International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 3, Number 1 (2010), pp. 65--84

http://www.irphouse.com

Optimum Design of Turbo-Alternator using Differential Evolution Algorithms

K.V.R.B. Prasad and Pravin M. Singru

Birla Institute of Technology and Science, Pilani, Goa Campus, Zuarinagar, India
E-mail: prasad_brahma@rediffmail.com, pravinsingru@gmail.com

Abstract

This paper presents the method of selecting an optimum design of turbo-alternator using Multi-objective Differential Evolution (MODE) algorithms. In this paper a theoretical problem of turbo-alternator design is considered. In recent years, Genetic Algorithms have been recognized as potent tool in design optimization of electrical machinery. Initially the complete design of turbo-alternator is worked out by conventional procedure. In the next stage, the optimum design is obtained by using the MODE algorithms. The optimum design obtained by the MODE algorithms is compared with the optimum design obtained by the NSGA-II algorithm with simulated binary crossover operator with lognormal distribution (SBX-LN). From the set of results, the suitable optimum design of turbo-alternator is chosen. The results obtained are near global optimized results.

Keywords: Design optimization, differential evolution, genetic algorithm, turbo-alternator.

Introduction

The turbo-alternator runs at a high speeds and is directly connected to a prime mover like steam turbine, diesel engine etc. The design of turbo-alternator includes stator-design, rotor-design, air-gap and cooling. In this design, power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connection are taken as input. The efficiency and cost of the turbo-alternator are obtained from the above data.

The classical optimization techniques are also used to optimize the multi-objective optimization problems. Most of the classical multi-objective optimization algorithms convert the multi-objective optimization problems into single-objective optimization problems using different procedures like weighted sum optimization etc. [1]. These algorithms may have to be used many times, each time finding a different Pareto-optimal solution. These classical methods also involve guessing initial solutions. The computing time for classical optimization algorithms is extremely high, hence not used nowadays.

The Genetic Algorithms (GAs) are optimization algorithms based on the mechanics of natural genetics and natural selection. The GA gives near global population of optimum solutions. They work with a population of solutions and give multiple optimal solutions in one simulation run. They have two distinct operations – selection and search. They are flexible enough to be used in a wide variety of problem domains. The operators use stochastic principles [2].

The elitist non-dominated sorting GA, NSGA-II, carries out a non-dominated sorting of combined parent and offspring population. For the solutions of the last allowed front, a crowding distance-based niching strategy is used to resolve which solutions are to be carried over to the new population. The diversity among non-dominated solutions is introduced by using the crowding comparison procedure which is used with the tournament selection and during the population reduction phase. The elitism mechanism does not allow an already found Pareto-optimal solution to be deleted [2]–[4].

The Differential Evolution (DE) is a simple and powerful population based, direct search algorithm for globally optimizing functions with real valued parameters. Like most of the evolutionary algorithms (EAs), DE is also a population based optimization algorithm. It attacks the starting point problem by sampling the objective function at multiple, randomly chosen initial points. Preset parameter bounds define the domain from which the number of vectors in the initial population is chosen. The DE generates new points that are perturbations of existing points [20], [21].

The multi-objective differential evolution (MODE) is used to solve multi-objective optimization problems. The concept of differential evolution is extended to the multi-objective problem domain. The initial population is generated at random. All dominated solutions are removed from the population. The remaining non-dominated solutions are retained for recombination. Three parents are selected at random. A child is generated from the three parents and is placed into the population if it dominates the first selected parent; otherwise a new selection process takes place [22], [24].

In the present work, a computer aided design (CAD) program of turbo-alternator is developed. Then the design parameters are given input to MODE algorithm to generate optimum design. The solutions of MODE are in the form of Pareto-optimal front between cost and efficiency. The solutions obtained by the MODE algorithm are compared with the solutions obtained by the NSGA-II algorithm with simulated binary crossover operator with lognormal distribution (SBX-LN). The user can choose the suitable design based on the requirement of cost and efficiency. The program then gives the complete design for this set of cost and efficiency after back substitution. Thus, this work is of importance to researchers and designers to get the optimum design. Thus the user has set of near global solutions, satisfying all the constraints, from which choice of design may be made.

Literature Review and State of Art

Lamme [5] presented the principal difficulties in the design of earlier turbo-alternators and their limitations. On account of the high rotating speeds, two types of turbo-alternator rotor designs, radial-slot type and parallel-slot type are used. There are two methods to overcome the ventilation problem, radial and circumferential method. Washing of air gives clean and cool air for ventilation purpose. To overcome the high temperature and insulation problem, mica is used as an insulating material on the buried parts of the coil. To reduce the eddy current losses, the current should be reduced, obtained by subdividing the conductors into a number of conductors in each individual slot, or parallel conductors in the two halves of a complete coil in the eddy current circuit. The steps like use of deeper slots, better subdivision of the copper to eliminate eddy currents, improved ventilation and conduction of heat etc, are used to overcome the regulation problem. To overcome the problem of short-circuit characteristic, the end windings can be strengthened by double metal racks between the two layers of windings, so arranged to key these two layers securely to one another at certain points. All the above parameters should be considered in optimizing the design of turbo-alternators.

Ula et al. [6] presented the effect of different parameters of the alternator on the damping and natural frequencies of the rotor oscillations when superconducting field windings are used in large turbo-alternators. The parameters having significant effect on the damping are inertia constant, rotor screen time constant, synchronous reactance, transformer and transmission line reactance, coupling between stator and rotor screen, and environmental screen.

Gimba et al. [7] presented the design of alternators incorporating dual-output switched-mode rectifiers to meet the requirements of automotive electrical systems. This approach enables the full load-matched power capability of the alternator machine to be achieved, with power delivered to the two outputs in any desired combination.

Azzouri et al. [8] presented a multi-objective optimization process of the axial flux permanent magnet synchronous generator (AFPMSG) which is computationally efficient and easily tunable. Firstly, a design analytical mode which is based on a coupled electromagnetic, thermal, and mechanical model has been presented. Later the multi-objective optimization method is used for optimization.

Prasad and Singru [9] presented extensive literature survey of GA in electrical machine design. The electrical machine design optimization is carried out, in most cited literature, using binary coding in combination with simple forms of GA, complex GA, taking the advantage of elitism, multi-objective genetic algorithms, evolutionary strategies, finite element method, parallel computing, niching techniques, dynamically adjustable algorithms etc. The GAs are used to optimize various parameters in electrical machines such as cost, efficiency, machine design parameters including high-speed parameters, motor design parameters for torque calculations, in-situ efficiency of motor. The design of three-phase machines, IPMSM, SPM three-phase motor, AFPMSG, permanent magnet synchronous machine, non-linear magnetic devices, permanent dc motors, electromagnetic devices, brushless permanent magnet motors, design of pole shape of brushless dc motor, cost of submersible motors etc. are cited in literature.

