Exploring Innovative Design Principles using Innovization in Multi- Objective Optimal Reactive Power Dispatch Problem

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Abstract*: Recently, researchers in the field of Evolutionary Multi-Objective Optimization give a systematic approach for exploring innovative design principles in a conflicting multi-objective optimization problem by analyzing pareto optimal solution using either manual or automated approach. They call it "Innovization" and defined as: "innovation through optimization". This paper applies manual innovization to multi-objective Optimal Reactive Power Dispatch Problem using Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) as multi-objective optimization algorithm and manually searches for all possible innovative design principles by analyzing multiple pareto optimal solutions. Standard IEEE 30 bus test system is considered for the current work. Simulation results reveal number of innovative design principles. Innovative design principles includes function approximation of relationship between conflicting objectives, characteristics of decision variable with respect to different objectives and actual range of decision variables. Simulation results clearly show much faster convergence when decision variables were obtained using innovative design principles for specified desired objectives as compared to normal case. Results also show some decision variables can be eliminated by setting it to a fixed value, which leads to simplification of optimization problem as the values of these variables remains constant with respect to the values of objective function.

***Keywords* : Power System, Reactive Power Dispatch, Evolutionary Algorithm, Innovization, Multi-Objective Optimization.**

I. INTRODUCTION

Over the years, solution to optimal reactive power dispatch problem has gained significance in providing economic and secure run to the operation of power system [1]. Optimal reactive power dispatch involves simultaneous minimization of Real Power Transmission Loss (RPTL) and Load Bus Voltage Deviation (LBVD) by controlling generator bus voltages, reactive power output of static Var compensator and transformer tap settings regulation [2]. Control should be in such a way that various equality and inequality constraints related to power flow equation and operating limits of various equipment were not violated. Multi-Objective Evolutionary Algorithms (MOEA) are quite popular for obtaining high performing solution to optimal reactive power dispatch problem in a reasonable amount of time. The main advantages of MOEA are their capabilities to generate multiple pareto optimal solutions in a single simulation run [3]. A vast literature exists on the application of different MOEA to multi-objective reactive power dispatch problem. Author in [4] uses a variant of Strength Pareto Evolutionary Algorithm (SPEA) for optimizing reliability and load bus voltage independently. In [5] the author presents an improved evolutionary programming (IEP) and its hybrid version combined with the nonlinear interior point (IP) technique to solve the optimal reactive power dispatch (ORPD) problems. A chaotic particle swarm optimization (CPSO) for solving optimal reactive power dispatch problem is presented in [6]. The performance of the proposed algorithm had been tested on number of standard IEEE test system. Author in [7] presents a Differential Evolution based method for solving optimal reactive power dispatch problem with real power transmission loss as main objective function. The effectiveness of proposed method were verified by comparing the obtained results with that obtained using Particle Swarm Optimization and Sequential Quadratic Programming technique. In [8] the author proposed a seeker optimization algorithm (SOA)-based reactive power dispatch method. Some other techniques can be found in [9-16].

Most of the existing literature work solves optimal reactive power dispatch problem in two parts and can be summarized as: (a) First, any multi-objective meta-heuristic is used to generate well converged and diverse (in objective space) multiple pareto optimal solutions. (b) Second, one solution based on some specified criterion is selected for implementation and rest are discarded. But it is well known fact that generation of well converged and diverse multiple trade-off solutions in a real world multiobjective optimization problem using any meta-heuristics very time consuming and expensive task. Therefore, throwing all pareto optimal solutions is not a good idea as it leads to wastage of efforts and resources. Also, these solutions are not any arbitrary solution, but pareto optimal solution .i.e. best possible compromised solution between two conflicting objectives. These solutions set carries valuable information about the nature of multi-objective optimization problem. Thorough analysis of these solutions can reveal innovative design principles which helps in a better understanding and paves a path for improved design of the system. Recently authors in [17] proposed a systematic approach for exploring innovative design principles in conflicting multiobjective optimization problems by analyzing pareto optimal solutions set using either manual or automated approach.

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They call it "Innovization" which is defined as: "creating innovation through optimization". Innovization extends the task of optimization algorithms beyond simple optimization and attempts to unveil new and innovative design principles related to decision variables and objectives, for a deeper understanding of the problem. Author in [17] demonstrated the usefulness of innovization by applying it on three different design problems. There exists two popular methods for innovization: (1) Manual Innovization and (2) Automated Innovization [18]. In manual innovization multiple trade-off solutions were manually analyzed for any commonality and innovative design principles while in automated innovization a high level algorithm is designed to find innovative design principles hidden in multiple trade-off data. Innovative design principles obtained in [17] are highly motivating for design engineers and practitioners to further apply it to more complex optimization problems. In literature, few other researchers had applied innovization to real world optimization problem [19-23].

