Congestion Management Using Multi-Objective Grenade Explosion Method

S. Surender Reddy
Department of Railroad and Electrical Engineering, Woosong University, South Korea.
*Corresponding Author: salkuti.surenderreddy@gmail.com

Abstract- The operational aspects of power systems pose some of the most challenging problems encountered in the restructuring of electric power industry. This paper focuses on Congestion Management within an Optimal Power Flow (OPF) framework in the deregulated electricity market scenario. The conventional OPF problem is modified to create a mechanism that enables the market players to compete and trade, and simultaneously ensures that the system operation stays within the security constraints. The centralized/pool and bilateral dispatch functions of an Independent System Operator (ISO) are considered in this paper. Here, Multi-Objective Grenade Explosion Method (MO-GEM) based approach is presented to formulate as multi-objective optimization problem with competing fuel cost and system loss minimization as objective functions. The proposed approach is tested on IEEE 30 bus system. The simulation results revealed the capabilities of the proposed MO-GEM approach to generate well distributed Pareto optimal non-dominated solutions of multi-objective generation cost and transmission loss minimization.

Key Words- Congestion Management, Optimal Power Flow, Electricity Markets, Evolutionary Algorithms.

1. Introduction

The restructuring of electric power industry has involved paradigm shifts in the real time control activities of the power grids. Managing dispatch is one of the important control activities in a power system. Optimal power flow (OPF) is the most important technique for obtaining minimum generation cost patterns in a power system with existing transmission and operational constraints. The role of an Independent System Operator (ISO) in a competitive market environment would be to facilitate the complete dispatch of the power that gets contracted among the market players. With the trend of an increasing number of bilateral contracts being signed for electricity market trades, the possibility of insufficient resources leading to network congestion may be unavoidable. In this scenario, Congestion Management (within an OPF framework) becomes an important issue. Real-time transmission congestion can be defined as the operating condition in which there is not enough transmission capability to implement all the traded transactions simultaneously due to some unexpected contingencies. It may be alleviated by incorporating line capacity constraints in the dispatch and scheduling process. This may involve re-dispatch of generation or load curtailment. Other possible means for relieving the congestion are operation of phase shifters or using Flexible AC Transmission Systems (FACTS) controllers.

The dispatch problem has been formulated with two different objective functions: cost minimization and minimization of transaction deviations. Congestion charges can be computed in both the cases. In a centralized/pool market mode, the sellers (competitive generators) may submit their incremental and decremental bidding prices in balancing i.e., real-time market. These can then be incorporated in the OPF problem to yield the incremental/decremental change in the generator outputs. Similarly, in case of a bilateral market mode, every transaction contract may include a compensation price that the buyer-seller pair is willing to accept and its transaction to be curtailed. This can then be modeled as a prioritization of the transactions based on the latter's sensitivities to the violated constraint in case congestion occurs. We also look at a modified OPF whose objective is to minimize the absolute MW of rescheduling. In this framework, we consider dispatching the bilateral contracts too in case of serious congestion, with the knowledge that any change in a bilateral contract is equivalent to modifying the power injections at both the buyer and the seller buses. This highlights the fact that, in a restructured scenario, contracts between trading entities must be considered as system decision variables (in addition to the usual generation, loads and flows).

In this paper, a new Multi-Objective Grenade Explosion Method (MO-GEM) is used for the Congestion Management (CM). After creating the OPF program, this OPF will give us some feasible solution while creating congestion by adding bilateral and multilateral transaction randomly between any nodes. Then, we will try to alleviate congestion by rescheduling the generation of each generating station. The Independent System Operator (ISO) in a competitive electricity market is responsible for determining the necessary actions to ensure that no violations of the grid constraints occur. The comprehensive set of actions or procedures are referred as Congestion Management (CM), which principally consists of re-dispatch of generation and load levels so as to establish a system state without violations of system constraints. The cost of congestion plays a major role in attaining such a state. In addition, ISO may divide a grid into separate pricing zones to manage the congestion. CM approaches are based on issuing orders by the System Operator (SO) to various parties to reschedule their contracts, re-dispatch generators, use various control devices, or shed loads in the extreme conditions when these measures are not able to mitigate congestion [1-3]. Other solutions are based on finding the new contracts that redirect flows on congested paths. Phase shifters, tap changing transformers, and FACTS controllers may play a vital role in a deregulated electricity markets to mitigate the transmission congestion problem [4-5].

