

An Improved Differential Evolution Algorithm for Congestion Management Considering Voltage Stability

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Abstract

In deregulated electricity market, Congestion Management (CM) is one of the most significant issues in order to maintain the system in secure state and to get the reliable system operation. While addressing Congestion Management voltage stability should also be taken into account. This paper elucidates an Improved Differential Evolution (IDE) algorithm to alleviate Congestion in transmission line by rescheduling of generators while considering voltage stability. Differential Evolution (DE) is one of the heuristic, population based algorithm which is well suited for solving complex and non-linear optimization problems. A Double Best Mutation Operator (DBMO) is proposed to improve DE algorithm's convergence rate. In order to validate suitability of the suggested approach, it has been evaluated on the IEEE-30 bus test system on both base case loading as well as 10% increased load. The test system has been also examined under critical line outages. The results and discussions clearly depicts the effectiveness of the projected approach in solving Congestion Management Problem.

Keywords: Congestion Management (CM), Differential Evolution (DE), Double Best Mutation Operator (DBMO), Generation Rescheduling

1. Introduction

The restructuring in electric power sector provides open access in the transmission systems which lead to larger use of transmission grids. Due to transmission open access, the power system is operated almost to its rated capacity all the times and thereby creating a condition known as Congestion. Congestion management is one of the important aspects in deregulated power systems. In regulated power system Generation (GENCOs), Transmission (TRANSCOs) and Distribution (DISCOs) all comes under the control of government whereas, in deregulated power systems, all comes under different

organizations¹⁻³. Independent System Operator (ISO) will co-ordinate all these companies, by collecting the details pertaining to power transactions from GENCOs and DISCOs. Hence ISO has the sole responsibility to maintain the system in secure state, when the transmission lines subjected to congestion.

The Congestion can be relieved by rescheduling of generators, load curtailment, on load tap changers, usage of FACTS devices etc., ISO generally use the first option to as much as possible because the load curtailment which may lead to financial incentives to the customers.

A number of techniques have been reported for congestion management in⁴. Congestion management technique

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applied to different market structure is proposed in⁵. Congestion Management by Load curtailment strategy for a pool and Bilateral/Multi lateral market structure is proposed in⁶. In⁷, Congestion Management along with voltage stability enhancement is discussed. FACTS devices like TCSC and TCPAR were used to manage congestion efficiently⁸. An OPF based approach that minimizes cost of congestion has been proposed in⁹. Later some Zonal congestion management techniques using cluster based methods have been proposed in¹⁰⁻¹² for dc as well as AC power flows. Sensitivity Index is proposed to identify the participating generators, to alleviate congestion is proposed in¹³, but no one has concentrated in order to reduce the numbers of generators responsible for congestion.

The conventional methods to relieve network congestion are not suitable for the new competitive environment. Hence many Artificial Intelligent (AI) techniques, have been proposed in the literature for congestion management problems. Recently some Evolutionary Algorithms (EA) named Genetic Algorithms (GA), Particle Swarm Optimization (PSO), etc.,^{14,15} have been proposed to overcome the computational difficulties of conventional algorithms, in solving such problem. But the introduction of parallel computation in Evolutionary Algorithms, results in improvement of computational time, which enhanced development of new algorithms like Ant Colony Optimization (ACO), Differential Evolution (DE), Simulated Annealing (SA), Scatter Search (SS), Bacterial Foraging Algorithm (BFA) etc., which predominant in convergence characteristics as well as capable of determining global optimum solution.

Rainer Storn R and Kenneth Price proposed a new heuristic algorithm called Differential Evolution in 1995¹⁶. It is a simple global optimization algorithm which has only a few control parameters¹⁷. Based on comprehensive studies, it is found that DE has more robustness than other optimization methods. But all population-based optimization algorithms, including DE, suffer from long computational times because of their evolutionary/stochastic nature. In this work a Double best mutation operator is introduced to speed up convergence characteristics of DE.