This paper moves a step ahead in the field of optimal reactive power dispatch and applies manual innovization to multi-objective Optimal Reactive Power Dispatch Problem using NSGA-II as multi-objective optimization algorithm and manually searches for all possible innovative design principles by analyzing multiple pareto optimal solutions. Optimal reactive power dispatch problem is generally modeled as a constrained nonlinear multi-objective optimization problem where Real Power Transmission Loss (RPTL) and Load Bus Voltage Deviation (LBVD) are to be minimized simultaneously without violating equality and inequality constraints. Standard IEEE 30 bus test system is considered for the current work. Simulation results reveal number of innovative design principles. Innovative design principles includes function approximation of relationship between conflicting objectives, characteristics of decision variable with respect to different objectives and actual range of decision variables. Simulation results clearly show much faster convergence when decision variables were obtained using innovative design principles for specified desired objectives as compared to normal case. Results also show some decision variables can be eliminated by setting it to a fixed value, which leads to simplification of optimization problem as the values of these variables remain constant with respect to the values of objective function.

The remaining of the work is arranged as follows: A brief introduction of Multi-objective optimal reactive dispatch problem formulation is given in Section (II). Manual Innovization Procedure is reviewed in Section (III). Test problem description is given in Section (IV). Sections (V) and Section (VI) gives Numerical Simulation and Simulation Results & Analysis respectively. Obtained Innovized design principles is given in Section (VII). Final Conclusion along with some directions of future scope is given in Section (VIII).

II. MULTIOBJECTIVE OPTIMAL REACTIVE POWER DISPATCH PROBLEM FORMULATION [4]

Problem of Optimal VAR Dispatch in power system constitutes simultaneous optimization Real Power Transmission Loss and Load Bus Voltage Deviation. Its mathematical formulation is given as:

A. Objective Function

1. Real Power Transmission Loss (RPTL): The first objective is minimization of real power loss in transmission lines. Mathematically it can be expressed as Eq. (5).

$$RPTL = \sum_{k=1}^{NL} g_k [V_i + V_j - 2V_i V_j \cos(\delta_i - \delta_j)] \qquad (1)$$

where NL denotes the total number of transmission lines, g_k indicates the conductance of the k^{th} line, $V_i\angle\delta_i$ and $V_j\angle\delta_j$ denotes bus voltages at i and j end of the lines respectively.

2. Load Bus Voltage Deviation (LBVD): The second objective is minimization of Load Bus Voltage Deviation from specified reference voltage which is generally set to 1.0 p.u. Mathematically it can be expressed as Eq. (6)

$$LBVD = \sum_{k=1}^{NL} |V_k - 1| \qquad (2)$$

where NL represent number of load buses; V_k is the voltage magnitude at the k^{th} load bus.

B. Constraints

Here the constraint are of two types - equality and inequality constraints.

1. Equality Constraints: These basically represent real and reactive power balance in power system.
2. Inequality Constraints: Inequality constraint includes operating limit of various devices in power system. Following inequality constraints are considered for this work:

a) Generator Constraints: This constraint ensures lower & upper limit of generator bus voltages V_G and generator reactive power outputs Q_G should not be violated.

b) Transformer Tap Setting Constraints: This ensures tap setting of transformer remains between its specified ranges.

c) VAR Output of VAR Sources: It limits the minimum & maximum value of VAR output Q_C from all VAR source remains between its specified ranges.

Combining all objectives and constraints the problem of optimal VAR dispatch can be formulated as multiobjective optimization problem. Mathematically it can be expressed as:

$$Minimize \quad [RPTL(v),\ LBVD(v)] \qquad (3)$$

$$Subject \quad to: g(v) \le 0 \qquad (4)$$

$$h(v) = 0 \qquad (5)$$

where v represents set of parameter need to be optimized which includes generator bus voltages V_G, transformer tap settings T, and VAR source output Q_c. Vector v can be given as:

$$x^T = [V_{G_1}, V_{G_2} ... V_{G_{NG}}, T_1, ... T_{NT}, Q_{C_1}, Q_{C_1}, ... Q_{C_{NC}}] \qquad (6)$$

$g(v)$ and $h(v)$ are the equality and inequality constraints respectively.

III. MANUAL INNOVIZATION PROCEDURE

General steps of manual innovization procedure proposed in [17] can be summarized in following steps:

1) Find end solutions or best solution in terms of all objectives using any single objective optimization algorithm. One objective is considered at a time and other objectives are ignored.
2) Find well converged and diverse multiple trade-off solutions using any multi-objective meta-heuristics.
3) Apply a local search technique and obtain the modified optimized pareto front.
4) Apply Normal Constraint Method (NCM) starting at a few locations to verify the obtained optimized front.
5) Cluster a few solutions (say 10 or 50) uniformly along the obtained pareto front.
6) Manually analyze the obtained solutions to reveal important innovative design principles.