Prasad et al. [10] presented the computer aided design of turbo-alternator and its optimization, without constraints, using NSGA-II. In this work , power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connections, are input variables. The efficiency and cost of the turbo-alternator are obtained from the design. The cost and efficiency of turbo-alternator are taken as objective functions and the ratings of machine are taken as variables of NSGA-II algorithm. The NSGA-II algorithm gives a Pareto-optimal front.

Babu et al. [23] presented the performance of original MODE (MODE-1) algorithm and two improved versions of MODE algorithms (MODE-2 and MODE-3). MODE-2 and MODE-3 algorithms gave better solutions than MODE-1 algorithm at the cost of extra computation. The number of non-dominated solutions obtained by MODE-2 algorithm is equal to the size of population.

This is the first attempt in solving multi-objective optimization problem of turbo-alternator, with multiple constraints, using MODE algorithms.

Problem Formulation

Design of turbo-alternator

In the design, the ratings of turbo-alternator such as power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connection are inputs. The efficiency and cost of the turbo-alternator are obtained from the above data [11], [12].

The relation for efficiency of a turbo-alternator is,

$$\eta = \left[\frac{(P_0)}{(P_0 + P_{TLoss})}\right] \tag{1}$$

The total losses in turbo-alternator are divided into five major types such as stator copper loss, stray load loss, friction and windage loss, stator iron loss and excitation loss.

The relation for total losses in turbo-alternator is,

$$P_{TLoss} = P_{L1} + P_{L2} + P_{L3} + P_{L4} + P_{L5} \tag{2}$$

The relation for cost of the turbo-alternator, neglecting insulation and frame cost, is,

$$C_T = [(C_1 * W_1) + (C_2 * W_2)] \tag{3}$$

The total weight of copper includes weight of copper in stator and weight of copper in rotor. The total weight of iron includes weight of iron in stator and weight of iron in rotor. The equations for W_1, W_2, P_{L1}, P_{L2}, P_{L3}, P_{L4} and P_{L5} are stated in Appendix – A.

The ratings of turbo-alternator such as power rating, operating voltage, current delivered by the machine, operating power factor, and operating frequency are allowed to vary within allowable range from the rated values. The power rating is allowed to vary from zero to its rated value. The operating voltage is allowed to vary ±5% from its rated value as per the Indian Electricity Rules [18]. The current delivered by the machine is allowed to vary from zero to its rated value. The operating power factor is allowed to vary from its rated value to unity power factor. In all practical applications, the operating power factor should not be less than its rated value. The operating frequency is allowed to vary from 97% to 100% of the rated value but as per the Indian Electricity Rules, the operating frequency is allowed to vary from 97% to 103% of the rated frequency [18]. The variation of frequency beyond the rated value will lead to instability, so it is not considered here. The other ratings of turbo-alternator such as operating speed, number of phases, and type of stator winding connections are maintained at rated values. The constraints, slot pitch, temperature difference between stator copper and iron, rotor critical speed, field excitation current, are considered in formulating the optimization problem of turbo-alternator.

Optimization problem

Most real-world search and optimization problems are naturally posed as multi-objective optimization problems [1], [2]. The optimization problem considered in this paper is a multi-objective optimization problem. In this case the cost and efficiency of turbo-alternator are the two objective functions. The task of multi-objective optimization is to find the Pareto-optimal set of solutions which form Pareto-optimal front. The two goals of a multi-objective optimization are to find a set of solutions as close as possible to the Pareto-optimal front and to find a set of solutions as diverse as possible.

The problem is defined as

$$Maximize, \eta = \left[\frac{(P_0)}{(P_0 + P_{TLoss})}\right] \tag{4}$$

$$Minimize, C = \left[(C_1 * W_1) + (C_2 * W_2)\right] \tag{5}$$

subjected to

$$\left[1 - \left(\frac{\lambda}{\lambda_m}\right)\right] \geq 0 \tag{6}$$

$$\left[1 - \left(\frac{TD_{sci}}{TD_{msci}}\right)\right] \geq 0 \tag{7}$$

$$\left[1 - \left(\frac{N_{rc}}{N_{mrc}}\right)\right] \geq 0 \tag{8}$$

$$\left[\left(\frac{I_{rme}}{I_{rmel}}\right)-1\right]\geq 0 \tag{9}$$

$$\left[1-\left(\frac{I_{rme}}{I_{rmeu}}\right)\right]\geq 0 \tag{10}$$

The shaft deflects due to the weight which it carries so that as it revolves, it is bent to and fro once in a revolution. If the speed at which the shaft revolves is such that the frequency of this bending is the same as the natural frequency of vibration of the shaft laterally between its bearings, then the equilibrium becomes unstable, the vibrations are excessive and the shaft is liable to break unless very stiff. The speed at which this takes place is called the critical speed and should not be within 20% of the actual running speed [11]. Hence, N_{rc} should be less than or equal to N_{mrc} which is 80% of the rated speed.

The field exciting current will be varying from no-load condition to full-load condition. Generally, the field exciting current will be increased by 25% from no-load to full-load, to maintain normal voltage [11]. Here the I_{rme} is allowed to vary by 20% i.e., from 80% to 100% of the rated field exciting current.

In this paper a real-life problem is considered for optimizing the turbo-alternator design, with constraints. The data which is taken as input is used to compute various parameters in design. The results are giving a set of near global optimal solutions. The design parameters, obtained from optimization, are found to be better, when compared with the CAD program design parameters, which is giving the actual design of turbo-alternator. The optimized design, obtained with unity power factor, is reducing the current delivered by the turbo-alternator, reducing its losses and weight. This optimized design is providing a better efficiency, low cost and reduction in field excitation current. From the obtained near global solutions, the user can select the optimum design of the turbo-alternator. This is helpful to the user to select a better design of turbo-alternator for a required set of efficiency and cost.

NSGA-II and its use in Optimum Design of Turbo-Alternator

NSGA-II

This is an elitist non-dominated sorting GA (NSGA-II) [2]–[4]. It uses an elite preservation strategy along with an explicit diversity preserving mechanism. This allows a global non-dominated check among the offspring and parent solutions. The diversity among non-dominated solutions is introduced by using the crowding comparison procedure which is used in the tournament selection and during the population reduction phase. Since solutions compete with their crowding distance, no extra niching parameter is required here. Although the crowding distance is calculated in the objective function space, it can also be implemented in the parameter space, if so desired [19]. However, in all simulations performed in this study, the objective function space niching is used.