Based on the literature review, three forms of CM have been adopted in the deregulated electricity market around the world [3]. One form is based on centralized optimization with some form of OPF program or depending upon the control measures executed by the SO for the congestion relief. A second form is based on the use of price signals derived from ex-ante market resolution to determine the congestion by constraining scheduled generator output prior to real time operation. A third form seeks to control congestion by allowing or disallowing bilateral transmission agreements between a producer and a consumer, based on the effect of transaction on the transmission system.

California ISO (CAISO) uses the grid portioning into a number of preferred zones [6]. The auction-based results provide preferred schedules established by several scheduling coordinators in the bilateral markets. In case the market dispatch results the congestion even after re-adjustment bids, then it is eliminated using re-dispatch with zonal partitioning. Congestion re-dispatch provides zonal prices and transmission usage prices with the interface flows. On the other hand, new markets for Firm Transmission Rights (FTR) have been introduced as a way to negotiate the ownership of congested paths and to provide market mechanisms to improve the economic efficiency in the use of transmission network.

England and Wales market has only one zone and no constrained interfaces are considered for market dispatch. In the congestion re-dispatch stage all the constraints of the system are considered and every bus becomes a zone. Loads do not participate in the CM. Generators are re-dispatched by the ISO and may receive compensation due to congestion. The additional congestion charge is distributed to consumers as part of uplift. Generators that are selected for relieving transmission congestion are *constrained* regardless of their bid prices. Locational market power screen is also currently used in New England market for CM.

Optimization is one of the challenging problems in power system operation. The goal of this optimization is to minimize/maximize a specific objective function subject to the operational constraints of power system [7]. In recent years, there has been an interest in applying the Multi-Objective Optimization (MOO) for power system problems [7-8]. Multi-Objective Optimization (MOO) can be considered as an optimizing many objective functions subject to different constraints. For power system applications, these objective functions can be cost, transmission loss, voltage deviation etc. Many tools are available to solve the MOO problems. Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) [9, 10] are some of the techniques that have been proposed recently.

An open transmission dispatch environment in which pool and bilateral/multilateral dispatches co-exist and proceeds to develop a Congestion Management (CM) strategy is presented in

[11]. Reference [12] presents papers/literature on CM issues in the deregulated electricity markets. A procedure for minimizing the number of adjustments of preferred schedules to alleviate congestion and apply control schemes to minimize interactions between zones while taking contingency-constrained limits into consideration is introduced in [13]. Reference [14] presents a method of CM by generation rescheduling and load shedding. The sensitivities of overloaded lines to bus injections and the costs of generation and load shedding are considered for ranking the generation and load buses. Reference [15] proposes a CM model that is appropriate for power pool, and PSO (particle swarm optimizer) is introduced to solve this complex non-linear model. A new method of fuzzy adaptive bacterial foraging based CM for the first time by optimal rescheduling of active powers of generators selected based on the generator sensitivity to the congested line is proposed in [16]. A sensitivity based CM technique based on the generation rescheduling and/or load shedding. A sensitivity index which relates the change in line current with respect to change in bus injections is developed in [17] to select the participating generators and/or loads. For power systems applications, many of the proposed methods for MOO focus on the constraints related to the steady state operation. Security constraints (i.e., operation of the power system under credible contingencies) are not considered in detail. The objective is to consider MOO for minimization of congestion rental and the transmission loss.

From the above discussion, it is observed that the operational aspects of power systems pose some of the most challenging problems encountered in the restructuring of the electric power industry. This paper focuses on CM problem within an OPF framework in a deregulated electricity market scenario. The conventional OPF problem is modified to create a mechanism that enables the market players to compete and trade, and it simultaneously ensures that the system operation stays within the security limits. The centralized/pool and bilateral dispatch functions of an ISO are considered in this paper.