IV. TEST PROBLEM DESCRIPTION

In this work innovization is applied on multi-objective reactive power dispatch problem of standard IEEE 30-bus test system. This system consist of 6 generator, 41 transmission lines and 4 tap setting transformers [24]. The total number of decision variables to be optimized for this system is 12 which includes 6 Generator bus voltage, 4 transformer tap setting and 2 Var source. Generator bus voltages were continuously varied between [0.90 − 1.10] p.u. Transformer tap settings were discretely varied in step of 0.0125 between [0.9 - 1.1]. The generator buses are 1, 2, 5, 8, 11 and 13. Tap setting transformer are placed between (6 − 9), (6 − 10), (4 − 12) and (27 − 28) buses. VAR output of VAR compensators were varied in range of [0 − 5] MVAr in discrete steps of 1 MVAr and placed at buses 10 and 24. The rest of the detail regarding standard IEEE 30-bus test system is given in [24].

V. NUMERICAL SIMULATION

Innovization is applied on multi-objective optimal reactive power dispatch problem on Standard IEEE-30 bus test system. All programs were written in MATLAB 2016(a) [25] and run on a PC with a core-i5 processor operating at 2.60 GHz and 4 GB of RAM. Single objective Genetic Algorithm (GA) has been used to obtain end solutions or best solutions in terms of individual objectives. NSGA-II [26] has been used to generate well converged and diverse multiple pareto optimal solutions. Normal Constraint Method (NCM) [27] has been used to verify intermediate points obtained using NSGA-II. Parameters of single objective GA and NSGA-II are given in Table-I. Maximum number of iterations is considered as termination criterion for both algorithms.

Table 1. Parameter setting of single objective and NSGA-II for standard IEEE-30 bus test system

Parameters	SOGA	NSGA-II
Number of population	50	50
Maximum iteration	200	500
Crossover Percentage	0.8	0.7
Mutation Percentage	0.35	0.4
Mutation Rate	0.015	0.02
Mutation Step Size	0.15	0.1

Instead of clustering few solutions, all solution with population size 50 were analyzed. Benson's method [28] is used for performing local search. Solutions were analyzed on the following aspects:

1) Possible relationship between different objectives.
2) Decision variable behavior with respect to different objectives.
3) Bus identification with minimum and maximum bus voltage deviation.
4) Line identification with minimum and maximum real power transmission loss.

VI. SIMULATION RESULTS AND ANALYSIS

Multiple pareto optimal solutions were obtained using NSGA-II and plotted in Figure 2. using single objective GA. The best solution in terms of Real Power Transmission Loss comes out to be 16.00 MWh and best solution in terms of Load Bus Voltage Deviation comes out to be 0.20. These obtained non-dominated solutions can be used to obtain hidden relationship between these two objectives i.e. RPTL and LBVD. This relationship would be very useful when it is required to find out decision variable for another desired objectives (explained in detail in later section). For example, if desired value of one objective is known then best value of other objective can be obtained using obtained relationship between RPTL and LBVD. The multiple non-dominated solutions are well converged and uniformly distributed along the entire pareto front. The end solution verified with that obtained.

Curve fitting tool box of MATLAB is used to obtain hidden relationship between RPTL and LBVD using obtained nondominated solutions. Table- II gives different aspects of obtained relationship between two objectives. The obtained model is an exponential model with degree 2. Different model coefficient (with 95 % confidence bounds) is given in Table-2

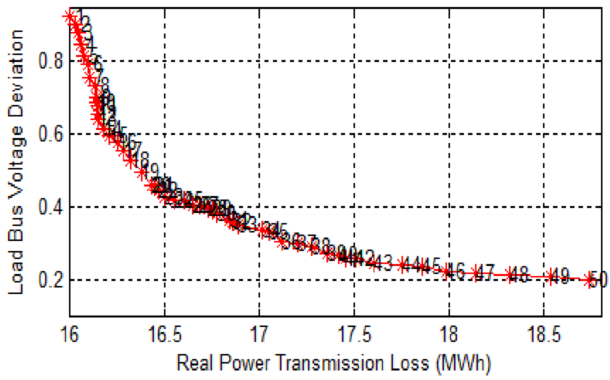

Figure 2. Final obtained pareto optimal solution for Standard IEEE-30 Bus test system

Table 2. Curve fitting parameter of two objectives (RPTL and LBVD) for standard IEEE 30 bus system

Coordinate Description	Model Description and Function	Coefficients(with 95 % confidence bounds)
x-Coordi-nate: RPTL y-Coordi-nate: LBVD	Exponential model: f(x)=a*exp(b*x)+ c*exp(d*x)	a=2.196e+14, b=-2.074, c=0.3831, d=-0.01578

Combined plot of actual pareto front along with modeled pareto front is plotted in Figure 3. As evident from figure 3 that the model almost resembles with that of actual pareto front. This is the first design principle obtained for multi-objective optimal reactive power dispatch problem using innovization. This is very crucial information for design engineers as demonstrated in later part of this section.

