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Multi-Objective Optimal Reactive Power Dispatch for Distribution System

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Abstract—**This paper presents Multi-Objective Differential Evolution (MODE) algorithm for multi-objective optimal reactive power dispatch to minimize real power loss, total voltage deviation and total capacity of reactive power sources in distribution system. In a distribution system integrated with distributed generation (DG), optimal reactive power dispatch can be carried out by controlling the reactive power of the DG and reactive power compensation devices like capacitor banks, FACTS devices and other sources of reactor power. Optimal reactive power dispatch (ORPD) problem has been formulated as a non-linear, constrained, multi-objective optimization problem, with equality and inequality constraints, for minimization of system real power losses, improvement voltage profile with minimum total capacity of reactive power sources. Effectiveness of the proposed MODE algorithm has been demonstrated for optimal reactive power Dispatch in the standard IEEE 33-bus radial distribution system having distributed generators and reactive power sources.**

Keywords—multi-objective optimal reactive power dispatch; real power loss minimization; total voltage deviation; total capacity of reactive power sources;

I. INTRODUCTION

All over the world, there is large demand for energy to support the growth of various areas of the economy and for this; Distributed Generation (DG) can be an important choice out of the various alternatives. DG includes generators based on solar energy, biomass, combustion turbines, fuel cells, mini and micro hydroelectric plants, and wind turbines etc. At a first glance, these technologies seem to be attractive, but there is a need for detailed studies on the impact of connecting them [1, 2]. Usually, distribution networks are radial and their R/X ratio is high. Most matrix based transmission load flow methods such as Gauss-Seidel, Newton-Raphson and etc. are not able to solve such systems. Instead backward-forward sweep load flow method is commonly used for load flow analysis in distribution systems. In an electric power system, to reduce transmission and distribution cost, real power loss, total voltage deviation and improve system stability etc., electric power is generated in distribution side or on customer side of network [3, 4] using distributed generation. As per the new technology, the trend is to use disbursed generators with ratings in the range of kW to MW at load side instead of using traditional centralized generating units with ratings in the range of 100MW to GW and located far from the loads at the locations, where the natural resource are available [5]. Optimal reactive power dispatch (ORPD) or reactive power control is one of the most essential functions in energy management system.

The main purpose of optimal reactive power dispatch is to minimize system real power losses, improve voltage profile and voltage stability in a power system [4]. Reactive power dispatch in a power system can be carried out by identifying and optimizing the reactive power control variables settings such as generator voltages, transformer tap-settings and other sources of reactive power like capacitor banks or FACTS devices to achieve one or more of the required objectives. ORPD or Optimal Reactive Flow is a sub-problem of optimal power flow (OPF) formulated by Carpentier in1962 [6].

Optimal reactive power dispatch provides the power system operator a set of control variables to minimize total real power loss and to maintain bus voltage within permissible limits by redistributing the power flows in a power system. The influence of distributed generation on the distribution of the reactive power is considerable in a radial distribution system with radial configuration and high R/X ratio [7–11]. Thus, ORPD of the distribution system having DG is essential to ensure the economic operation of the distribution system without violating any operating limits and to provide the customers enough power of good quality. Reactive power dispatch of the distribution system with integrated DG has been investigated, and several optimization models and methods for RPD problem have been proposed. Firstly, various types of single-objective optimization models based on population based random search techniques were studied and different single-objective optimization algorithms were applied for solving ORPD problem [11-14]. Afterwards, more than one objective functions were considered simultaneously and a multi-objective formulation was formed to effectively achieve different objectives of ORPD problem.

The common feature of such researches was that a multi-objective optimization problem was converted into a single-objective one using a weighted aggregation approach [8,9,13,14] or fuzzy optimization method [7,10]. It is important to note that fuzzy based approach and weighted aggregation method are mainly single-objective optimization techniques and simplify the optimization procedure of multi-objective ORPD problem to a great extent. The main limitation of these methods is that they yield only one best solution for multi-objective optimization problem and, the only one best solution fails to provide the decision maker with other choices [15,16].

Also, such conversion of multi-objective optimization problem into single-objective optimization problem is not able to reflect precisely the relationship between the various objectives, particularly when the concerned objectives are conflicting in nature. The solution obtained by this approach is largely sensitive to the relative weights used in forming the composite function [17].