In this paper, Multi-Objective Grenade Explosion Method (MO-GEM) is used to minimize the congestion rental and transmission loss in the system. The solution of the problem discussed will help to the calculate transmission line overload removal, transmission system control, available transfer capability (ATC) calculations, active and reactive power pricing, transmission component valuation, and transmission system marginal pricing. The MO-GEM based approach is presented in this paper to formulate a multi-objective optimization (MOO) problem with competing fuel cost and system loss minimizations as the objective functions. A MO-GEM approach is presented for generating the Pareto optimal solutions for CM problems. On achieving good results for test cases, the approach was applied to a case study of multi-objective congestion management problem. The solutions of MO-GEM yield a trade-off curve, identifying a set of alternatives that define optimal solutions to the problem.

The remainder of the paper is organized as follows: Section 2 presents the Congestion Management (CM) problem formulation. Section 3 describes the Grenade Explosion Method (GEM) and Multi-Objective Grenade Explosion Method (MO-GEM) algorithms. Section 4 presents the results and discussion. Finally, Section 5 presents the contributions with concluding remarks.

2. Congestion Management (CM): Problem Formulation

The Congestion Management (CM) problem is formulated as a Multi-Objective Optimization (MOO) problem considering the fuel cost and system loss minimizations as the objective functions. The considered two objective functions are presented next:

The first objective function is to minimize the total cost of generation (F_T), and is given by,

$$\mathrm{F_T} = \sum_{\mathrm{i}=1}^{\mathrm{N_G}} \mathrm{F(P_{Gi})} \qquad (1)$$

where P_{Gi} is the active power generation of the ith generator, $F(P_{Gi})$ is the generation cost function of ith generator and N_G is the total number of generators in the system. $F(P_{Gi})$ can be expressed by,

$$F(P_{Gi}) = \sum_{i=1}^{NG} (a_i + b_i P_{Gi} + c_i P_{Gi}^2) \qquad (2)$$

If we consider, the bidding prices in the market, then the first objective becomes congestion rental, and is given by,

$$f_1 = minimize \left(\sum_{i=1}^{N_G} C_i^+ \Delta P_i^+ - \sum_{i=1}^{N_G} C_i^- \Delta P_i^- \right) \quad (3)$$

The above equation is optimized, subjected to the following equality and inequality constraints:

The power balance constraints are based on the equilibrium between total system generation and system loads. These are expressed by the following non-linear equations,

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (4)$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (5)$$

where P_{Gi} and Q_{Gi} are the active and reactive power generation at i^{th} bus; P_{Di} and Q_{Di} are the active and reactive load demands, respectively. $|Y_{ij}|$ and θ_{ij} are the magnitude and angle of the bus admittance. δ_i and δ_j are the voltage angles at bus i and bus j.

The inequality constraints of active power generation (P_{Gi}), reactive power generation (Q_{Gi}), voltage magnitude ($|V|$) and line flow limit (S_L^{max}) are expressed by,

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (6)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (7)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (8)$$

$$S_L \le S_L^{\max} \quad (9)$$

The second objective function is to minimize the system transmission loss, and is given by,

$$P_L = \sum_{n=1}^{N} P_{Loss\ n} \quad (10)$$

where $P_{Loss,n}$ is the power loss in the line connected between bus i and bus j. The transmission loss ($P_{Loss,n}$) can be expressed by the following expression,

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \quad (11)$$

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) - B_{ij} \sin(\delta_{ij})] \quad (12)$$

$$P_{Loss\ n} = \sum_{k=1}^{N_L} G_{ij} \left[|V_i|^2 + |V_j|^2 - 2|V_i||V_j| \cos(\delta_i - \delta_j) \right] \quad (13)$$

$$f_2 = \min P_{Loss} = \sum_{k=1}^{NL} (V_i^2 G_{ij} + V_j^2 G_{ij} - 2 V_i V_j G_{ij} \cos \delta_{ij}) \quad (14)$$