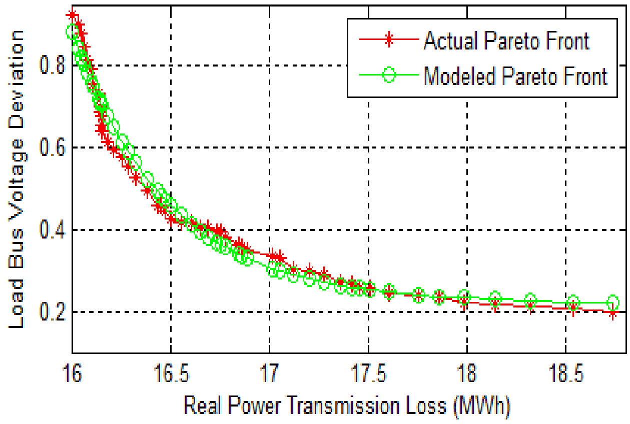

Figure 3. Actual and modeled pareto front for Standard IEEE-30 Bus test system

Next, behavior of decision variable with respect to different objectives were analyzed. Figure 4 gives characteristics of six generator bus voltage (G1, G2, G3, G4, G5 and G6) with respect to RPTL. It is clearly evident from Figure 4 that generator G1 & G2 bus voltage decreases with increase in RPTL. G1 bus voltage uniformly decreases with increase in RPTL while G1 bus voltage non-uniformly decreases with increase in RPTL. G3 bus voltage initially decreases with respect to RPTL but starts in increasing hen RPTL reaches to 17.40 MWh. G4 and G6 shows very little variation with little fluctuation with respect to RPTL between two limits. G5 bus voltage almost remains constant at 1.0 p.u with respect to RPTL. This variable can be eliminated from optimization problem by fixing its value to 1.0 p.u. This would lead to simplification to optimization problem in hand.

Similarly, Figure 5 gives characteristics of four transformer tap setting (T1, T2, T3, and T4) with respect to RPTL. Transformer tap settings T2 & T3 decreases with little fluctuation with respect to RPTL. Transformer tap settings T1 & T4 initially decreases with respect to RPTL and then settles to almost a fixed value after 17.0 MWh. If the real power transmission loss is more than 17.0 MWh then these two variable can be eliminated by fixing its value to 1.03 and 0.97 respectively. This is very crucial information for any power engineers.

Figure 6 gives characteristics of reactive power output of two Var source (QC1 and QC2) with respect to RPTL. From Figure 6 it is clear that Var output of QC1 takes only three values i.e. 3 MVars, 4 MVars and 5 MVars. And hence instead of taking 0 MVars as its minimum limit the power engineers can set its minimum limit at 3 MVars. This would led to reduction in search space. Also its value remains at 5 MVars when RPTL is below 17.50 MWh. Therefore, if RPTL is below 17.50 MWh then this variable can also be eliminated by setting it to optimal value. Reactive power source QC2 shows similar kind of behavior with minimum limit of 2 MVars and maximum limit of 5 MVars.

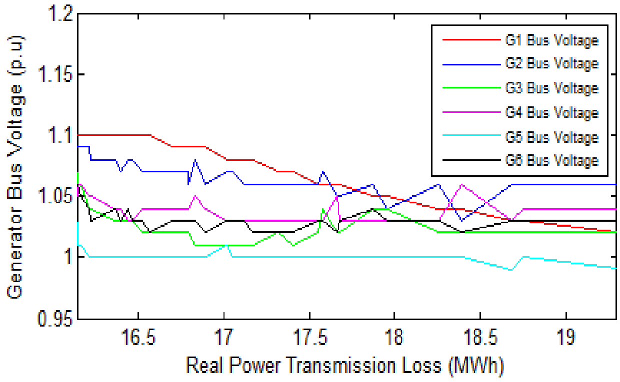

Figure 4. Generator bus voltage (G1-G56) behavior with respect to Real Power Transmission Loss.

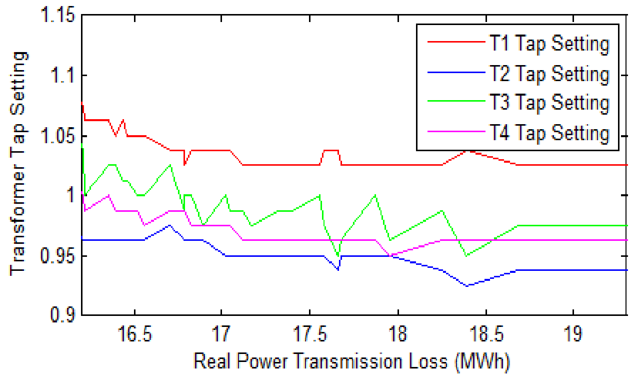

Figure 5. Transformer tap setting (T1-T4) behavior with respect to Real Power Transmission Loss.

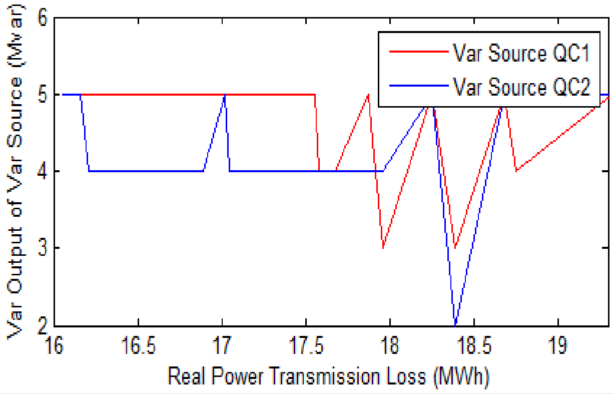

Figure 6. Reactive power output of Var source behavior with respect to Real Power Transmission Loss.

