An Interactive Fuzzy Satisfying Method Based on Particle Swarm Optimization for Multi-Objective Function in Reactive Power Market

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Abstract: Reactive power plays an important role in supporting real power transmission, maintaining system voltages within proper limits and overall system reliability. In this paper, the production cost of reactive power, cost of the system transmission loss, investment cost of capacitor banks and absolute value of total voltage deviation (TVD) are included into the objective function of the power flow problem. Then, by using particle swarm optimization algorithm (PSO), the problem is solved. The proposed PSO algorithm is implemented on standard IEEE 14-bus and IEEE 57-bus test systems and with using fuzzy satisfying method the optimal solutions are determined. The fuzzy goals are quantified by defining their corresponding membership functions and the decision maker is then asked to specify the desirable membership values. The obtained results show that solving this problem by using the proposed method gives much better results than all the other algorithms.

Keywords: Reactive power market; Particle swarm optimization; Total voltage deviation; Fuzzy satisfying method.

1. Introduction

Reactive power dispatch problem is impressive on safe and economical operation of power systems. In fact, it plays an important role for secure operation of power systems. For this reason, the reactive power dispatch has been of great interest to researchers as well as system operators, especially after the restructuring of the power industry [1]. This interest is mainly because of the significant effect that reactive power has on system security given its close relationship with the bus voltages throughout the power network [2]. Traditionally, reactive power dispatch has always been viewed by researchers as a power loss minimization problem, subject to different system constraints such as nodal real and reactive power balance, power generation limits and bus voltage limits [2, 3]. Multi-objective optimization models have also been presented for the reactive power dispatch problem. In these models, the reactive power dispatch includes simultaneous minimization of transmission loss, voltage stability index and voltage deviation [4-6]. In deregulated electricity markets, the independent system operator (ISO) is responsible for the provision of ancillary services that are necessary to support the transmission of electrical energy while maintaining secure and reliable operation of the power system [4]. In deregulated electricity markets, the reactive power ancillary services can be provided based on a two-stage approach, namely, reactive power dispatch and reactive power procurement [7]. In [8], the problem of reactive power procurement by an ISO in deregulated electricity markets has been presented. In [9], the technical and economic issues of determining reactive power pricing structures in an open-access environment have been examined. In the competitive electricity markets, the reactive power dispatch refers to short-term allocation of reactive power needed from generators, based on current system operating conditions. The independent system operator's problem is to specify the optimal reactive power schedule for all providers based on a given objective that depends on system operating condition. The ISO can use different objective functions besides the traditional transmission loss minimization such as minimization of deviations from contracted transactions [10] or minimization of reactive power cost [11, 12]. In [13], an interactive fuzzy satisfying method based on evolutionary programming technique is proposed for economic emission load dispatch of

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thermal plants with non-smooth fuel cost and emission level functions in coordination with multi-reservoir cascaded hydro plants. An interactive fuzzy satisfying method for solving an economic emission load dispatch problem is presented in [14].

In this paper, a new framework that defines the reactive power dispatch problem to suit the ISO requirements in the competitive electricity markets is proposed. The model seeks to minimize the ISO's total payments that include payments for improving TVD, reactive power dispatched from service providers and payments associated with the increase in total system losses. Interactive fuzzy satisficing method for multi-objective nonlinear programming is presented, by considering that the decision maker has fuzzy goals for each of the objective functions. After determining the membership functions for each of the objective functions the completed max (min) problem is solved, and the decision maker is supplied with the corresponding Pareto optimal solution and the trade-off rates between the membership functions. The rest of the paper is organized as follows: The mathematical formulation of the reactive power pricing and TVD cost is presented. Then, a brief overview of the PSO algorithm is described. In finally, the simulation results are presented and discussed.

2 Problem formulation

In this paper, the objective function consist of two function. The first objective function is to minimize the system active power loss and overall production cost of reactive power which includes reactive power production cost of generators and capital cost of capacitors. The second objective function is to improve the voltage profile.