The description of Grenade Explosion Method (GEM) algorithm is presented next:

3. Grenade Explosion Method (GEM) Algorithm

The evolutionary/meta-heuristic algorithms are stochastic methods that maintain a population of individual solutions, and rely on Darwinian operators of selection, mutation, and recombination. These algorithms have been immensely popular as they are (i) derivative free techniques (ii) population based, and not as prone to getting trapped in local minima (iii) sample a wide region of the search space (iv) can be tailored specifically to suit the problem and (v) hybridize with other algorithms for improved performance. Such features makes the evolutionary algorithms good candidates for fitting differential equation models of gene networks.

3.1 Overview of GEM Algorithm

The GEM is a new evolutionary algorithm for optimizing real-valued bounded black-box optimization problems inspired by the mechanism of grenade exposition [18-20]. In the GEM, once the grenades explode, the resulting shrapnel hit objects that are located within a neighborhood radius called L_e. The damages caused by shrapnel on objects are calculated. The damage-per-shrapnel value indicates the value of objects in that area. In order to cause more damage, the next grenade is thrown in the location of the greatest damage that has been caused. The overall damage caused by the hit is considered as the fitness of the solution at the object's location.

GEM has a unique feature, which is the concept of agent's territory radius (R_t) [18-20]. Each agent (i.e., grenade), does not allow other agents to come closer than a certain distance that is R_t. Hence, when several grenades expose in the search space, a high value of R_t guarantees that grenades are spared quit uniformly in the search space while a small value of R_t allows the grenades to search local regions together [18-20].

3.2 Algorithm of GEM

GEM starts by scaling all independent variables within the interval [-1,1]. Then, the problem parameters such as number of grenades (N_g) and maximum number of iterations are selected, and L_e, R_t are initialized. After that, N_g grenades, distant by R_t from each other, are randomly generated in the n-dimensional scaled space. These grenades are ranked in a descending order based on their fitness. For each grenade, N_q pieces of shrapnel are generated using the following equation,

$$X_j^{'} = [X_m + sign(r_m) \times |r_m|^p \times L_e] \qquad (15)$$

where $j = 1,2,\ldots,N_q$. X_m is the location of grenade, r_m is a uniformly distributed random number in $[-1,1]$ and p is a constant used to tune the intensity of exploration. The value of p is updated using the probability of territory search (T_w) as follows,

$$p = max\left[1, n \times \frac{log\left(\frac{R_t}{L_e}\right)}{\log(T_w)}\right] \qquad (16)$$

While generating the N_q pieces of shrapnel, some produced shrapnel my collide to objects outside the scaled feasible space and they have to be transported to the $[-1,1]^n$ interval. Then, the damage caused by every piece of shrapnel around a grenade is computed. If the fitness of the best generated point is better than the fitness of current location of the grenade, the position of grenade is updated and the grenade moves to the location of best point. To increase the global search ability, L_e and R_t are adjusted during the iterations. High values of these parameters are necessary to cover the whole search space in initial iterations, however, they have to be reduced over the iterations with taking fitness value into account. The territory radius is updated by using,

$$R_t = \frac{R_{t-initial}}{R_{rd}\left(\frac{Iteration\ \ Number}{Total\ \ Number\ \ of\ Iterations}\right)} \qquad (17)$$

where R_{rd} represents the ratio of value of R_t in the first iteration to its value in the last iteration, and it has to be set before the algorithm starts. Similarly, L_e is decreased over the iterations as follows:

$$L_e = (L_{e-initial})^m (R_t)^{1-m} \quad 0 \le m \le 1 \quad (18)$$

where m is calculated using,

$$m = m_{max} - \left(\frac{Iteration\ \ Number}{Max.\ No.\ of\ Iterations}\right)(m_{max} - m_{min}) \qquad (19)$$

In order to save the global search ability, the rate of decrease of L_e during the iterations is slower than the one of R_t [18-20]. Once L_e and R_t are adjusted, the value of p has to be updated accordingly. Finally, the termination criterion used in GEM is the number of iterations, i.e., if the number of iterations exceeds a maximum value the algorithm stops. The step-by-step procedure for the Grenade Explosion Method (GEM) algorithm is described in [18].