Figure 7 gives characteristics of six generator bus voltage (G1, G2, G3, G4, G5 and G6) with respect with respect to LBVD. All generator bus voltages increase with respect to load bus voltage deviation. Most of the generator bus voltage initially increases with respect to LBVD and then finally settles to its final value. Generator G1 bus voltage is the quickest to settles to its final value at LBVD of 0.4. It means when desired LBVD is more than 0.4 generator voltage G1 can be eliminated as decision variable by setting its value to 1.10 p.u. Generator G1 and G4 also shows similar kind of behavior as that of G1 with addition of little fluctuation when LBVD is more than 0.45. Generator G3 bus voltage initially decreases with respect to LBVD and then starts increasing after LBVD exceeds 0.38 with huge fluctuation.

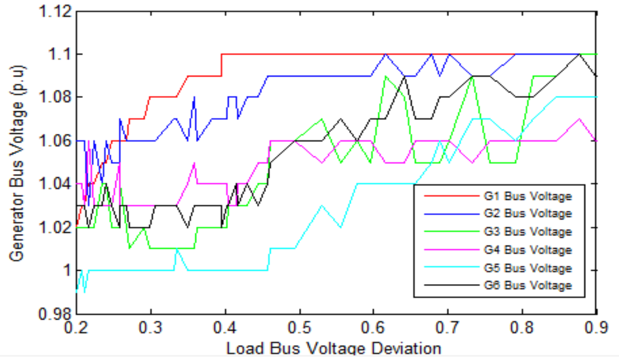

Figure 7. Generator bus voltage (G1-G6) behavior with respect to Load Bus Voltage Deviation.

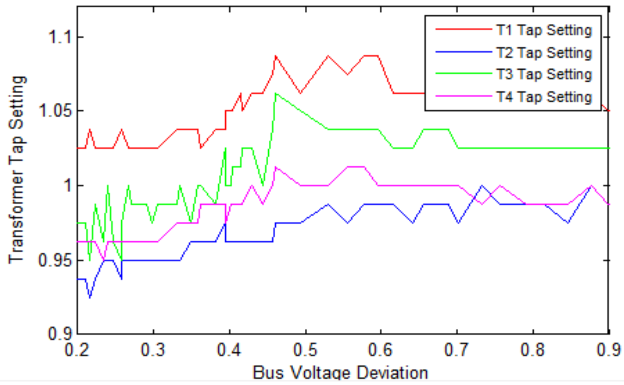

Figure 8. Transformer tap setting (T1-T4) behavior with respect to Load Bus Voltage Deviation.

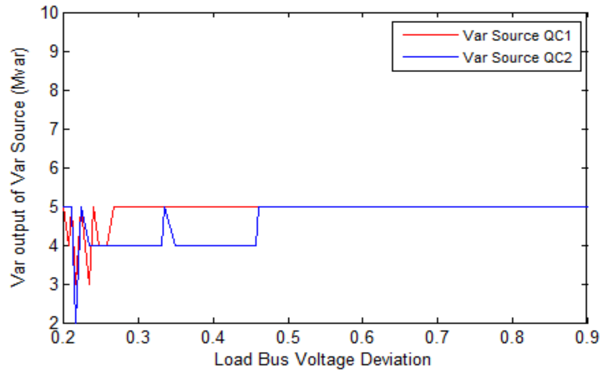

Figure 9. Reactive power output of Var source (Q1 and Q2) behavior with respect to Load Bus Voltage Deviation.

Figure 8 gives characteristics of the four Transformer tap setting (T1, T2, T3 and T4) with respect with respect to LBVD. All transformer tap setting increases with respect to load bus voltage deviation. Range of transformer tap setting T2 & T4 are much small as compared to that of transformer T1 & T3 which shows large variation in its value with respect to LBVD. Figure 9 gives characteristics of the reactive power output of Var source (Q1 and Q2) with respect with respect to load bus voltage deviation. As evident from the figure that Var source QC1 only takes three values (i.e. 3 MVars, 4 MVars and 5 MVars) and it settles to 5 MVars when LBVD exceeds 0.26. Also Var source QC2 only takes four values (i.e. 2 MVars, 3 MVars, 4 MVars and 5 MVars) and it settles to 5 MVars when LBVD exceeds 0.46. If the desired LBVD is more than 0.46 then these two variables can be eliminated by setting its value to 5 MVars without affecting the optimization problem. This leads to massive simplification of optimization problem in hand. This information would be very useful to any power system engineers.

Identification of behavior and special behavior of a certain decision variable along with identification of possible decision variables which can be eliminated after setting it to a fixed value is the second innovative design principle obtained with the help of innovization.