2.1 First Objective Function

2.1.1 Cost of System Transmission Loss

The reactive support will affect the transmission loss. The cost function of transmission loss and P_{Loss} are considered as follows:

$$\mathrm{C}(\mathrm{P}_{Loss}) = \lambda \times \mathrm{P}_{Loss} \tag{1}$$

$$\mathrm{P}_{Loss} = \sum_{k=1}^{N_{TL}} G_k (V_i^2 + V_j^2 - 2V_iV_j \cos\alpha_{ij}) \tag{2}$$

where λ is price of electricity; P_{Loss} is the total active power loss; G_k is the conductance of the kth branch connected between the ith and the jth bus; N_{TL} is number of transmission lines; V_i, V_j are the voltage magnitude of the ith and the jth bus, respectively; α_{ij} is the admittance angle of the transmission line connected between the ith and the jth bus.

2.1.2 Cost of Generator's Reactive Power

The generators provide reactive support by consuming or producing reactive power when operating at leading or lagging power factors, respectively. The production of reactive power may require a decrease of real power output. Opportunity cost is the lost benefit of this decrease of real power output of the generator. Opportunity cost depends on supply and demand in market, so it is hard to determine its exact value. Hence, this paper considers the opportunity cost of generator reactive power production as modeled in [15]:

$$C(\mathrm{Q}_{Gi}) = k \times \left[C(S_{Gi,\max}) + C(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}) \right] \tag{3}$$

where k is the reactive power efficiency rate (usually between 5% and 10 %), $S_{Gi,\max}$ is the maximum apparent power in ith bus and Q_{Gi} the reactive power of generator in ith bus. In (3), $C(\mathrm{S}_{Gi,\max})$ and $C(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2})$ are obtained as follows:

$$C(\mathrm{S}_{Gi,\max}) = a + b\mathrm{S}_{Gi,\max} + cS_{Gi,\max}^2 \tag{4}$$

$$\begin{aligned} C(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}) &= a + b(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}) \\ &\quad + c(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2})^2 \end{aligned} \tag{5}$$

2.1.3 Cost of Capacitor Compensation

The charge for using capacitors is assumed proportional to the amount of the reactive power output purchased and can be expressed as [16]:

$$C_{Cj}(Q_{Cj}) = r_j\, Q_{Cj} \tag{6}$$

where r_j and Q_{Cj} are the reactive cost and amount purchased at location j, respectively. The production cost of the capacitor is assumed as its capital investment return, which can be expressed as its depreciation rate. For example, if the investment cost of a capacitor is 11600 \$/MVA, and their life span and average working rate are 15 years and 2/3, respectively, the cost or depreciation rate of the capacitor can be calculated by:

$$r_j = \frac{\text{investment cost}}{\text{operating hours}} = \frac{\$11600}{15 \times 365 \times 24 \times \frac{2}{3}} = \frac{\$0.1234}{MVAh} \tag{7}$$

Therefore, the first objective function is proposed as minimizing the summation of reactive power production costs, produced by generators and capacitor banks and cost of power loss as follows:

$$f_1 = \min \left[C(P_{loss}) + \sum_{i \in N_g} C(\mathrm{Q}_{Gi}) + \sum_{j \in Nc} C_{Cj}(\mathrm{Q}_{Cj}) \right] \tag{8}$$

where Ng is the number of generators, N_c the number of buses which capacitor banks are installed.

2.2 Second Objective Function

2.2.1 Improvement of Voltage Profile

Treating the bus voltage limits as constraints in reactive power dispatch often results in setting all the voltages toward their maximum limits after optimization, which means the power system lacks the required reserves to provide reactive power during contingencies. One of the effective ways to avoid this situation is to choose the minimization of the absolute deviations of all the actual bus voltages from their desired voltages as an objective function. Minimization of TVD of load buses can allow the improvement of voltage profile [17]. This objective function can be formulated as follows:

$$f_2 = \min(TVD) = \min\left(\sum_{i\in N_L}\left|V_i - V_i^{ref}\right|\right) \quad (9)$$

where, V_i^{ref} is the desired voltage magnitude value at bus i which is usually set to 1.0 p.u.

2.3 Multi Objective Function

The proposed model seeks to minimize the following objective function *f:*

$$f = w\times\left(\frac{f_1}{f_{1base}}\right) + (1-w)\times\left(\frac{f_2}{f_{2base}}\right) \quad (10)$$

where w is weighted coefficient, f_{1base} and f_{2base} are base value of first and second objective function, respectively.