Use of NSGA-II in optimum design of turbo-alternator

In this problem the objective functions are efficiency and cost of turbo-alternator. The input variables are power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connection. This data is used to find various parameters such as stator copper loss, stray load loss, friction and windage loss, stator iron loss, excitation loss, weight of copper in stator, weight of copper in rotor, weight of iron in stator and weight of iron in rotor. From the above losses, the efficiency of the turbo-alternator can be estimated by (1) and (2). The weights of copper and iron of both stator and rotor calculated in design helps us in estimating the cost of turbo-alternator by (3).

The NSGA-II algorithm for the given problem with two objective functions and five constraints gives a set of near global optimized results. It is always useful to the user to select the required design from a set of results.

MODE and Its use in Optimum Design of Turbo-Alternator

MODE

This is a multi-objective differential evolution algorithm. It is also a population based optimization algorithm. The initial population is generated at random. The non-dominated solutions are retained for recombination. A child is generated from the three parents and is placed into the population if it dominated the selected parent; otherwise a new selection process takes place. To solve an optimization problem with constraints, the optimization problem is reformulated by including the constraints. Penalty function method is employed for handling constraints. The constraints dominated solutions are penalized by assigning a very high value, in case of minimization type of problems [2], [22], [23].

Use of MODE in optimum design of turbo-alternator

In this problem the objective functions are efficiency and cost of turbo-alternator. The input variables are power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connection. This data is used to find various parameters such as stator copper loss, stray load loss, friction and windage loss, stator iron loss, excitation loss, weight of copper in stator, weight of copper in rotor, weight of iron in stator and weight of iron in rotor. From the above losses, the efficiency of the turbo-alternator can be estimated by (1) and (2). The weights of copper and iron of both stator and rotor calculated in design helps us in estimating the cost of turbo-alternator by (3). To handle the constraints in this problem, penalty function method is used. The optimization problem is reformulated by including the constraints.

The MODE algorithm for the given problem with two objective functions and five constraints gives a set of near global optimized results. It is always useful to the user to select the required design from a set of results.

Testing of Algorithm and Test Results

The data for turbo-alternator design is as follows: 5000 kW, 2400 V, three-phase, 1500 A, 60 C/s, star-connected, 1800 r.p.m. machine, to operate at 80 percent power factor. The efficiency and cost of the turbo-alternator are the objective functions, found from the given data, using the relations given in Appendix – A. The value of λ_m is 0.07 m, TD_{msci} is 19^0 C, N_{mrc} is 1440 r.p.m., I_{rmel} is 262.4 A and I_{rmeu} is 328.0 A.

The GA's performance will be improved by modifying the probability distribution of crossover operator [17], [20]. The obtained solutions are close to the optimal solutions and the diversity is better between the solutions, when the initial population is large [16]. It is found that the NSGA-II algorithm with simulated binary crossover operator having lognormal distribution (SBX-LN) gave more optimum solutions with better diversity. These results are obtained for a random seed of 0.9749, population of 1000 and generation of 10000. The crossover probability is 0.8, mutation probability is 0.2 (five-variables), crossover index is 0.05 and mutation index is 0.5 [17]. These results are taken as the Pareto-optimal solutions (POS).

The DE's performance will be improved by selecting a scale factor (F) which will affect the differential mutation and crossover probability (Cr) which will control the uniform crossover [20]. In the MODE algorithm the Cr is changed to improve the performance of the MODE algorithm. The Cr is selected as 0.9 for all MODE algorithms to get better optimized results.

The mean and variance of the generational distance (GD) for convergence and diversity metrics, with different MODE algorithms, are given in Tables I, II and III. These results are obtained after running each algorithm ten times with different number of populations and generations. The MODE algorithms ran with and without providing the reference of POS. The Table I shows the results obtained by MODE-I algorithm for a particular set of population and generation. It is observed that the variance of the convergence and diversity metrics are small for the solutions obtained with the POS. The Table II shows the results obtained by MODE-III algorithm for a particular set of population and generation. It is observed that the variance of the convergence and diversity metrics are same for the solutions obtained with and without the POS. The Table III shows the results obtained by MODE-Hybrid algorithm for a particular set of population and generation. It is observed that the variance of the convergence and diversity metrics are same for the solutions obtained with and without the POS.

The design parameters of turbo-alternator are found at points 1, 2, 3 and 4 in each case when MODE-I, MODE-III and MODE-Hybrid algorithms are used to optimize the turbo-alternator design. These parameters are compared with the POS. These results, along with the results obtained by the CAD program, are shown in Table IV, V, VI and VII.

The near global optimal solutions obtained by MODE-I algorithm along with the POS are shown in Fig. 1 and 2. The near global optimal solutions obtained by MODE-III algorithm along with the POS are shown in Fig. 3. The near global optimal solutions obtained by MODE-Hybrid algorithm along with the POS are shown in Fig. 4.

Table I : Mean and Variance of Convergence and Diversity metrics for MODE-I algorithm

Parameters	**Mean GD of Convergence Metric**	**Variance GD of Convergence Metric**	**Mean GD of Diversity Metric**	**Variance GD of Diversity Metric**	**Remarks**
Cr = 0.9, Population = 500 and Generation = 200	4.006E-02	2.9834E-02	0.8932	8.7953E-02	without POS
Cr = 0.9, Population = 500 and Generation = 200	3.920E-02	1.5946E-02	0.8685	**6.9613E-02**	with POS
Cr = 0.9, Population = 10000 and Generation = 100	8.700E-03	1.4697E-03	0.9885	7.7716E-02	without POS
Cr = 0.9, Population = 10000 and Generation = 100	8.560E-03	**1.1157E-03**	1.0014	1.0705E-01	with POS

Table II : Mean and Variance of Convergence and Diversity metrics for MODE-III algorithm

Parameters	**Mean GD of Convergence Metric**	**Variance GD of Convergence Metric**	**Mean GD of Diversity Metric**	**Variance GD of Diversity Metric**	**Remarks**
Cr = 0.9, Population = 100 and Generation = 300	5.61E-03	6.4541E-04	1.0212	8.37E-02	without POS
Cr = 0.9, Population = 100 and Generation = 300	5.61E-03	6.4541E-04	1.0212	8.37E-02	with POS
Cr = 0.9, Population = 500 and Generation = 200	4.66E-03	**4.3256E-04**	1.0695	9.1239E-02	without POS
Cr = 0.9, Population = 500 and Generation = 200	4.66E-03	**4.3256E-04**	1.0695	9.1239E-02	with POS
Cr = 0.9, Population = 10000 and Generation = 100	3.53E-03	4.62E-04	0.9949	**6.3907E-02**	without POS
Cr = 0.9, Population = 10000 and Generation = 100	3.53E-03	4.62E-04	0.9949	**6.3907E-02**	with POS