In the open electricity market maintaining voltage stability is an important issue. Voltage stability is the ability of the power system to sustain acceptable voltage profile under normal condition and after being subjected to disturbances. Voltage stability can be assessed using static and dynamic approaches. In this work, L-index¹⁸ one of

the static voltage stability index is used for assessing voltage stability of the system. Hence this work considers the voltage stability margin as an additional constraint in the congestion management problem.

An Improved Differential Evolution (IDE) algorithm has been proposed to solve the OPF based Congestion Management problem in a pool based electricity market along with voltage stability enhancement. The projected method has been evaluated on IEEE-30 bus standard system.

The organization of the article is as follows: The formulation of multi-objective congestion management problem in deregulated environment is presented in Section 2. Section 3 gives a brief introduction of DE algorithm along with performance measures are presented along with detailed discussion and the proposed algorithm. Section 4 deals with the implementation of DE for the congestion management problem. The results and discussions showing the better performance of the projected method while applying to IEEE 30 bus are elaborated in Section 5. Section 6 discusses about the conclusion.

2. Problem Statement

Generation Rescheduling is considered for Congestion Management. It can be done by identifying the sensitive generators contributing severe power flows to contingencies. The first part of the problem focuses on identification of sensitive generators. The second part is about the rescheduling of generators which comprises of minimization of congestion cost. Contingency state L-index (maximization of voltage security level) is considered as the additional objective to achieve voltage security enhancement.

2.1 Computation Generator Sensitivity Factor

It is observed that the sensitivities of all generators to the power flow on the congested line are not equal. The generators will have different sensitivities to the power flow. A sensitivity factor is calculated to identify the critical generators, whose influence is more on the congested line. Generator Sensitivity Factor (GSF) can be defined as the ratio between the changes in real power flow in a transmission line to changes in power generation by generator. Mathematically, GSF for line k can be written as,

$$GSF_g = \frac{\Delta P_{ij}}{\Delta P_{G_g}} \quad (1)$$

The active power flow on the congested line can be,

$$P_{ij} = -V_i^2 G_{ij} + V_i V_j G_{ij} \cos(\delta_i - \delta_j) + V_i V_j B_{ij} \sin(\delta_i - \delta_j) \quad (2)$$

Rewriting equation (1), neglecting P-V coupling,

$$GSF_g = \frac{\partial P_{ij}}{\partial \delta_i} \cdot \frac{\partial \delta_i}{\partial P_{G_g}} + \frac{\partial P_{ij}}{\partial \delta_j} \cdot \frac{\partial \delta_j}{\partial P_{G_g}} \quad (3)$$

Differentiating equation (2) with respect to δ_j , we obtain,

$$\frac{\partial P_{ij}}{\partial \delta_i} = -V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j G_{ij} \cos(\delta_i - \delta_j) \quad (4)$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = +V_i V_j G_{ij} \sin(\delta_i - \delta_j) - V_i V_j G_{ij} \cos(\delta_i - \delta_j) \quad (5)$$

$$= -\frac{\partial P_{ij}}{\partial \delta_j} \quad (6)$$

We know that the active power injection at bus-i can be,

$$P_i = P_{G_i} - P_{D_i} \quad (7)$$

where P_{D_i} the active load at bus i. The active Power Injection at bus i (P_i) can also be expressed as,

$$P_i = |V_i| \sum_{t=1}^n ((G_{it} \cos(\delta_i - \delta_t) + B_{it} \sin(\delta_i - \delta_t)) |V_t|) \quad (8)$$

$$= |V_i|^2 G_{ii} + |V_i| \sum_{\substack{t=1 \\ t \neq i}}^n \{ (G_{it} \cos(\delta_i - \delta_t) + B_{it} \sin(\delta_i - \delta_t)) |V_t| \}$$

Differentiating the above equation (8) w.r.t. δ_i and δ_t , we can obtain the following relations.

