demand side in managing market power has been examined. The findings for market power show that the ability of firm to exercise market power depends upon nature of demand. Hence, it can be concluded that market power can be controlled with demand responsiveness.

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