Table III : Mean and Variance of Convergence and Diversity metrics for MODE-Hybrid algorithm

Parameters	**Mean GD of Convergence Metric**	**Variance GD of Convergence Metric**	**Mean GD of Diversity Metric**	**Variance GD of Diversity Metric**	**Remarks**
Cr = 0.9, Population = 100 and Generation = 300	1.118E-02	8.1378E-03	1.2329	9.9062E-02	without POS
Cr = 0.9, Population = 100 and Generation = 300	1.118E-02	8.1378E-03	1.2329	9.9062E-02	with POS

Table IV : Parameters of Turbo-Alternator Design

S. No.	**Variable/Constraint/Objective function**	**MODE-I without POS (Pop = 500 and Gen = 200)**				**MODE-I with POS (Pop = 500 and Gen = 200)**				**NSGA-II (SBX-LN)**				**CAD Prog.**	**Remarks**
		1'	**2'**	**3'**	**4'**	**1''**	**2''**	**3''**	**4''**	**1**	**2**	**3**	**4**		
1	Output Power (MW)	4.84	0.50	0.21	0.015	4.33	0.87	0.31	0.036	5.00	0.68	0.3374	0.0061	5.00	Variable (0.0 to 5.0)
2	Line Voltage (kV)	2.39	2.29	2.40	2.36	2.341	2.30	2.342	2.30	2.28	2.30	2.311	2.314	2.4	Variable (2.28 to 2.52)
3	Line Current (kA)	1.2395	1.0798	0.4785	0.3720	1.2400	1.1126	1.0151	0.8513	1.2395	1.0692	0.4861	0.3283	1.5	Variable (0.0 to 1.5)
4	Power Factor	0.99	0.89	0.96	0.84	0.87	0.88	0.87	0.86	1.0	1.0	1.0	1.0	0.8	Variable (0.8 to 1.0)
5	Frequency (Cy/s)	59.18	58.83	58.86	58.63	58.97	59.97	59.34	59.79	60.0	60.0	59.50	58.26	60.0	Variable (58.2 to 60.0)
6	Stator slot pitch (m)	0.059	0.059	0.059	0.058	0.059	0.059	0.059	0.058	0.059	0.059	0.059	0.058	0.06	Constraint ($\leq$ 0.07)
7	Temp. diff. b/w cu & iron (^{0} C)	14.59	13.79	18.60	15.91	14.59	13.97	13.44	12.42	14.59	13.75	18.78	14.66	15.57	Constraint ($\leq$ 19)
8	Rotor Cri. Speed (r.p.m.)	1385	1426	1434	1430	1426	1426	1430	1431	1410	1431	1427	1429	1405	Constraint ($\leq$ 1440)
9	Field Exci. Current (A)	325.28	317.61	264.97	264.32	321.34	320.65	311.34	313.70	324.23	316.07	262.40	265.06	326.31	Constraint ($262.4 \leq I_f \leq 328.0$)
10	Efficiency	0.96	0.78	0.75	0.19	0.95	0.85	0.70	0.24	0.96	0.83	0.829	0.09	0.939	Objective function
11	Cost (normalized by1300000 units)	1.00	0.87	0.45	0.39	0.98	0.89	0.86	0.77	0.94	0.87	0.44	0.37	1.16	Objective function

Table V : Parameters of Turbo-Alternator Design

S.No.	Variable/Constraint/Objective function	MODE-I without POS (Pop = 10000 and Gen = 100)				MODE-I with POS (Pop = 10000 and Gen = 100)				NSGA-II (SBX-LN)				CAD Prog.	Remarks
		1'	2'	3'	4'	1''	2''	3''	4''	1	2	3	4		
1	Output Power (MW)	4.88	0.80	0.27	0.026	4.81	0.86	0.22	0.013	5.00	0.68	0.3374	0.0061	5.00	Variable (0.0 to 5.0)
2	Line Voltage (kV)	2.36	2.28	2.44	2.41	2.47	2.30	2.38	2.36	2.28	2.30	2.311	2.314	2.4	Variable (2.28 to 2.52)
3	Line Current (kA)	1.2605	1.0945	0.4908	0.4104	1.2449	1.1210	0.48	0.3615	1.2395	1.0692	0.4861	0.3283	1.5	Variable (0.0 to 1.5)
4	Power Factor	0.99	0.82	0.94	0.99	0.99	0.99	0.88	0.82	1.0	1.0	1.0	1.0	0.8	Variable (0.8 to 1.0)
5	Frequency (Cy/s)	59.34	58.69	58.36	59.31	58.60	59.91	59.20	59.82	60.0	60.0	59.50	58.26	60.0	Variable (58.2 to 60.0)
6	Stator slot pitch (m)	0.059	0.059	0.059	0.058	0.059	0.059	0.059	0.058	0.059	0.059	0.059	0.058	0.06	Constraint (≤ 0.07)
7	Temp. diff. b/w cu & iron (^{0} C)	14.68	13.88	18.88	16.92	14.61	14.0	18.64	15.62	14.59	13.75	18.78	14.66	15.57	Constraint (≤ 19)
8	Rotor Cri. Speed (r.p.m.)	1430	1431	1426	1435	1410	1431	1431	1429	1410	1431	1427	1429	1405	Constraint (≤ 1440)
9	Field Exci. Current (A)	321.28	316.49	265.06	264.27	322.95	321.44	269.59	266.14	324.23	316.07	262.40	265.06	326.31	Constraint ($262.4 \le I_f \le 328.0$)
10	Efficiency	0.96	0.84	0.79	0.28	0.96	0.85	0.76	0.17	0.96	0.83	0.829	0.09	0.939	Objective function
11	Cost (normalized by1300000 units)	1.00	0.89	0.47	0.42	1.04	0.89	0.45	0.39	0.94	0.87	0.44	0.37	1.16	Objective function