$$\frac{\partial P_i}{\partial \delta_i} = |V_i| |V_t| \{ G_{it} \sin(\delta_i - \delta_t) - B_{it} \cos(\delta_i - \delta_t) \} \quad (9)$$

$$\frac{\partial P_i}{\partial \delta_t} = |V_i| \sum_{\substack{t=1 \\ t \neq i}}^n \{ -G_{it} \sin(\delta_i - \delta_t) + B_{it} \cos(\delta_i - \delta_t) |V_t| \} \quad (10)$$

Also the relation between active power change to the phase angles of voltages (Neglecting P-V coupling) in matrix form as given below,

$$[\Delta P] = [H][\Delta \delta] \quad (11)$$

Where,

$$[H] = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \frac{\partial P_1}{\partial \delta_2} & \dots & \frac{\partial P_1}{\partial \delta_n} \\ \frac{\partial P_2}{\partial \delta_1} & \frac{\partial P_2}{\partial \delta_2} & \dots & \frac{\partial P_2}{\partial \delta_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \frac{\partial P_n}{\partial \delta_2} & \dots & \frac{\partial P_n}{\partial \delta_n} \end{bmatrix} \quad (12)$$

$$[\Delta \delta] = [H]^{-1} [\Delta P] \quad (13)$$

$$= [M][\Delta P] \quad (14)$$

The values of $(\partial \delta_i) / (\partial P_{G_g})$ and $(\partial \delta_j) / (\partial P_{G_g})$ in (3), can be obtained by expressing the matrix $[M]$. Since Bus 1 is considered as slack bus, the first row and first column of $[H]$ can be neglected to obtain $[H_{-1}]$ matrix as well as $[M_{-1}]$. Hence,

$$[\Delta \delta_{-1}] = [M_{-1}][\Delta P_{-1}] \quad (15)$$

Now a new strategy have been adopted for selecting critical generators for alleviating congestion. The generators which rendering unequal contributions to the congested line and also having maximum value of GSF_g , have been selected for rescheduling the active power generation.

2.2 Rescheduling of the Sensitive Generators

The congestion management problem is considered as an optimization problem with the main objective of minimization of congestion cost. The system operator decides the rescheduling of generators based on the bids submitted by each Generating Unit. The bids received from the GENCO are used to calculate the congestion cost after rescheduling.

Mathematically, this is stated as,

Minimize Congestion Cost (CG)

$$CG = \sum_{g=1}^{N_g} C_{gu}(\Delta P)_g + C_{gd}(\Delta P)_g \quad (16)$$

Where,

C_{gu} is the incremental bid cost of the generators in \$ per MW

C_{gd} is the decremental bid cost of the generators in \$ per MW

N_g is the number of generators to be rescheduled

ΔP_g is the active power generation for relieving congestion.

To enhance the voltage stability an objective is framed in order to minimize the Congestion Cost as well as the voltage stability indicator, L-index values of all load buses under contingency state. Here both the objectives were combined together to a single objective optimization problem by a weighting factor as follows,

$$\text{Minimize } J = \sum_{i=1}^N CG + wL_{\max} \quad (17)$$

where w is the weighting factor which range from [0 1] and $L_{\max}$ is the maximum value of L-index.

2.3 Equality Constraints

$$P_i = V_i \sum_{j=1}^N V_j [G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}] \quad (18)$$

$$Q_i = V_i \sum_{j=1}^N V_j [G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}] \quad (19)$$

2.4 Inequality Constraints

Voltage Constraints :

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (20)$$

Unit Constraint :

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} \quad (21)$$

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \quad (22)$$

Transmission line flow limit:

$$S_l \leq S_l^{\max} \quad (23)$$

Generation Rescheduling Constraint:

$$P_{gi}^{\min} - P_{gi} \leq \Delta P_{gi} \leq P_{gi}^{\max} - P_{gi} \quad (24)$$

Where $P_g^{\min}$ & $P_g^{\max}$ the active are power limits and $Q_g^{\min}$ & $Q_g^{\max}$ are the reactive power limits of the generators. $V^{\min}$ & $V^{\max}$ are the limits of bus voltages and their values are 0.95 and 1.05 p.u. respectively. $S_l^{\max}$ is the

maximum MVA flow of transmission line. An improved Differential Evolution is applied to solve this composite optimization problem. The details of DE algorithm are presented in the next section.