Consequently, some multi-objective optimization techniques, which have been proved to be competent in solving multi-objective optimization problems by considering multiple objectives simultaneously, were applied to solve the multi-objective ORPD problem. Usually, the objectives involved in multi-objective ORPD are conflicting with each other, and it is not possible to find a solution which can optimize all the objectives at one time [18]. Instead of a single optimal solution, the solution to a multi-objective optimization problem yields a set of many solutions called Pareto optimal set in a single simulation run [15,18]. Using multi-objective optimization (MOO) algorithms, the aim is to find Pareto solutions that represent the best possible trade-offs among the competing objectives. Such MOO technique has been applied to solve the multi-objective ORPD problem of distribution system having DG and reactive power sources.

This paper presents MODE algorithm for multi-objective optimal reactive power dispatch for distribution system penetrated with distributed generation. The reactive power of the distributed generators is incorporated in the decision variables together with the traditional ORPD decision variables in the multi-objective optimization model. The objective functions of the Multi-objective ORPD problem include minimization of the system real power loss, total voltage deviation and total capacity of the reactive power sources (RPS). To provide the decision maker with alternatives and to analyze the correlations between optimization objectives, multi-objective DE (MODE) algorithm has been presented to solve the non-linear Multi-objective ORPD problem. For demonstrating the effectiveness of the proposed MODE algorithm, it has been implemented for solving ORPD problem on modified IEEE 33-bus system [19].

II. MULTI-OBJECTIVE OPTIMAL REACTIVE POWER DISPATCH

In this paper, the multiple objectives of optimal reactive power dispatch consist of minimizing the real power loss, the total voltage deviation and the total capacity of RPS, while satisfying various equality and inequality constraints. The objective functions and constraints are formulated as follows.

A. Objective Functions

- *Minimization of Real Power Loss :*

The real power loss *PLoss* is the sum of real power loss in various transmission lines *nl* of a power system and can be calculated as

$$F_1 = PLoss = \sum_{k=1}^{nl} G_k [V_i^2 + V_j^2 - 2V_i V_j \cos\delta_{ij}] \quad (1)$$

Where G_k is conductance of k^{th} line; $V_i \angle \delta_i$ and $V_j \angle \delta_j$ are the voltages at terminal buses *i* and *j* of k^{th} line, respectively. $\delta_{ij} = \delta_i - \delta_j$.

- *Minimization of Total Voltage Deviation :*

The purpose of this objective function is to improve the voltage profile of a power system. This objective can be achieved by minimizing the deviations in voltage magnitudes $|V_i|$ at load buses of a power system from a pre-specified reference value V_i^{ref}. This objective function can be written as follows:

$$F_2 = TVD = \sum_{i=1}^{LB} (V_i - V_i^{ref})^2 \quad (2)$$

Where *LB* is number of load buses. In this paper, V_i^{ref} is set to be 1.0 pu.

- *Minimization of total capacity of reactive power source:*

The purpose of this objective function is to minimize the investments on reactive power sources. The total capacity of RPS units, *TCRPS* can be calculated as

$$F_3 = TCRPS = \sum_{i=1}^{NQ} Q_{RPSi} \quad (3)$$

Where, Q_{RPSi} represents the actual capacity of RPS required from i^{th} RPS unit and N_Q denotes the total number of RPS units.

B. Constraints for ORPD Problem

- *Equality constraints:*

The equality constraints used in ORPD problem are the typical load flow equations, which can be expressed as:

$$\begin{cases} P_{Gi} + P_{DGi} - P_{Li} = V_i \sum_{j=1}^{N_{bus}} V_j \left(G_k \cos\delta_{ij} + B_k \sin\delta_{ij}\right) \\ Q_{Gi} + Q_{DGi} + Q_{RPSi} - Q_{Li} = V_i \sum_{j=1}^{N_{bus}} V_j \left(G_k \sin\theta_{ij} + B_k cos\delta_{ij}\right) \end{cases} \quad (4)$$

Where P_G, P_{DG} and P_L are the real power of generator, DG and load at bus *i*, respectively. Q_G, Q_{DG}, Q_{RPSi} and Q_L represent reactive power of the generator, *DG*, *RPS* unit and load at bus *i*, respectively. B_K represents the susceptance of branch *k*.