Table VI : Parameters of Turbo-Alternator Design

S.No.	Variable/Constraint/Objective function	MODE-III without POS (Pop = 100 and Gen = 300)				MODE-III without POS (Pop = 500 and Gen = 200)				MODE-III without POS (Pop = 10000 and Gen = 100)				CAD Prog.	Remarks
		1'	2'	3'	4'	1''	2''	3''	4''	1'''	2'''	3'''	4'''		
1	Output Power (MW)	4.79	0.54	0.26	0.029	4.94	0.66	0.32	0.014	4.85	0.75	0.33	0.014	5.00	Variable (0.0 to 5.0)
2	Line Voltage (kV)	2.39	2.31	2.46	2.43	2.37	2.30	2.37	2.37	2.30	2.28	2.37	2.33	2.4	Variable (2.28 to 2.52)
3	Line Current (kA)	1.2485	1.0729	0.4847	0.4054	1.2410	1.0714	0.4876	0.3363	1.2411	1.0953	0.4954	0.336.8	1.5	Variable (0.0 to 1.5)
4	Power Factor	0.98	0.93	0.98	0.92	0.98	0.98	0.95	0.86	0.99	0.87	1.0	0.90	0.8	Variable (0.8 to 1.0)
5	Frequency (Cy/s)	59.94	59.68	59.29	59.85	58.96	59.05	59.68	58.90	59.41	59.22	59.86	58.28	60.0	Variable (58.2 to 60.0)
6	Stator slot pitch (m)	0.059	0.059	0.059	0.058	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.058	0.06	Constraint (≤ 0.07)
7	Temp. diff. b/w cu & iron (^{0} C)	14.63	13.76	18.74	16.8	14.59	13.75	18.82	14.90	14.60	13.88	18.99	14.92	15.57	Constraint (≤ 19)
8	Rotor Cri. Speed (r.p.m.)	1415	1426	1426	1427	1400	1426	1436	1432	1365	1436	1431	1434	1405	Constraint (≤ 1440)
9	Field Exci. Current (A)	323.18	317.70	265.16	267.46	324.25	318.42	265.39	266.97	327.76	315.25	263.11	265.47	326.31	Constraint ($262.4 \le I_f \le 328.0$)
10	Efficiency	0.96	0.793	0.781	0.30	0.96	0.824	0.818	0.17	0.96	0.84	0.82	0.18	0.939	Objective function
11	Cost (normalized by1300000 units)	0.99	0.88	0.47	0.42	1.0	0.88	0.45	0.38	0.96	0.88	0.46	0.37	1.16	Objective function

Table VII : Parameters of Turbo-Alternator Design

S.No.	Variable/Constraint/Objective function	MODE-Hybrid without POS (Pop = 100 and Gen = 300)				NSGA-II (SBX-LN)				CAD Prog.	Remarks
		1'	2'	3'	4'	1	2	3	4		
1	Output Power (MW)	4.96	0.34	0.13	0.073	5.00	0.68	0.3374	0.0061	5.00	Variable (0.0 to 5.0)
2	Line Voltage (kV)	2.28	2.28	2.28	2.28	2.28	2.30	2.311	2.314	2.4	Variable (2.28 to 2.52)
3	Line Current (kA)	1.2432	0.9730	0.4443	0.4413	1.2395	1.0692	0.4861	0.3283	1.5	Variable (0.0 to 1.5)
4	Power Factor	0.99	0.99	0.99	0.99	1.0	1.0	1.0	1.0	0.8	Variable (0.8 to 1.0)
5	Frequency (Cy/s)	59.99	60.0	59.99	59.99	60.0	60.0	59.50	58.26	60.0	Variable (58.2 to 60.0)
6	Stator slot pitch (m)	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.058	0.06	Constraint (≤ 0.07)
7	Temp. diff. b/w cu & iron (^{0} C)	14.61	13.21	17.79	17.72	14.59	13.75	18.78	14.66	15.57	Constraint (≤ 19)
8	Rotor Cri. Speed (r.p.m.)	1410	1436	1428	1437	1410	1431	1427	1429	1405	Constraint (≤ 1440)
9	Field Exci. Cureent (A)	324.36	319.24	262.51	262.64	324.23	316.07	262.40	265.06	326.31	Constraint ($262.4 \leq I_f \leq 328.0$)
10	Efficiency	0.96	0.73	0.66	0.53	0.96	0.83	0.829	0.09	0.939	Objective function
11	Cost (normalized by1300000 units)	0.95	0.82	0.412	0.411	0.94	0.87	0.44	0.37	1.16	Objective function

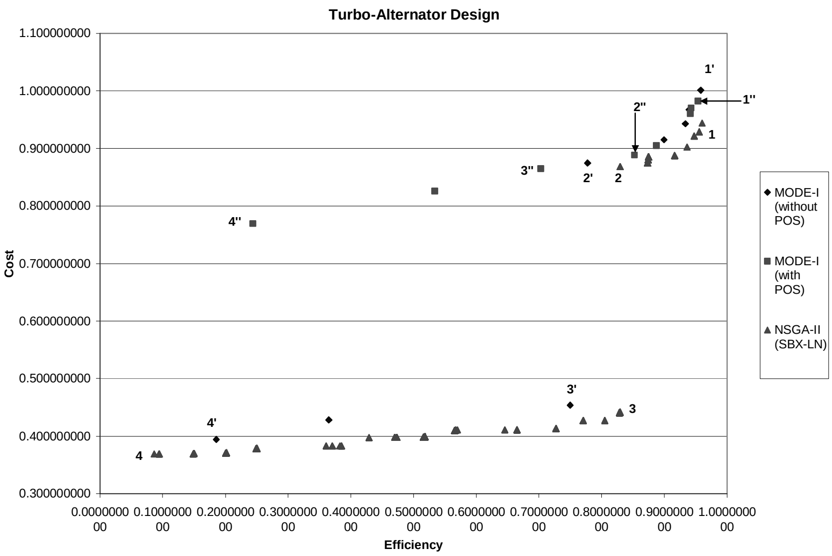

Figure 1 : MODE-I (Cr = 0.9, Pop = 500 and Gen = 200)

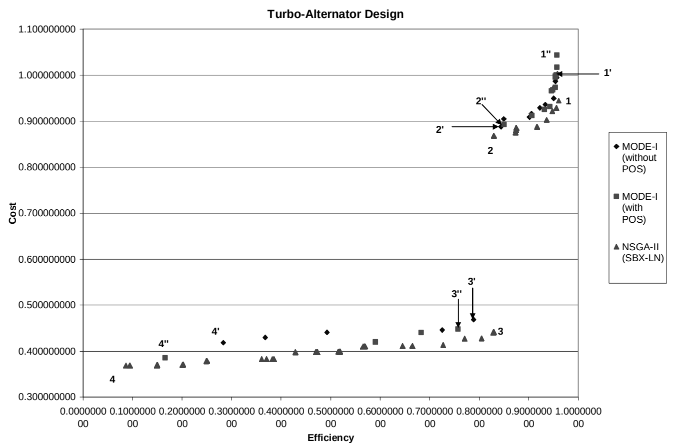

Figure 2 : MODE-I (Cr = 0.9, Pop = 10000 and Gen = 100)