3. Overview of Differential Evolution

Differential Evolution (DE) is a simple, robust and population based stochastic search algorithm, proposed by Price and Storn¹⁶ for optimization problems over a continuous domain. Unlike other evolutionary algorithms DE performs a special adapting strategy to perturb the population members to reach the global optimum position. And also having faster convergence rate because of one-to-one competition among the fittest of an offspring with the corresponding parent. In¹⁷, DE is described with ten different working strategy. The DE algorithm is described as follows:

3.1 Initialization

The initial population of N_p vectors is randomly generated for all variables within their boundary.

$$X_{ij}^0 \sim \text{Rand}(X_j^{\min}, X_j^{\max}) \quad (25)$$

where $i = 1, \dots, N_p$ and $j = 1, \dots, D$; $X_j^{\min}$ and $X_j^{\max}$ are the lower and upper bounds of the j th decision variable; $\text{Rand}(X_j^{\min}, X_j^{\max})$ represents a uniform random variable ranging over $[X_j^{\min}, X_j^{\max}]$. X_{ij}^0 is the randomly generated initial variable of individual j in i th population. The generated initial population must satisfy all the constraints.

3.2 Evaluate Objectives

The objective function value of each vector should be evaluated by the objective function or fitness function $f(X_i^0)$.

3.3 Mutation

DE generates new parameter vectors (Target vector) by randomly selecting three distinct member from population using the following equation. The mutant vector X_i^{mg} is obtained by

$$X_i^{\text{mg}} = X_a^g + F(X_b^g - X_c^g), \quad i \in N_p \quad (26)$$

where X_a^g , X_b^g and X_c^g are randomly selected members from Population vectors at g th generation and $a \neq b \neq c \neq i$. The main control parameter called scaling factor (F),

which should be in the range $0 < F < 1.2$, controls the amount of perturbation to be added to the parent vector in order to form the mutant vector. The resultant mutant vector should also satisfy the constraints.

3.4 Cross Over

The initial vector as well as the mutant vector are swapped together in order to form trial vector by the operator called crossover. For each trial vector X_i^{tg} , crossover should be performed by its mutant vector X_i^{mg} as well as initial vector. The trial vector X_i^{tg} can be

$$X_i^{tg} = \begin{cases} X_i^{tg}, & \text{if } \rho < C_R \\ X_i^{mg}, & \text{otherwise} \end{cases} \quad (27)$$

where C_R is the crossover constant, controls the diversity of the population and enhances the algorithm to converge in the global optimum solution instead of getting settled with local optima. Normally C_R ranges from 0 to 1. And ρ is an uniformly distributed random number between $[0,1]$.

3.5 Selection

The fitness values of initial vector (X_i^0) and the trial vector (X_i^{tg}) are compared for selecting each parameter of the target vector. The vector that has lesser fitness of the two would survive for the next generation.

$$X_i^{g+1} = \begin{cases} X_i^{tg}, & \text{if } f(X_i^{tg}) \leq f(X_i^g) \\ X_i^g, & \text{otherwise} \end{cases} \quad (28)$$

The process is will repeat until it reaches the maximum number of iterations or there is no significant improvement in the fitness values for many iterations.