3.3 Proposed Multi-Objective Optimization (MOO) Approach

Multi-Objective Optimization (MOO) is used when the objective functions are of conflicting behavior. Therefore, the task is to determine a Pareto optimal solution. A point $x_0 \in X$ is said to be a Pareto optimal solution to an optimization problem P if there is no $x \in X$ such that $F(x) \le F(x_0)$ [20]. For the multi-objective optimal power flow (MO-OPF) problem, considering the vague or fuzzy nature of human judgment, it is quite logic to assume that the Decision Maker (DM)/System Operator (SO) may have a fuzzy goal for each of the objective functions. Therefore, the objective functions can be replaced by fuzzy membership functions. The following steps describe the proposed MO-OPF approach:

Step 1: Minimization and maximization of each objective function separately in order to calculate the individual minimum and maximum values of each objective function under constraints.

Step 2: Computation of the membership functions μ_1, μ_2 by taking into account the calculated individual maximum, and maximum values of each objective function in Step 1.

The first step of the proposed approach consists of minimizing then maximizing each objective function separately in order to compute the maximum and minimum values of each objective function. These two values correspond to the best and worst values that can each objective function reach, respectively. Then, using these values, fuzzy membership functions are calculated. The membership function of the i^{th} objective function is expressed by [21-23]:

$$\mu_i = \begin{cases} 1 & f_i \le f_i^{max} \\ \frac{f_i^{max} - f_i}{f_i^{max} - f_i^{min}} & f_i^{min} < f_i < f_i^{max} \\ 0 & f_i \ge f_i^{max} \end{cases} \quad (20)$$

where f_i^{min} and f_i^{max} are the minimum and maximum values of i^{th} objective function, respectively.

Step 3: Compute the aggregation function $\mu_D(\mu_1, \mu_2)$.

Step 4: Maximization of μ_D using the GEM method.

Step 5: If the Decision Maker (DM)/Independent System Operator (ISO) is satisfied with the current results i.e., the values of the membership functions, then go to Step 6. Otherwise, modify the aggregation function, and then go to Step 4.

Step 6: Print the optimal results.

4. Results and Discussion

The proposed optimization problem is tested on IEEE 30 bus system [23]. IEEE 30 bus system consists of 41 branches/lines of which 4 branches are transformer tap settings. Table 1 presents the generation schedules when there is no congestion in the system. Now, we are creating congestion by reducing the capacity of a double circuit line in IEEE 30 bus system from 130 MVA to 100 MVA. Under this condition to supply the load power will start generating from the farther generator which is associated with more loss. In this paper, our objective is to minimize the losses as well as the generation.

If we do not consider their bidding prices in the market clearing, i.e. simply considering their normal quadratic cost function, then the obtained generation schedules after the removal of congestion are also presented in Table 1. Figure 1 depicts the Pareto optimal front of generation cost and the total system losses.