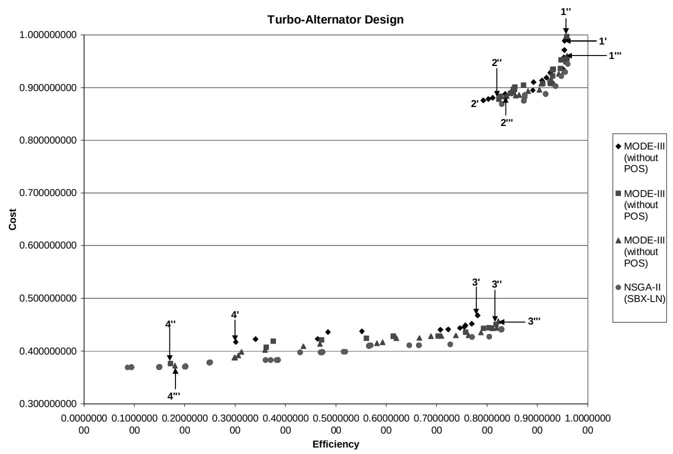

Figure 3 : MODE-III (Cr = 0.9, Pop = 100, 500 and 10000, Gen = 300, 200 and 100)

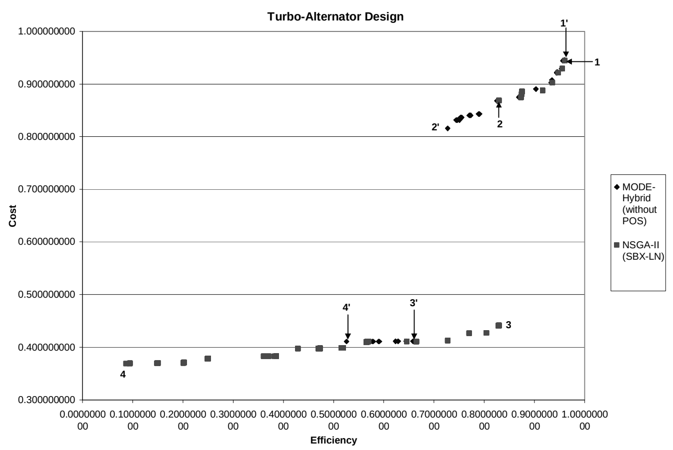

Figure 4 : MODE-Hybrid (C.R. = 0.9, Pop = 100 and Gen = 300)

Discussion of Result

1. The NSGA-II algorithm with simulated binary crossover operator having lognormal distribution (SBX-LN) has given more optimized solutions with better diversity. Its performance is better when compared with other probability distributions such as the principle of single point crossover operator on binary strings, Cauchy, Fisher-Tippett, Logistic, Rayleigh and Uniform. These solutions are even better than the solutions obtained by the MODE-algorithms. Hence, these results are taken as the POS.
2. From the Table I, it is observed that the variance GD of the convergence and diversity metrics are small for the solutions obtained by MODE-I algorithm when the POS information is given as reference to it. From the Tables II and III, it is observed that there is no effect of the POS information on the variance GD of the convergence and diversity metrics, for the solutions obtained by MODE-III and MODE-Hybrid algorithms. The variance GD of the convergence and diversity metrics are equal in both the cases, for a set of population and generation. Hence the solutions obtained by the MODE-III and MODE-Hybrid algorithms, when the POS information is not given as reference, are considered for the analysis.
3. The variance GD of the convergence metric is smallest for large number of populations and the variance GD of the diversity metric is smallest for small number of populations. From this it is concluded that for small number of populations the solutions are maintaining a good diversity between the solutions and for large number of populations the solutions are more converging towards the POS.
4. From Table II, it is observed that the variance GD of the convergence metric is smallest for small number of populations and the variance GD of diversity metric is smallest for large number of populations. From this it is concluded that for small number of populations the solutions obtained are more converging towards the POS and for large number of populations the solutions obtained are maintaining a better diversity between them.
5. When all rated values of the turbo-alternator are considered, the CAD program gives a design with low efficiency at high cost, as the rated value of power factor is 0.8. The optimum design at rated output power gives high efficiency at low cost, as the operating power factor is 1.0 (U.P.F.). This is reducing the line current value by 16% while the line voltage and field excitation current are reduced slightly from their rated values.
6. From Table IV, V, VI and VII and Fig. 1, 2, 3 and 4, it is noted that there is no much variation in the efficiency from point 2 to point 3, but there is reduction in the cost. This is because of considerable variation in the output power and line current which gives a considerable variation in temperature difference between copper and iron (TD_{sci}) and field excitation current (I_{rme}). Hence there is a considerable change in the cost of the turbo-alternator design.
7. The line voltage is allowed to vary within certain allowable range from its rated value. This allowed the program to select an optimum value of line voltage slightly less than its rated value, within the allowable range. The

output power and line current are allowed to vary from 0.0 (no-load) to their rated values (full-load). This made the algorithm to provide a number of solutions at different power ratings and currents. It is observed that the output power and line current are changing with load on the turbo-alternator. In this problem, the number of layers of conductors in stator slot (depth) is taken as 1.

Conclusion

Following are the conclusions of this study.

1. The field excitation current is having very large effect on the turbo-alternator design. When it is allowed to vary in the allowable range from its rated value, many near global solutions are obtained within allowable range. Hence this constraint is called a hard constraint. Three more parameters such as stator slot pitch, temperature difference between copper and iron and rotor critical speed are also formed as constraints. But their effect is not much on the turbo-alternator design. Hence these constraints are called soft constraints.
2. The NSGA-II algorithm with SBX-LN works better for this problem when compared with the MODE algorithms. These solutions are taken as Pareto-optimal solutions for the problem considered in this paper. The optimum solutions obtained by MODE-Hybrid algorithm are more converging with the Pareto-optimal solutions while the optimum solutions obtained by MODE-I algorithm are less converging with the Pareto-optimal solutions.
3. The constraints are handled by using penalty function method. The constraint violated solutions are penalized by assigning a very high value (10000).
4. The important contribution of this work is to optimize the turbo-alternator design using MODE algorithms, comparing these results with the optimum solutions obtained by the NSGA-II algorithm with SBX-LN crossover and identifying the Pareto-optimal solutions of the turbo-alternator design.