3.6 Improved Differential Evolution (DBMO-DE)

Though Differential Evolution (DE) is an competent algorithm, capable of managing any kind of optimization problem, still there is much room for improvement in reaching global optimum solution as well as the convergence speed. All evolutionary algorithms inclusive of DE undergo with the difficulty of long computational times, for the reason that of the probabilistic nature of all algorithms in solving the objective function. In this work, we proposed a double best mutation operation to speed up the convergence and to explore the global search capability.

3.7 Double Best Mutation Operator (DBMO)

Here a Double Best Mutation Operator is introduced to quicken the convergence speed. The following equation denotes DBMO operator of DE.

$$X_i^{mg+1} = X_{gbest}^g + C_1 * rand_1 (X_{pbest}^g - X_i^g) + C_2 * rand_2 (X_{gbest}^g - X_i^g) \quad (29)$$

Where X_{gbest}^g is the global best solution of all the individuals in the population, X_{pbest}^g denotes the individual best solution.

$rand_1, rand_2$: uniform random number within $[0, 1]$.

C_1, C_2 constants: Constants preferably 2.

This mutation operator ensures that the mutant vector is reaching the global solution in the right direction by the action of information sharing among the best particles. Hence, no doubt it definitely speed up the entire process in reaching desired the global optimum solution.

4. DE Implementaton for Congestion Management

The details of DE implementation for the CM are summarized as follows:

4.1 Representation

While solving the Congestion Management problem, the decision variables are identified as the generator's active power which is to be rescheduled. The generators to be rescheduled for the considered test system (IEEE30 bus System) are identified using the Generator Sensitivity factor is 3, 11 and 13. These decision variables and are randomly generated within their limits. Hence the population vector consisting of number of solutions for solving CM problem. The representation of the variables looks like the following.

13.5	11.8	5.6
ΔP_{g5}	ΔP_{g11}	ΔP_{g13}

4.2 Fitness function

The objective function is formulated in order to minimize the Congestion Cost meanwhile fulfilling all the constraints including line flow constraints. The fitness function is formulated in consideration of all state variables

violations, which could be added as a quadratic penalty function to the objective function.

5. Simulation

The proposed IDE algorithm was applied to IEEE-30 bus test system. The test system consisting of six generator buses, among which bus 1 considered as slack bus. Also the system is having twenty four load buses with the base case loading of 283.4 MW and 126.2 MVAR, the active and the reactive load respectively. And there are forty one transmission lines including four tap setting transformers on the branches (6-9), (6-10), (4-12) and (28-27). The values of the unit and system constraints are given in the Appendix. The DE base algorithm was implemented using MATLAB program.

The test system is stressed by increasing the load and by simulating line outages. The performance of proposed algorithm has been evaluated under two different cases. In the first case, the proposed approach is applied to a single objective, which is nothing but the minimization of Congestion Cost objective. In the second case the maximum value of the L-index is used as an additional constraint in the CM problem so as to enhance the voltage stability. The optimal settings of the DE parameters applied for the simulation are,

Population size	: 50
Maximum generation	: 50
Scaling Factor (F)	: 0.8
Scaling Factor (C_1)	: 2
Scaling Factor (C_2)	: 2
Crossover Constant (C_R)	: 0.8

5.1 Case 1: Minimization of Congestion cost

Contingency analysis has been done in order to know the severe contingency cases which results in congestion in many of the transmission lines. From the (N-1) contingency analysis, the line outage (1-2) is identified as the most severe line, making the power flow violations on the lines (1-3), (3-4) and (4-6). Hence Congestion has been created by making the line (1-2) into outage and also the system load is increased by 10% from its base case loading. The Generator Sensitivity factor for all the generators have been calculated for this line outage and the values are listed in Table 1.