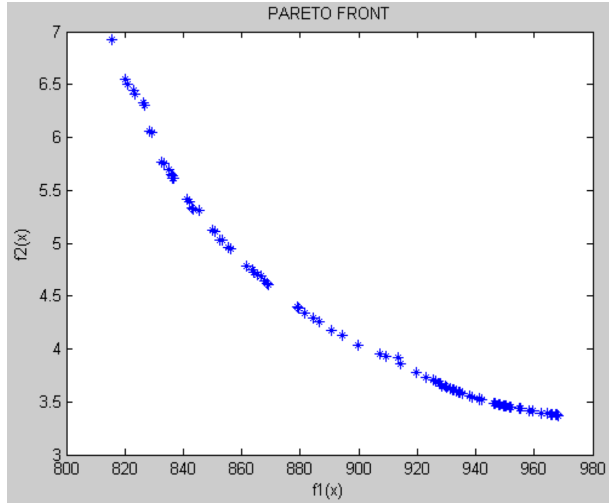

Figure 1. Pareto optimal front of generation cost and system losses

Table 1. Scheduled Power Generations in MWs before and after the Congestion

Generator Number and Objective Function Values	**Generation Schedules Before the Congestion**	**Generation Schedules After the Removal of Congestion**
P_{G1} (MW)	176.32	133.98
P_{G2} (MW)	48.89	56.35
P_{G5} (MW)	21.52	27.58
P_{G8} (MW)	21.95	35
P_{G11} (MW)	12.17	24.65
P_{G13} (MW)	12	12.46
Total Generation (in MWs)	288.85	290.02
System Losses (in MWs)	5.45	6.62
Optimum Generation Cost (in $/hr)	**802.21**	**891.82**

In practice, the market incremental/ decremental bidding is different from the natural quadratic cost characteristics. This is due to the fact that social welfare will increase in incrementing the generation and reduces in decrementing the generation. The decemental bid will be more than the incremental bid, because if any one generator is asked to bring down the generation by one unit then the generator has to pay that much money to the system operator. Therefore, the system operator must try to maximize the profit.

4.1 Congestion Management Considering the Bidding Prices in the Market

As explained earlier, if we consider the bidding prices in the market, then the generation cost minimization objective function becomes the congestion rental. Table 2 presents the generator incremental/decremental bidding prices. The different case studies simulated are,

Case 1: Congestion management by reducing the capacity of the line 1-2 from 130MVA to 100VA.
Case 2: Congestion management by reducing the capacity of the line 12-13 from 65MVA to 40MVA, and line 12-15 from 32MVA to 20MVA.
Case 3: Congestion management for outage of unit/generator 3 at bus number 5 and by reducing the capacity of the line 2-5 from 130 MVA to 80 MVA.

Table 2. Generator Incremental and Decremental Bidding Prices

Generator Number	Incremental Cost	Decremental Cost
1	45	40
2	40	28
3	45	32
4	40	38
5	42	40
6	48	25

Table 3 presents the scheduled power generations and objective function values for Cases 1, 2 and 3. In Case 1, the obtained congestion rental is 198.1605$/hr, and the system losses are 6.796MW. Figure 2 depicts the Pareto Optimal front for Case 1.

Table 3 also presents the congestion rental and total system losses obtained in Case 2 and they are 208.669$/hr and 7.477MW, respectively. Figure 3 depicts the Pareto optimal front for Case 2. The congestion rental and total system losses obtained in Case 3 are 367.4061$/hr and 8.718MW, respectively. Figure 4 depicts the Pareto optimal front for Case 3.

Table 3. Scheduled Power Generations and Objective Function Values for Cases 1, 2 and 3

Generator Number and Objective function values	**Case 1: Scheduled Power Generations after congestion removal using MO-GEM**	**Case 2: Scheduled Power Generations after congestion removal using MO-GEM**	**Case 3: Scheduled Power Generations after congestion removal using MO-GEM**
P_{G1} (MW)	131.38	142.36	145.46
P_{G2} (MW)	56.35	49.74	47.40
P_{G5} (MW)	27.58	24.18	0
P_{G8} (MW)	37	22.19	35
P_{G11} (MW)	24.65	12.36	24.26
P_{G13} (MW)	12.46	40	40
Total Generation (MW)	288.85	290.83	292.19
Congestion rental (in $/hr)	**198.16**	**208.67**	**367.41**
System Losses (in MW)	**6.80**	**7.48**	**8.72**