- *Inequality constraints:*

a) Voltage limit for buses

The voltage magnitude of each bus in a network reflects the quality of power supply. Hence, the voltage magnitude at each bus is restricted be within some maximum and minimum limits. For any bus *i*, voltage limit can be expressed as

$$V_i^{min} \leq V_i \leq V_i^{max}, \quad i = 1,2,..NB \qquad (5)$$

Where, V_i^{min} and V_i^{max} represent the minimum and maximum limits respectively.

b) Feeder transmission capacity constraints

Power flow through any distribution feeder must be within its thermal limit, which can be written as by

$$S_k^{min} \leq S_k \leq S_k^{min}, \quad k = 1,2,..nl \qquad (6)$$

Where S_k represents the transmission capacity of branch *k*.

c) Constraints for generators, transformers and RPS units

These constraints generally include limits on terminal voltage and reactive power output of the generators, transformers' tap settings and reactive power output of DG and of RPS unit. These constraints may be expressed as

$$V_{gi}^{min} \leq V_{gi} \leq V_{gi}^{max} \quad i = 1,2,..NG \qquad (7)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad i = 1,2,..NG \qquad (8)$$

$$T_s^{min} \leq T_s \leq T_s^{max} \quad s = 1,2,..NT \qquad (9)$$

$$Q_{DGi}^{min} \leq Q_{DGi} \leq Q_{DGi}^{max} \quad i = 1,2,..NDG \qquad (10)$$

$$Q_{RPSi}^{min} \leq Q_{RPSi} \leq Q_{RPSi}^{max} \quad i = 1,2,..NQ \qquad (11)$$

Where, *NT* and *NDG* stand for the number of transformers and DG, respectively.

III. PRPD as Multi-Objective Optimaization

In a multi-objective optimization problem, the innovative rule for finding the most favorable solution cannot be used to one objective alone, because the other objectives are also equally important. In various real world problems, these objective functions are non-commensurable and generally conflicting in nature. In a single-objective optimization problem there is only one global optimum, but in a multi-objective optimization there is a set of optimal solutions, which is known as Pareto-optimal set or efficient set. The solutions in the Pareto-optimal set are considered to be equally important. Also, these solutions provide the decision maker to opt a reasonable choice. The multi-objective ORPD problem can be written as (12), which has several equality and inequality constraints and variable bounds given by

Minimize $F = [F_1\ F_2\ F_3]$ (12)
Subject to;
Equality constraints $g(x,u) = 0$ (13)
Inequality constraints $h(x,u) \leq 0$ (14)
and
Variable bounds $u_j^{(L)} \leq u_j \leq u_j^{(U)}, j=1,2,\ldots, n$ (15)

Where
$u_j^{(L)}$ = Lower bound of *j*th decision variable
$u_j^{(U)}$ = Upper bound of *j*th decision variable

Multi-objective as ORPD problem can be written as

$F_1 = PLoss(x,u)$, $F_2 = TVD(x,u)$, and $F_3 = \mathrm{TC}RPS(x,u)$

Where, the dependent variables *x* is given as

$$x^T = [V_1 \ldots.\ V_{LB},\ Q_{g1} \ldots Q_{gNG},\ S_1, \ldots.S_{nl}] \qquad (16)$$

and independent or decision variables u are given as

$$u^T = [V_{g1}, V_{g2}, .. V_{gNG}, T_1, T_2, .. T_{NT}, Q_{DG1}, Q_{DG2}, .. Q_{DGNDG}, Q_{RPS1}, Q_{RPS2}, .. Q_{RPSNQ}] \qquad (17)$$

The equality and inequality constraints for RPDO problem are as listed in (4)–(11). The solutions satisfying the equality and inequality constraints and variable bounds constitute a feasible decision variable space. MODE algorithm has been applied for this multi-objective ORPD problem, which is a combinatorial optimisation problem and has the multi-extremism and non-linear property. In this paper, the ORPD problem has been solved by optimising the reactive power outputs of Distributed generators and the shunt reactive power sources connected in the distribution system and these decision variables are considered as continuous values.

IV. MODE Algorithm

MODE is an expansion of Differential Evolution for solving multi-objective optimization problems. Differential evolution [20] is a population-based stochastic search algorithm that works in the general framework of evolutionary algorithms. Unlike traditional evolutionary algorithms, DE variants perturb the generation population members with the scaled difference of randomly selected and distinct population members. This optimization process is carried out with three basic operations namely, mutation, crossover and selection [21].