Appendix – A

Design Variables

The values of parameters W_1, W_2, P_{L1}, P_{L2}, P_{L3}, P_{L4}, and P_{L5} are obtained from the turbo-alternator design. The input data such as power rating, operating voltage, current delivered by the machine, operating power factor, operating frequency, operating speed, number of phases, and type of stator winding connection of turbo-alternator is used to calculate various losses, weight of copper, and weight of iron.

The total weight of copper is

$$W_1 = f\begin{bmatrix} DNT_{co}, PV_{rm}, N_r, C, f, SP_{sm}, N_{sp}, V_L, \\ \psi, a_{sc}, I_L, L_{rsa}, P_0, ST_{rsm}, V_{ex}, R_{rcoci}, S_{rp}, \\ DP_{rw}, pf, N, DNT_i, W_{cs} \end{bmatrix} \tag{A.1}$$

The total weight of iron is

$$W_2 = f\begin{bmatrix} f, N_r, SP_{sm}, PV_{rm}, C, \psi, DP_{sw}, DP_{scs}, \\ N_{ssd}, DP_{si}, DNT_i, V_L, N_{sp}, \\ DNT_{co}, L_{rsa}, P_0, ST_{rsm}, V_{ex}, R_{rcoci}, \\ I_L, S_{rp}, DP_{rw}, pf, N, a_{sc}, WD_{scs}, W_{cs} \end{bmatrix} \quad (A.2)$$

The stator copper loss is

$$P_{L1} = f\begin{bmatrix} \rho_c, N_{sp}, f, N_r, SP_{sm}, C, PV_{rm}, \psi, I_L, \\ a_{sc}, DP_{si}, WD_{scs}, P_0, pf, N, V_L, W_{cs}, N_{sp} \end{bmatrix} \quad (A.3)$$

The stray load loss is

$$P_{L2} = f[P_{L1}] \quad (A.4)$$

The friction and windage loss is

$$P_{L3} = f[P_0, pf] \quad (A.5)$$

The stator iron loss is

$$P_{L4} = f\begin{bmatrix} a_{teeth}, \psi, SP_{sm}, f, N_r, PV_{rm}, C, V_L, \\ N_{sp}, DP_{sw}, DP_{scs}, N_{ssd}, DP_{si}, DNT_i, \\ W_{cs}, a_{core}, P_0, pf, N, a_{sc}, I_L, WD_{scs} \end{bmatrix} \quad (A.6)$$

The excitation loss is

$$P_{L5} = f\begin{bmatrix} f, N_r, DP_{rw}, ST_{rsm}, PV_{rm}, P_0, S_{rp}, \\ SP_{sm}, C, I_L, V_{ex}, L_{rsa}, \psi, R_{rcoci}, \rho_c, \\ W_{cs}, VD_{rb}, \eta_{re}, pf, N, V_L, N_{sp}, DNT_i \end{bmatrix} \quad (A.7)$$

The following variables are chosen with suitable values in this design.

PV_{rm} = 6100 m/min, (L_{sn}/L_{sc}) = 0.68, (λ/t) = 1.5, C = 1.0, ψ = 1.0, BL_{sc} = 0.0508 m, SP_{sm} = 0.07 m, a_{sc} = 0.4053 mm^2/A, WD_{scs} = 0.003353 m, DP_{si} = 0.0006096 m, DP_{scs} = 0.004115 m, DP_{sw} = 0.00635 m, N_{ssd} = 1, N_{ssw} = 1, DNT_i = 7800 kg/m^3, E = 195000000000 Pa, E_{li} = 28000000 psi, ST_{rsm} = 9863656 kg/m^2, DP_{rw} = 0.03175 m, L_{rsa} = 0.0127 m, V_{ex} = 120 V, R_{rcoci} = 1 O/cirm/in, S_{rp} = 6, DP_{rcs} = 0.0041148 m, TH_{ic} = 0.000381 m, WD_{rsi} = 0.003353 m, ρ_c = 0.000000021 O.m, N = 1, a_{teeth} = 6.5, a_{core} = 4.7, VD_{rb} = 1 V, η_{re} = 0.88, VOL_{air} = 100 ft^3/min, DNT_{co} = 8920 kg/m^3, C_1 = 325 units/kg, C_2 = 28.5 units/kg.

The following variables are taken from the design as per standard design data. The values of WD_{scs}, N_{ssd}, DP_{si}, DP_{scs}, DP_{sw}, DP_{rcs}, TH_{ic}, WD_{rsi} and N are chosen from the design [10], [14]. The nomenclature of these variables is given in Appendix – B.

Appendix – B

Nomenclature of Variables

Variable	Description
PV_{rm}	maximum peripheral velocity of rotor in m/min
(L_{sn}/L_{sc})	ratio of net length of iron in the core and frame length
(λ/t)	ratio of slot pitch and tooth width
C	Carter coefficient
ψ	percent pole enclosure
BL_{sc}	blocks of iron in the core in m
SP_{sm}	maximum permissible slot pitch in m
a_{sc}	stator conductor area in mm^2/A
WD_{scs}	insulation width from stator slot to conductor in m
DNT_i	density of iron in kg/m^3
E	Young's modulus in Pa
E_{li}	Young's modulus in psi
ST_{rsm}	stresses to be allowed at maximum speed in kg/m^2
DP_{rw}	rotor probable depth of wedge in m
L_{rsa}	shortage of rotor axial length from stator core to allow the rotor to oscillate freely in m
V_{ex}	rotor field circuit voltage in V
R_{rcoci}	rotor conductor resistance in O/cirm/in
S_{rp}	rotor slots per pole
ρ_c	resistivity of copper in O.m
a_{teeth}	constant for stator teeth
a_{core}	constant for stator core
VD_{rb}	voltage drop at each brush in V
η_{re}	exciter efficiency
DNT_{co}	copper density in kg/m^3
C_1	cost of copper in units/kg
C_2	cost of iron in units/kg
N_{ssd}	number of conductor strips in each stator slot (depth)
DP_{si}	insulation on each stator conductor in m
DP_{scs}	total depth of stator slot insulation in m
DP_{sw}	depth of stator wedge in m
DP_{rcs}	rotor insulation depth between slot and conductor in m
TH_{ic}	rotor insulation thickness (depth) in m
N	number of layers of conductors in stator slot (depth)
P_0	rated output power rating of machine in W
V_L	stator line voltage in V
N_{sp}	stator number of phases
I_L	stator line current in A
F	stator frequency in Cy/s
N_r	rotor speed in r.p.m.
pf	stator power factor
W_{cs}	stator winding connection