After that, model of decision variable with respect to different objectives are also obtained using curve fitting tool box of MATLAB. Table- 3 gibes curve fitting parameter of decision variables (6 Gen Bus voltage) with respect to RPTL. Similarly, Table-4 gives curve fitting parameter of decision variables (4 Transformer Tap Setting) with respect to RPTL. Table-5 gives curve fitting parameter of decision variables (Var output of 2 Var sources) with respect to RPTL. Similarly curve fitting parameter of all decision variables is also obtained with respect to LBVD but not included due to space limitation.

Decision variable modeling is very crucial in obtaining good value of decision variables without using any optimization technique for a given desired value of objective functions. This is very useful to design engineers as it helps them in obtaining near optimal solution without using any meta-heuristics technique as these meta-heuristics are time consuming and expensive in nature. This can be better explained with the help of a simple example. Let us consider a situation that maximum allowed LBVD is 0.20 and using this value in the relationship developed earlier (Table-2) between two objectives, the value of RPTL comes out to be 16.4350 MWh. Using these two values and established relationship between decision variables with respect to different objectives given in Table-3 to Table-5, a good value of decision variable can be obtained without using any multi-optimization technique. This is a great advantage as multi-objective meta-heuristics are generally highly complex and time consuming in nature. Although the obtained decision variable may not be the best optimal solution but it has very good probability that it is very close to the optimal solution. It also helps in reducing the complexity of optimization problem. As already mentioned the maximum value of allowed voltage deviation is 0.20 the current multi-objective optimization problem is reduced to a single optimization problem with RPTL as main objective function and maximum LBVD as constraint. Instead of random initialization of decision variable, the obtained decision variable relationship with respect to different objective function can be used to put good some solution in population. Also Table-3 to Table-5 gives a minimum and maximum value of decision variable between which all pareto optimal solution lie. This is very useful to narrow down the search space as G1 bus voltage varies between 1.02 p.u to 1.10 p.u for all pareto optimal solution instead of varying between 0.90 p.u to 1.10 p.u.

Figure 10 gives convergence characteristics of a single objective Genetic Algorithm for a single objective optimization problem in which minimum value of RPTL is to be obtained with a constraint of having maximum load bus voltage deviation of 0.20. Two cases were considered as:

1) Normal initialization of solutions within specified limit of decision variables.
2) Customized initialization using obtained relationship (listed in Table 3-5) and within a minimum and maximum value of obtained pareto front (listed in Table 3-5).

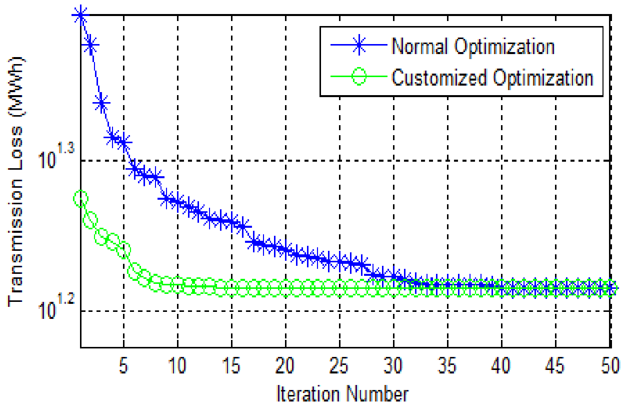

Figure 10. Convergence properties comparison for two cases: (a) Normal Optimization and (b) Customized Optimization

Figure 10 clearly shows much faster convergence when good solutions were introduced using obtained relationship between decision variable and objective function and within the range of obtained minimum and maximum range as compared to the case when solutions are randomly initialized. It merely takes 9 iteration to converge to best solution (16.4350 MWh) as compared to 39 iterations for single objective GA. It is also evident that initial solution for the customized case have much batter objective function value as compared to case when random initialization is done. This bring tremendous advantage to design engineers as solution to multi-objective optimization can be obtained with the help of single objective optimization method with much faster convergence. Therefore, third innovative design principles obtained using innovization is relationship among decision variables and objective function value which helps in simplification of multi-objective optimization problem and its solution with single objective optimization algorithm with faster convergence.

Next all non-dominated solutions were analyzed individually. For each solution the load bus number having minimum & maximum load bus voltage deviation and the transmission line number having minimum & maximum individual line losses were identified. Table-6 summarizes all results. Interesting results evident from Table-9 that load bus number 3 shows the maximum voltage deviation for almost all solution. Line number 11 shows minimum individual line losses for almost all solutions. It remains almost constant irrespective of different values of RPTL and LBVD. Similarly, for each solution line number 1 shows maximum individual line losses and remains independent of objective function values. This is very crucial information for any power system engineers.

Identification of load bus voltage having maximum voltage deviation, transmission line having minimum and maximum individual line losses are fourth innovative design principles obtained with the help of innovization.

VII. INNOVIZED PRINCIPLE

All hidden design principle obtained using manual exploration and exploitation of pareto optimal solution manually is summarized here.