The optimization variables are represented as floating point numbers in the DE population. It starts to explore the search space by randomly choosing the initial candidate solutions within the boundary as:

$$y_{ij}(0) = y_j^l + rand(0,1) \times (y_j^u - y_j^l) \qquad (18)$$

Where, y_{ij} is the j^{th} component of the i^{th} member in the population, y_j^u and y_j^l are the upper and lower bounds respectively of the j^{th} variable and *rand* (0,1) is a random number uniformly distributed between 0 and 1.

In each generation, a mutant (donor) vector $v_i(t)$ is created in order to perturb the population member vector $y_i(t)$. The j^{th} component of mutant vector can be expressed as:

$$v_{i,j}(t+1) = x_{d1,j}(t) + F(x_{d2,j}(t) - x_{d3,j}(t)) \tag{19}$$

Where y_{d1}, y_{d2} and y_{d3} are any three vectors selected randomly from the current population other than the member y_i and F is a scalar number used to control the perturbation and to improve the convergence.

To increase the diversity of the population, crossover operator is applied in which the mutant vector exchanges its components with those of the current member $y_i(t)$. The crossover operator creates the trial vectors, which are used in the selection process. In this paper, binomial crossover scheme is used for all the D variables, which can be expressed as:

$$u_{i,j}(t) = \begin{cases} v_{i,j}(t) & if \quad rand(0,1) < CR \\ y_{i,j}(t) & else \end{cases} \tag{20}$$

To keep the population size constant over the subsequent generations, the selection process is applied to find out which one of the trial vector and target vector will survive in the next generation, i.e. at time $t = t + 1$. DE algorithm thus adopts the survival of the fittest principle in the selection process. Selection process can be outlined as,

$$Y_i(t+1) = \begin{cases} U_i(t) & if \;\; f(U_i(t)) \le f(Y_i(t)) \\ Y_i(t) & if \;\; f(Y_i(t)) < f(U_i(t)) \end{cases} \tag{21}$$

where $f(Y)$ is the function to be minimized. Hence, if the trial vector $U_i(t)$ yields a better fitness function value, it is used in the next generation; otherwise, the target $Y_i(t)$ remains in the population. Thus, as generations proceed, in terms of fitness function, the population either gets improved or remains constant but never deteriorates.

The stopping criteria adopted in MODE algorithm is the reaching of maximum generations C. After completion of the last generation, to remove the dominated solutions non-dominated sorting is carried out. The computational steps of the MODE algorithm for solving ORPD problem are as follows:

i. Generate an initial population NP randomly within the decision variables' lower and upper bounds.
ii. Set the generation count $c = 1$.
iii. For each individual in the population, run Back-Forward Sweep Load Flow program [22, 23] to find the objective functions PLoss (F_1), TVD (F2) and TCRPS (F3) using (1), (2) and (3) respectively.
iv. Determine fitness of the individuals using the objective functions and the penalty factor corresponding to the constraints and boundary violations as

$$FF_1 = F_1 + PF$$
$$FF_2 = F_2 + PF$$
$$FF_3 = F_3 + PF$$

v. Apply the mutation and crossover using (19) and (20).
vi. Apply selection operator using (21) to select individuals for next generation.
vii. If generation count c is less than maximum generation C ($c < C$), put $c = c+1$ and go to step *iii.* Otherwise go to step *viii.*
viii. Perform non-dominating sorting to achieve Pareto-optimal solutions.
ix. Stop.
x. Select the decision variables setting corresponding to the Pareto-optimal solutions.

V. RESULTS AND DISCUSSION

The proposed MODE algorithm has been tested for solving ORPD problem of IEEE 33-bus radial distribution system [19] integrated with two distributed generators at locations 2 and 13 and two reactive power sources at locations of 6 and 31 as shown in Fig. 1. The real power loss *PLoss* values under the two situations without installed DG and without RPS units are 0.211MW and 0.128 MW, respectively, while the TVD values are 0.133796 and 0.046534, respectively.

The proposed MODE algorithm is employed to determine the best reactive output of DGs and optimal capacities of RPS units for reducing the real power loss, total voltage deviation and the total capacity of RPS in the distribution system. The values of the parameters involved are listed in Table 1.