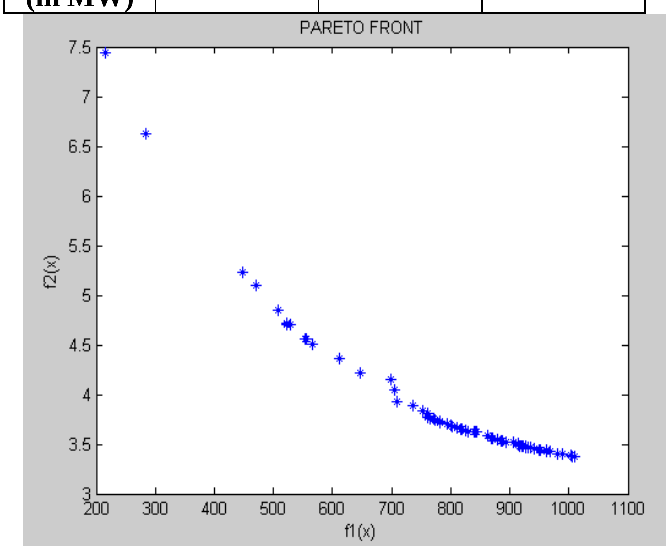

Figure 2. Pareto optimal front for Case 1

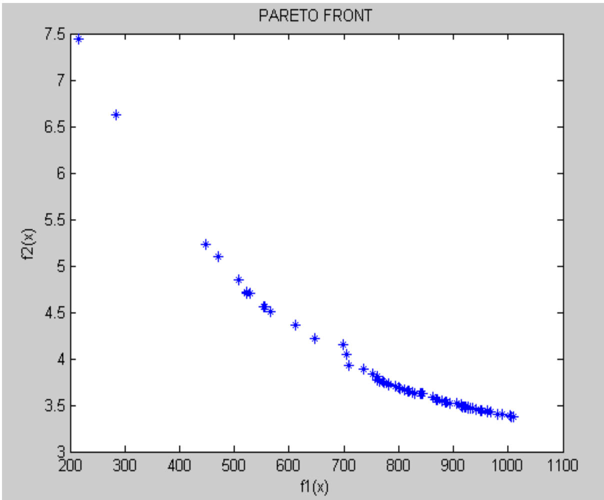

Figure 3. Pareto optimal front for Case 2.

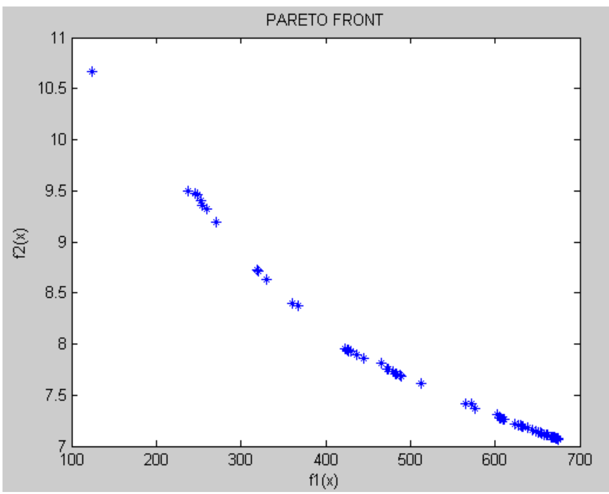

Figure 4. Pareto optimal front for Case 3.

In view of the above, it can be observed that the dispatch problem has been formulated with two different objective functions, i.e., cost minimization/minimization of total congestion cost and total system losses. Congestion charges can be computed in both the cases. In a pool based market model, the sellers/competitive generators may submit their incremental and decremental bid prices in a real time balancing market. These can then be incorporated in the OPF problem to yield the incremental/decremental change in the generator outputs. Similarly, in the case of the bilateral market mode, every transaction contract may include a compensation price that the buyer-seller pair is willing to accept should its transaction be curtailed. The simulation results presented the effectiveness of the proposed congestion management approach.

5. Conclusions

This paper proposes a new method for the Congestion Management (CM) in the transmission grids using cost-efficient generation rescheduling and loss minimization. This CM problem is solved using the Grenade Explosion Method (GEM). The proposed approach also provides a set of Pareto optimal solutions for any kind of congestion problem, giving the system operator options for judicious decision in solving the congestion. The proposed approach is tested on IEEE 30 bus system. The simulation results revealed the capabilities of the proposed Multi-Objective Grenade Explosion Method (MO-GEM) approach to generate well distributed Pareto optimal non-dominated solutions (i.e., Pareto optimal front) of multi-objective generation cost and transmission loss minimization.

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