1) Relationship between different objectives is obtained in the form of an exponential model with degree 2. This model could be very helpful in knowing optimum value of other objective function when expected value of first objective function is known or specified. This could be also used in transforming a multiobjective optimization problem into much simpler single objective optimization problem.
2) Relationship of decision variable (i.e. Generator bus voltages, Transformer tap settings and Var output of Var sources) with respect to different objectives function (i.e. RPTL and LBVD) were obtained. These model could very useful in obtaining good value of decision variable without using any multi-objective meta-heuristics. Special behavior of some generator bus voltages, transformer tap settings and Var output of Var sources with respect to objective function were also explored.
3) Obtained minimum and maximum limit of all decision variable in which these decision variable actually are varying. The ranges in which these decision variables were actually varied are much low as compared original specified range. This would lead to much simplification of optimization problem in hand.
4) Decision variable that can be eliminated without affecting optimization problem is identified.

VIII. CONCLUSION AND FUTURE SCOPE

This paper applies manual innovization to multi-objective Optimal Reactive Power Dispatch Problem with NSGA-II as multi-objective optimization algorithm and manually search for all possible innovative design principles. Numerical simulation reveals number of innovative design principles. Simulation results from Figure 2-3 and Table-2 confirms an exponential relationship with degree 2 between RPTL and LBVD. Simulation results from Table-3-5 gives parameter of polynomial model of decision variable behavior with respect to objective function values. These model are helpful in obtaining good value of decision variable without using any multiobjective meta-heuristics and its validity is demonstrated using the convergence plot of Figure 10. Figure 4-9 shows behavior of some generator bus voltage, transformer tap setting Var output of Var sources which could be very useful to power system engineers. Table-6 gives very interesting results in terms of maximum bus voltage deviation and minimum & maximum individual line loses. It is observed that load bus number 3 have maximum bus voltage deviation most of the times. Line number 11 have minimum individual line losses for almost all solutions and line number 1 have maximum individual line losses for almost all solutions and is independent of RPTL and LBVD. Future research direction in this area includes: (a) Application of automated innovation to explore more innovative design principles. (b) Exploring relationship among decision variables.

APPENDIX

Table 3. Curve fitting parameter of decision variables (6 gen bus voltages) vs. RPTL.

Sl. No	x-Coordi - nate	y-Coordi-nate (Gen Bus Voltage)	Model Description and Function	Coefficients (with 95% confidence bounds)	y-Coordinate Minimum and Maximum
1	RPTL	G1	Polynomial model Poly3:f(x)= p1*x^3 + p2*x^2 + p3*x + p4	p1=0.005118, p2=-0.2707, p3 = 4.735. p4 = -26.32	Min=1.0200 Max=1.1000
2	RPTL	G2	Polynomial model Poly3:f(x) =p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.001718,p2 = 0.0999, p3 =-1.929, p4 = 13.42	Min=1.0300 Max=1.1000
3	RPTL	G3	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.01727, p2 = 0.9242 p3 = -16.46, p4 =98.56	Min=1.0100 Max=1.1000
4	RPTL	G4	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1 =-0.005411, p2 =0.293 p3 = -5.278, p4 = 32.67	Min=1.0300 Max=1.0700
5	RPTL	G5	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.01689,p2= 0.902, p3 = -16.05, p4 = 96.04	Min=0.9900 Max=1.0800
6	RPTL	G6	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.01413, p2 = 0.7589 p3 =-13.57, p4 = 81.74	Min=1.0200 Max=1.1000

Table 4. Curve fitting parameter of decision variables (transformer tap settings of 4 transformer) vs. RPTL

Sl. No	x-Coordi - nate	y-Coordi-nate (Transformer Tap Setting)	Model Description and Function	Coefficients (with 95% confidence bounds)	y-Coordinate Minimum and Maximum
1	RPTL	T1	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.002499, p2= 0.140, p3 =-2.617, p4 = 17.31	Min=1.0250 Max=1.0875
2	RPTL	T2	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.002825,p2=0.1553, p3 = -2.851, p4 = 18.42	Min=0.9250 Max=1.0000
3	RPTL	T3	Linear model Poly3:f(x) = p1*x^3 + p2*x^2 + p3*x + p4	p1=-0.0009154, p2= 0.0598 p3 =-1.274 p4 = 9.842	Min=0.9500 Max=1.0625
4	RPTL	T4	Linear model Poly3:f(x)= p1*x^3 + p2*x^2 + p3*x + p4	p1 =0.001022, p2 =-0.0461 p3 = 0.6604, p4 = -1.941	Min=0.9500 Max=1.0125

Table 5. Curve fitting parameter of decision variables (reactive power output of 2 VAR source) vs. RPTL