TABLE I. PARAMETER VALUES

Parameter	**values**	**Parameter**	**values**
Population *NP*	100	$Q_{DG1}^{min}/Q_{DG2}^{min}$	-100kVAR
Crossover Rate *CR*	0.95	$Q_{DG1}^{max}/Q_{DG2}^{max}$	500kVAR
Mutation *F*	0.35	$Q_{RPS1}^{min}/Q_{RPS2}^{min}$	0.0kVAR
Max. Generation *C*	250	Q_{RPS1}^{max}	600kVAR
P_{DG1}/P_{DG2}	1MW	Q_{RPS2}^{max}	1050kVAR

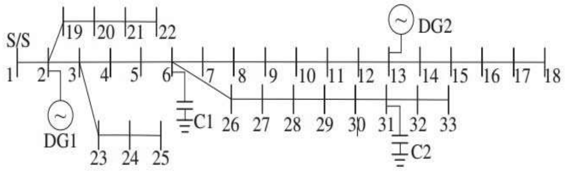

Fig. 1.Single line diagram of IEEE 33-bus system [19]

In order to demonstrate the effectiveness of the proposed MODE algorithm, it was applied for solving three cases of ORPD with different objective functions and the results obtained were compared with the reported results.
Case A: Minimization of *PLoss* and *TVD*
Case B: Minimization of *PLoss* and *TCRPS*
Case C: Minimization of *PLoss*, *TVD* and *TCRPS*

Case A: Minimization of PLoss and TVD

In this case, MODE algorithm has been applied to minimize *PLoss* and *TVD* and the various optimized values of these two objectives along with decision variables were obtained. The Pareto solutions achieved using MODE algorithm are depicted in Fig. 2. Table 2 lists some of the Pareto solutions and the corresponding decision variables and compares with already reported results using DAMOPSO [19]. It can be observed from Table 2 that MODE algorithm provided superior results. Also, the Pareto solutions are well diversified, which is useful for decision maker to opt a reasonable choice. These objective functions are non-comparable and even conflict with each other.

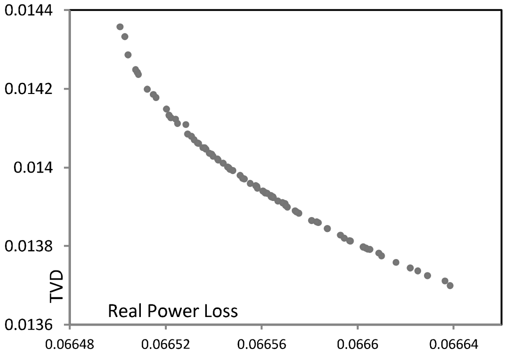

Fig. 2. Pareto Front of PLoss and TVD minimization

TABLE II. PARETO SOLUTIONS OF CASE 1

Method	S. No.	Objective Functions		Decision Variables			
		PLoss	TVD	QDG1	QDG2	QRPS1	QRPS2
MODE	1	0.06650	0.0144	0.500	0.388	0.60	0.547
	2	0.06650	0.0143	0.500	0.393	0.60	0.547
	3	0.06654	0.0140	0.499	0.411	0.60	0.547
	4	0.06656	0.0139	0.500	0.417	0.60	0.547
	5	0.06664	0.0137	0.500	0.433	0.60	0.547
DAPSO [19]	1	0.08120	0.0143	0.500	0.490	0.60	1.050
	2	0.08060	0.0149	0.500	0.440	0.60	1.050
	3	0.08010	0.0157	0.500	0.370	0.60	1.050
	4	0.07970	0.0170	0.500	0.260	0.60	1.050
	5	0.07930	0.0182	0.500	0.350	0.60	0.900

Case B: Minimization of PLoss and TCRPS

In this case, the two objective functions considered were real power loss and total capacity of RPS units. In this case also the various optimized values of the two objectives PLoss and TCRPS along with decision variables were obtained. Some of the Pareto solutions are listed and compared with the reported results in Table 3, while the Pareto solutions achieved using MODE algorithm are shown in Fig. 3. It can be observed from Table 3 that, MODE algorithm provided superior results. Also, the Pareto solutions are well diversified, which is useful for decision maker to opt a reasonable choice.