N_{ssw}	number of conductor strips in each stator slot (width)
WD_{rsi}	rotor slot insulation width in m
VOL_{air}	volume of air per kilowatt loss in ft^3/min
η	efficiency of turbo-alternator
P_{TLoss}	Total losses in turbo-alternator in W
C_T	total cost of turbo-alternator in units
W_1	total weight of copper in kg
W_2	total weight of iron in kg
P_{L1}	stator copper loss in W
P_{L2}	Stray load loss in W
P_{L3}	friction and windage loss in W
P_{L4}	Stator iron loss in W
P_{L5}	excitation loss in W
λ	stator slot pitch in m
TD_{sci}	temperature difference between stator copper and iron in ^{0}C
N_{rc}	Rotor critical speed in r.p.m.
I_{rme}	Rated field exciting current in A
I_{rmel}	lower bound of rated field exciting current in A
I_{rmeu}	Upper bound of rated field exciting current in A
λ_m	stator maximum slot pitch in m
TD_{msci}	maximum temperature difference between stator copper and iron in ^{0}C
N_{mrc}	Rotor maximum critical speed in r.p.m.
L_{sn}	net length of iron in the core in m
L_{sc}	Frame length in m
T	stator tooth width in m

m = meter, min = minute, AC = ampere conductors, Wb = weber, mm = millimeter, A = ampere, kg = kilogram, Pa = pascal, psi = pound-force per square inch, V = volt, O = ohm, cirm = circular mil, in = inch, W = watt, Cy = cycles, s = second, r.p.m. = revolutions per minute, ft = foot, ^{0}C = degree Celsius.

Acknowledgement

The authors gratefully acknowledge the contributions of Prof. B.V. Babu, Professor of Chemical Engineering and Dean – Educational Hardware Division, Birla Institute of Technology and Science, Pilani, India, who provided the MODE algorithms to solve the turbo-alternator design optimization problem.

References

[1] Deb, K., 1998, Optimization for engineering design, Prentice-hall of India private limited, Newdelhi.

[2] Deb, K., 2002, Multi-objective optimization using evolutionary algorithms, John wiley & sons limited, Chichester.

[3] Deb, K., Agarwal, S., Pratap, A., and Meyariven, T., 2002, “A fast and elitist multi-objective genetic algorithm: NSGA-II,” IEEE Trans. Evolutionary Computation, 6(2), pp. 182-197.

[4] Deb, K., Pratap, A., and Moitra, S., 2002, “Mechanical component design for multiple objectives using elitist non-dominated sorting GA,” Kangal technical report no. 200002.

[5] Lamme, B.G., 1984, “High-speed turbo-alternators-designs and limitations,” Proceedings of the IEEE, 72(4), pp. 494-526.

[6] Ula, A.H.M.S., Stephenson, J.M., and Lawrenson, P.J., 1988, “The effect of design parameters on the dynamic behavior of the superconducting alternators,” IEEE Trans. Energy Conversion, 3(1), pp. 179-186.

[7] Gimba, H., David, J.P., and Thomas, A.K., 2005, “Design of dual output alternators with switched-mode rectification,” IEEE Trans. Power Electronics, 20(1), pp. 164-172.

[8] Azzouri, J., Abdel, K.N., Barkat, G., and Dakyo, B., 2005, “Axial flux permanent magnet synchronous generator design optimization: robustness test of the genetic algorithm approach,” ESPE 2005, Dresden, ISBN:90-7581-08-5, pp. 1-10.

[9] Prasad, K.V.R.B., and Singru, P.M., 2007, “Optimum design of electrical machines using genetic algorithm: an overview and future research paths,” Proc. National Conf. Recent Advances in Electrical Engineering, Visakhapatnam, pp. 4-26 – 4-33.

[10] Prasad, K.V.R.B., Bacher, G., and Singru, P.M., 2008, “Turbo-alternator design optimization using NSGA-II,” Proc. Int. Conf. Power Electronic Drives & Power Systems, Salem, paper code: PEDROT11, pp. 1-5.

[11] Gray, A., 1913, Electrical Machine Design – The design and specification of direct and alternating current machinery, Mcgrawhill book company, Inc.

[12] Sawheny, A.K., 1991, Electrical machine design, Dhanpat rai & sons, Newdelhi.

[13] Mittle, V.N., and Mittal, A., 2006, Design of electrical machines, Standard publishers distributors, Newdelhi.

[14] Say, M.G., 2002, The performance and design of alternating current machines, CBS publishers & distributors, Newdelhi.

[15] Shanmugasundaram, A., Gangadharan, G., and Palani, R., 2005, Electrical machine design data book, New age international publishers, Newdelhi.

[16] Deb, K., and Agarwal, S., 1999, “Understanding interactions among genetic algorithm parameters,” Kangal technical report no. 99003.

[17] Raghuwanshi, M.M., Singru, P.M., Kale, U., and Kakde, O.G., 2005, “Simulated binary crossover with lognormal distribution,” Complexity International, 12, pp. 1-10.

[18] Central electricity board: “Indian electricity rules, 1956 (as amended up to 25th No., 2000),” Under section 37 of the Indian electricity act, 1910 (9 of 1910), Ministry of power, Government of India.

[19] Deb, K., 1999, "Multi-objective genetic algorithms: problem difficulties and construction of test functions," Evolutionary Computation, 7, pp. 205-230.

[20] Price, K.V., Storn, R.M., and Lampinen, J.A., 2005, Differential evolution – a practical approach to global optimization, Verlag berlin Heidelberg, Springer.

[21] Price, K.V., and Storn, R.M., 1997, "Differential evolution – a simple evolution strategy for fast optimization," Dr. Dobb's journal, 22(4), pp. 18-24.

[22] Babu, B.V., Mubeen, J.H.S.Y., and Chakole, P.G., 2005, "Multi-objective optimization using differential evolution," Tech-Genesis – The joutnal of information technology, 2(2), pp. 4-12.

[23] Babu, B.V., Gujarathi, A.M., Katla, P., and Laxmi, V.B., 2007, "Strategies of multi-objective differential evolution (MODE) for optimization of adiabatic styrene reactor," Proc. EMTMN, pp. 243-250.

[24] Xue, F., Sanderson, A.C., and Graves, R.J., 2003, "Pareto-based multi-objective differential evolution," IEEE Congress Evolutionary Computation, pp. 862-869.

[25] Deb, K., and Agrawal, R.B., 1994, "Simulated binary crossover for continuous search space," Kangal technical report no. 94027.