Sl. No	x-Coor di- nate	y-Coordinate (Reactive Power Output)	Model Description and Function	Coefficients (with 95% confidence bounds)	y-Coordinate Minimum and Maximum
1	RPTL	Qc1	Linear model Poly1:f(x) = p1*x + p2	p1 = -0.279 p2 = 9.527	Min=3.00 Max=5.00
2	RPTL	Qc2	Linear model Poly3:f(x)= p1*x^3 + p2*x^2 + p3*x + p4	p1 =-0.1323 p2 =7.405 p3 = -137.5 p4 = 850.6	Min=2.00 Max=5.00

Table 6. Further analysis of all solution in terms of minimum & maximum load bus voltage deviation and transmission line having minimum & maximum power loss

Sol. No.	Minimum Load Bus Voltage Deviation	Load Bus Number with Minimum Voltage Deviation	Maximum Load Bus Voltage Deviation	Load Bus Number With Maximum Voltage Deviation	Minimum Individual Line Loss	Line Number having Minimum Individual Line Loss	Maximum Individual Line Loss	Line No. having Maximum Individual Line Loss
1	0.0002	28	0.0179	30	8.1472e-05	11	5.7644	1
2	0.0254	30	0.0752	3	9.0579e-05	11	4.8342	1
3	0.0254	30	0.0752	3	1.2698e-05	11	4.8342	1
4	0.0002	14	0.0162	30	9.1337e-05	11	5.6397	1
5	0.0002	29	0.0201	27	6.3235e-05	12	5.2694	1
6	0.0001	17	0.0183	30	9.7540e-06	11	5.5369	1
7	0.0005	6	0.0196	30	2.7849e-05	12	5.5325	1
8	0.0006	25	0.0216	30	5.4688e-05	13	5.6503	1
9	0.0008	23	0.0705	3	9.5750e-05	11	4.6984	1
10	0.0002	9	0.0639	3	9.6488e-05	11	4.7172	1
11	0.0230	30	0.0742	3	1.5761e-05	12	4.8391	1
12	0.0196	30	0.0710	3	9.7059e-05	11	4.6906	1
13	0.0004	14	0.0176	27	9.5716e-05	11	5.2420	1
14	0.0009	21	0.0572	3	4.8537e-05	11	4.9623	1

15	0.0004	9	0.0269	3	8.0028e-05	11	5.0589	1
16	0.0006	17	0.0466	3	1.4188e-05	14	4.8003	1
17	0.0080	30	0.0714	3	4.2176e-05	12	4.6911	1
18	0.0002	9	0.0569	3	9.1573e-05	11	4.6988	1
19	0.0009	24	0.0293	3	7.9220e-05	11	4.9297	1
20	0.0000	17	0.0246	3	9.5949e-05	11	5.0192	1
21	0.0090	30	0.0707	3	6.5574e-05	12	4.6904	1
22	0.0001	9	0.0499	3	3.5711e-06	11	4.7248	1
23	0.0005	15	0.0311	3	8.4912e-05	11	4.9225	1
24	0.0003	15	0.0180	12	9.3399e-05	12	5.1726	1
25	0.0000	24	0.0383	3	6.7873e-05	11	4.8257	1
26	0.0242	30	0.0746	3	7.5774e-05	11	4.8378	1
27	0.0025	26	0.0695	3	7.4313e-05	11	4.6977	1
28	0.0058	30	0.0708	3	3.9222e-05	11	4.6928	1
29	0.0005	19	0.0671	3	6.5547e-05	11	4.7066	1
30	0.0069	30	0.0711	3	1.7118e-05	11	4.6919	1
31	0.0034	30	0.0704	3	7.0604e-05	11	4.6942	1
32	0.0002	19	0.0670	3	3.1832e-06	11	4.7106	1
33	0.0001	24	0.0411	3	2.7692e-05	11	4.8163	1
34	0.0005	9	0.0342	3	4.6171e-06	11	4.9065	1
35	0.0000	29	0.0356	3	9.7131e-06	12	4.9028	1
36	0.0004	30	0.0669	3	8.2345e-05	11	4.7059	1
37	0.0003	9	0.0228	3	6.9482e-05	11	5.1490	1
38	0.0107	30	0.0715	3	3.1709e-05	11	4.6879	1
39	0.0017	26	0.0704	3	9.5022e-05	11	4.6936	1
40	0.0005	23	0.0436	3	3.4446e-06	11	4.8074	1
41	0.0203	30	0.0784	3	4.3874e-05	11	4.8200	1
42	0.0011	30	0.0668	3	3.8155e-05	11	4.7067	1
43	0.0006	15	0.0522	3	7.6551e-05	11	4.7200	1
44	0.0010	9	0.0506	3	7.9519e-05	11	4.7194	1
45	0.0000	15	0.0414	3	1.8687e-05	11	4.8201	1
46	0.0145	30	0.0684	3	4.8976e-05	11	4.7004	1
47	0.0001	24	0.0187	27	4.4558e-05	11	5.1653	1
48	0.0008	29	0.0530	3	6.4631e-05	12	4.7143	1
49	0.0007	15	0.0561	3	7.0936e-05	11	4.7054	1
50	0.0011	29	0.0208	3	7.5468e-05	11	5.1526	1

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