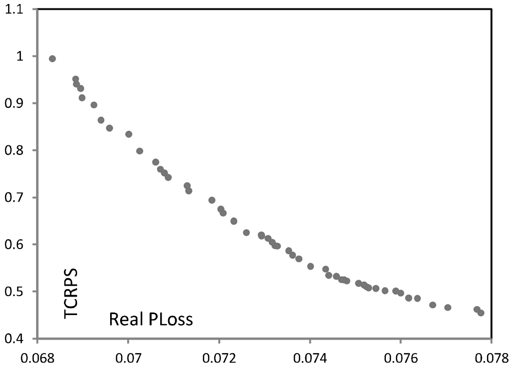

Fig. 3. Pareto Front of PLoss and TCRPS Minimization

TABLE III. PARETO SOLUTIONS OF CASE 2

Method	S. No.	Objective Functions		Decision Variables			
		PLoss	TCRPS	QDG1	QDG2	QRPS1	QRPS2
MODE	1	0.0700	0.834	0.468	0.418	0.089	0.537
	2	0.0713	0.714	0.475	0.410	0.199	0.515
	3	0.0725	0.625	0.286	0.420	0.083	0.535
	4	0.0730	0.621	0.468	0.418	0.089	0.537
	5	0.0735	0.586	0.481	0.403	0.050	0.536
	6	0.0743	0.547	0.330	0.422	0.020	0.528
	7	0.0754	0.507	0.419	0.416	0.000	0.507
DAPSO [19]	1	0.080	1.50	0.150	0.360	0.600	0.900
	2	0.090	0.60	0.500	0.500	0.150	0.450
	3	0.095	0.45	0.500	0.500	0.150	0.300
	4	0.101	0.30	0.500	0.500	0.150	0.150
	5	0.082	1.05	0.470	0.500	0.300	0.750
	6	0.084	0.90	0.500	0.500	0.300	0.600
	7	0.086	0.75	0.450	0.500	0.150	0.600

Case C: Minimization of PLoss, TVD and TCRPS

In this case, the three objective functions considered for ORPD problem were real power loss, total voltage deviation and total capacity of RPS units. In this case also the various optimized values of the three objectives PLoss, TVD and TCRPS along with decision variables were obtained. Some of the Pareto solutions are listed and compared with the reported results in Table 4, while the Pareto solutions achieved using MODE algorithm are shown in Fig. 4. It can be observed from Table 4 that, MODE algorithm provided superior results.

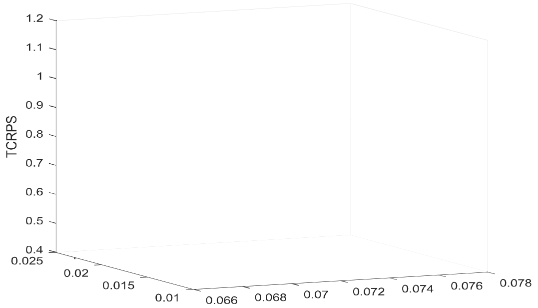

Fig. 4. Pareto front of PLoss, TVD and TCRPS

TABLE IV. PARETO SOLUTIONS OF CASE 3

Method	S. No.	Objective Functions			Decision Variables			
		PLOSS	TVD	TCRPS	QDG1	QDG2	QRPS1	QRPS2
MODE	1	0.0674	0.0148	1.0380	0.392	0.429	0.506	0.532
	2	0.0701	0.0173	0.7804	0.346	0.423	0.243	0.537
	3	0.0718	0.0184	0.6756	0.470	0.424	0.158	0.518
	4	0.0720	0.0187	0.6652	0.447	0.410	0.135	0.530
	5	0.0736	0.0194	0.5738	0.433	0.418	0.031	0.542
DAPSO [19]	1	0.0799	0.0175	1.5000	0.157	0.421	0.600	0.900
	2	0.0810	0.0254	1.0500	0.464	0.489	0.300	0.750
	3	0.0822	0.0282	0.7500	0.363	0.500	0.150	0.600
	4	0.0904	0.0312	0.6000	0.370	0.481	0.150	0.450
	5	0.0953	0.0345	0.4500	0.309	0.500	0.150	0.150

VI. CONCLUSION

In this paper, Multi-Objective Differential Evolution algorithm has been developed for optimal reactive power dispatch in distribution system penetrated with DG. The objectives of the Multi-Objective ORPD were to minimize real power loss, total voltage deviation and total capacity of reactive power sources in distribution system. Pareto-optimal solutions obtained using MODE algorithm provide the decision maker a choice to select a reasonable solution. The optimization results obtained using MODE algorithm were compared with already reported results and were found to be superior. As future scope of the work, the MODE based proposed approach may be implemented for large size distribution systems.

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