Table 1. Selection of sensitive generators for rescheduling

Line Outage (1-2)		Congested Lines		
		(1-3)	(3-4)	(4-6)
Generator Sensitivity Factors	GSF 2	0.7267	-0.6126	-0.2500
	GSF 5	-0.4918	-1.1238	-1.3716
	GSF 8	-0.2284	-0.002	-0.008
	GSF 11	-0.1238	1.4900	-2.4918
	GSF 13	-0.0602	-1.3103	-2.6931

From Table 1, it is clear that the GSF values for congested line (1-3) is almost uniform. It indicates that all the generators having equal impact on congested line (1-3). For line (3-4) and (4-6) the generators 5, 11 and 13 are having higher impact than other generators. The positive sign in the GSF denotes, the power flow in the congested line will increase when the generator's power get increased. The negative sign in the GSF denotes, the power flow in the congested line will decrease when the generator's power get increased. The DE algorithm is used to find the amount of power need to be rescheduled in order to alleviate congestion as well as increase in load.

The incremental and the decremental bidding prices provided in²¹ for IEEE 30 bus system were taken for the calculation of Congestion cost. The generator data, Load data, Voltage limits, Branch details were taken from²⁰, considered as the base case loading data. The rescheduling of sensitive generators is carried out by the market operator from base case to contingency states under 110% loaded conditions. The Minimum Congestion Cost as well as the optimal settings of the decision variables obtained are listed in Table 2. Comparison of obtained results with other evolutionary algorithms like GA, PSO and DE are tabulated in Table 3. Table 3 shows the the line flows before and after the rescheduling process under line outage (1-2), which clearly shows that the congestion has been totally relieved from the competitive market in the PoolCo model. The change in real power settings from

Table 2. Rescheduled power and congestion cost

ΔP_5	ΔP_{11}	ΔP_{13}	Generation cost (\$/hr)	Congestion Cost (\$/hr)	L_{max}
7.19	17.76	14.39	924.91	1655.65	0.1887

base case to contingency (1–2) for the six GENCOs in the system is shown in Figure 1.

Table 3. Comparison with other evolutionary algorithms

Control parameters	GA (Results reported in ¹⁸)	PSO (Results reported in ¹⁹)	DE	DBMO - DE
ΔP_5	9.0909	13	8.10	7.1936
ΔP_{11}	22.9717	19.9	17.54	17.7600
ΔP_{13}	10.1662	19.5	15.80	14.3915
Congestion Cost (\$/hr)	1770.6	2201.2	1742.22	1655.65

Table 4. Line flow details of congested lines

Congested Lines	Before rescheduling (MVA)	After rescheduling (MVA)	Maximum line flow limit (MVA)
(1-3)	142.13	128.68	130
(3-4)	135.61	117.74	130
(4-6)	86.58	58.91	65

The congestion cost obtained by DBMO-DE have been compared with DE.

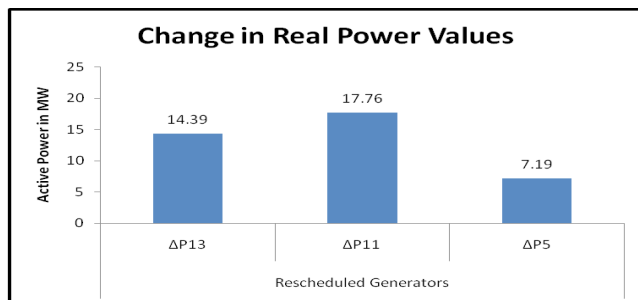


Figure 1. Change in Real Power values of Rescheduled Generators.

Table 5. Optimal solution obtained for Case 2

Objective Function	Case 1	Case 2
$L_{\max}$	0.1887	0.1330
Generation cost (\$/hr)	924.91	883.87
Congestion Cost (\$/hr)	1655.65	1672.0

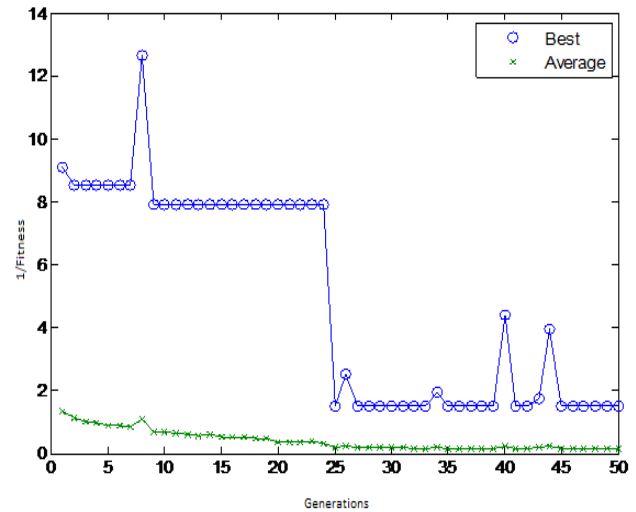


Figure 2. Convergence characteristics for case 1.

5.2 Case 2: Congestion Management Ensuring Voltage Stability

In this case, two objectives were considered, one is congestion cost minimization and the other is voltage stability enhancement. While framing the objective function for this case, both objectives were converted in a single objective function by weighted sum method.

$$\text{Minimize } J = \sum_{i=1}^N CG + wL_{\max} \quad (30)$$

Where w is the weighting factor and $L_{\max}$ is the maximum value of L -index. The calculation of L -index value is discussed in²⁰. The Congestion cost as well as the L -index value obtained using DBMO-DE for case1 and case 2 are tabulated in Table 5. The L -index value got reduced in case 2 when the voltage stability has also been considered.

5. Conclusion

In this article, an improved DE algorithm has been proposed to solve the Congestion Management problem along with voltage stability enhancement based on Generation Rescheduling. The GSF values plays a vital role in selecting the most severe generators which should be rescheduled to alleviate the congestion. The congestion management task has been framed as an optimization problem along with the voltage stability constraint. The performance of the projected approach has been evaluated on IEEE-30 bus test system. From the results, it is more evident that the projected approach is best suited

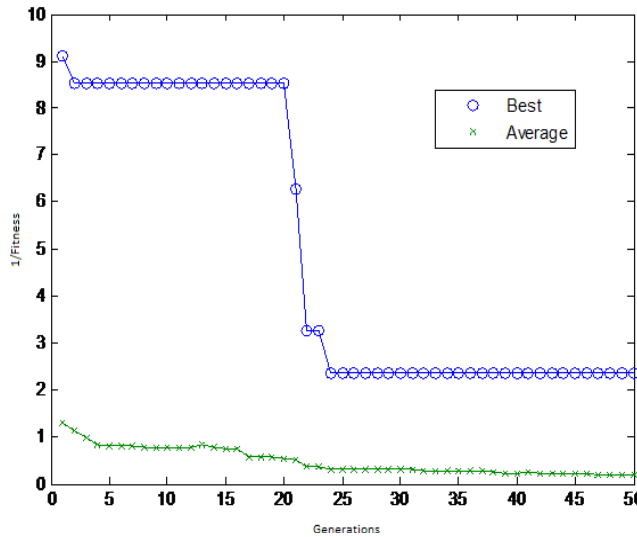


Figure 3. Convergence characteristics for case 2.

for achieving better solution than the Differential Evolution Algorithm. From the mutual sharing concept, the Double best mutation operation has been proposed results in faster convergent process.

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Appendix

Nomenclature

n	Number of buses in the system
t_i	Transformer tap setting of branch i
V_i	Voltage magnitude at bus i
P_i, Q_i	The injected Active and reactive powers at bus i
G_{ij}, B_{ij}	Mutual conductance and susceptance between bus i and j
G_{ij}, B_{ij}	Self conductance and susceptance of bus i
δ_i	Voltage angle of bus i
δ_j	Voltage angle of bus j
ΔP_{ij}	Change in Active power flow on congested line-k
P_{G_i}	Active power generation of i^{th} generator
P_{D_i}	Active load at bus i
ΔP_{G_s}	Change in active power generation by the i^{th} sgenerator towards congestion