2.4 System Constraints

2.4.1 Equality Constraint

The reactive and real power balance equations are the equality constraints of optimal reactive power dispatch problem and are expressed as follows:

$$P_{G_i} - P_{D_i} - V_i\sum_{j=1}^{N_B} V_j[G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)] = 0; \quad (11)$$

$$for \quad \mathrm{i} = 1,...,\mathrm{N}_B$$

$$Q_{G_i} - Q_{D_i} - V_i\sum_{j=1}^{N_B} V_j[G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)] = 0 \quad (12)$$

$$for \quad \mathrm{i} = 1,...,\mathrm{N}_B$$

where G_{ij} and B_{ij} are the real and imaginary part of the *ij*th entry of the admittance matrix, respectively. P_{Di} and Q_{Di} are the active and reactive load demand of the ith bus, respectively. P_{Gi} and Q_{Gi} represent the active and reactive power generation of the *i*th bus, respectively. V_i, V_j are the voltage magnitude of the *i*th and the *j*th bus, respectively. θ_i and θ_j represent the phase angle of the *i*th and the *j*th bus voltages, respectively

2.4.2 Inequality Constraints

The reactive power source capacity restrictions, transformer tap setting limits, reactive generation restriction, bus voltage restriction and power flow through the transmission lines restriction are used as inequality constraints. In reactive power dispatch problem, the tap position of transformers, generator bus voltages and the amount of the reactive power source installations are the independent variables and these inequality constraints are mathematically expressed as [4]:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}; \qquad i = 1,...,N_G \quad (13)$$

$$Q_{C_i}^{\min} \le Q_{C_i} \le Q_{C_i}^{\max}; \qquad i = 1,...,N_C \quad (14)$$

$$T_i^{\min} \le T_i \le T_i^{\max}; \qquad i = 1,...,N_T \quad (15)$$

where $V_{G_i}^{\min}$ and $V_{G_i}^{\max}$ are the minimum and maximum generator voltage of the ith bus, respectively. $Q_{C_i}^{\max}$ and $Q_{C_i}^{\min}$ are the maximum and minimum reactive power injection of the ith shunt compensator, respectively. $T_i^{\max}$ and $T_i^{\min}$ are the maximum and minimum tap setting of the ith transmission line, respectively. N_T is the number of tap changing transformers and N_C is the number of shunt compensators. The reactive power output of generators, load voltages and transmission line loading are the dependent variables and they are restricted by their upper and lower limits as follows:

$$V_{L_i}^{\min} \le V_{L_i} \le V_{L_i}^{\max}; \qquad i = 1,...,N_L \quad (16)$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \qquad i = 1,...,N_G \quad (17)$$

$$|S_{L_i}| \le S_{L_i}^{\max}; \qquad i = 1,...,N_{TL} \quad (18)$$

where, $V_{L_i}^{\max}$ and $V_{L_i}^{\min}$ are the maximum and minimum voltage of the *i*th load bus, respectively. $Q_{G_i}^{\max}$ and $Q_{G_i}^{\min}$ are the maximum and minimum reactive power generation of the *i*th generator bus, respectively. $S_{L_i}^{\max}$ is the maximum apparent power flow in the *i*th line and N_L is the number of load buses.

2.5 Fuzzy Satisfying Method

Fuzzy satisfying (or max (min)) method is a popular technique for selection of the best solution among the obtained Np Pareto optimal solutions [18]. Suppose we have a problem with N objectives to be minimized. The linear membership function for the *n*-th solution of the *k*-th objective function is defined as:

$$\mu_k^n = \begin{cases} 1 & f_k^{\mathrm{n}} \le f_k^{\min} \\ \dfrac{f_k^{\max} - f_k^{\mathrm{n}}}{f_k^{\max} - f_k^{\min}} & f_k^{\min} \le f_k^{\mathrm{n}} \le f_k^{\max} \\ 0 & f_k^{\mathrm{n}} \ge f_k^{\max} \end{cases} \quad (19)$$

$$for \quad k = 1,...,N \;; n = 1,...,N_p$$

where $f_k^{\max}$ and $f_k^{\min}$ are maximum and minimum values of the objective function *k* in solutions of Pareto optimal set. μ_k^n represents the optimality degree of the *n*-th solution of the *k*-th objective function. The membership function of *n*-th solution can be calculated using the following equation:

$$\mu^n = \min(\mu_1^n,...,\mu_N^n); \quad for \quad n = 1,...,N_p \quad (20)$$

The solution with the maximum weakest membership function is the best solution. The corresponding membership function of this solution ($\mu^{\max}$), is calculated as follows:

$$\mu^{\max} = \max(\mu^1, ..., \mu^{N_P}) \quad (21)$$

3 Proposed Methodology

The PSO is one of the algorithms based on swarm intelligence and introduced by Kennedy and Eberhart in 1995 for the first time [19]. The PSO is based on swarm intelligence (SI) and models the swarm behaviors such as birds flocking and fishes schooling [20]. In PSO, the population is consisted from candidate solutions which called particles. In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. Each particle updates its position and velocity with the following equations:

$$X_i(t+1) = X_i(t) + \mathrm{C} \times V_i(t+1) \quad (22)$$

where $X_i(t)$ and $V_i(t)$ are vectors representing the position and velocity of the i-th particle, respectively and C is the constriction factor and can be calculated as follows:

$$C = \frac{2}{2 - \phi - \sqrt{\phi^2 - 4\phi}} \quad (23)$$

The velocity of every particle will be updated by using the following equation.

$$\begin{aligned} V_{ij}(t+1) = {} & \omega \times V_{ij}(t) + c_1 r_{1j} \times (pb_{ij} - X_{ij}(t)) \\ & + c_2 r_{2j} \times (gb_j - X_{ij}(t)) \end{aligned} \quad (24)$$

where $j \in 1, 2, \ldots$; d represents the dimension of the particle; w is inertia weight; c_1 and c_2 are cognitive and social component acceleration coefficients, respectively; r_{1j}, r_{2j} are two uniform random sequences sampled from [0, 1]; pb_{ij} is the personal best position found by the ith particle; gb_j is the best position found by the entire swarm so far and ϕ equals to C_1+C_2. The PSO has been proven to be very effective for static and dynamic optimization problems.

4 Simulation Results and Discussions

In this paper, the proposed method is applied to IEEE 14-and 57-bus standard test power systems for the solution of reactive power market problem. The proposed algorithm is implemented by using the MATLAB 7.0 software on a PC with Intel(R) Core(TM) i3-2330M CPU 2.20GHz 2GB RAM. Set population size of PSO is 100 and the number of maximum iterations is 1500.

4.1 IEEE 14-Bus System

The standard IEEE 14-bus system is consists of two generators (at the buses 1, 2), twenty transmission lines and three branches under load tap setting transformer branches. The possible reactive power compensation bus is 9. In this case, $f_{1\text{base}}$ and $f_{2\text{base}}$ are 1066.3 \$, 0.4036 p.u, respectively.

The proposed multi-objective function is solved by using PSO algorithm. Thus the Eq. (10) will be optimal for changes in w from zero to 1 in steps of 0.1 and present the set of solutions for f_1 and f_2. These solutions are called the set of Pareto optimal solutions. This set is non-convex solution in the all space search for f_1 and f_2 that between two different answers cannot prefer one over the other. The pareto diagram is shown in Fig. 1. For choosing the best solution from the Pareto diagram, the fuzzy satisfying method is used. The membership function for f_1 and f_2 are defined with using Eq. (19).

Table 1 Degree of optimization satisfaction for each solution.

W	F_1	F_2	μ_1	μ_2	Min (μ_1,μ_2)	F
0	1098.056	0.032905	0	0.999784	0	0.0815
0.1	1076.791	0.032898	0.347108	0.999813	0.347108	0.1743
0.2	1072.025	0.032853	0.424907	1	0.424907	0.2662
0.3	1068.659	0.033733	0.479856	0.996396	0.479856	0.3592
0.4	1060.966	0.035531	0.605418	0.989031	0.605418	0.4508
0.5	1059.805	0.035664	0.62437	0.988485	0.62437	0.5411
0.6	1057.284	0.036528	0.665521	0.984948	0.665521	0.6311
0.7	1052.662	0.039855	0.740971	0.97132	0.740971	0.7207
0.8	1044.371	0.04827	0.876309	0.936854	0.876309	0.8075
0.9	**1042.776**	**0.051624**	**0.902337**	**0.923114**	**0.902337**	0.8930
1	1036.793	0.276999	1	0	0	0.9723

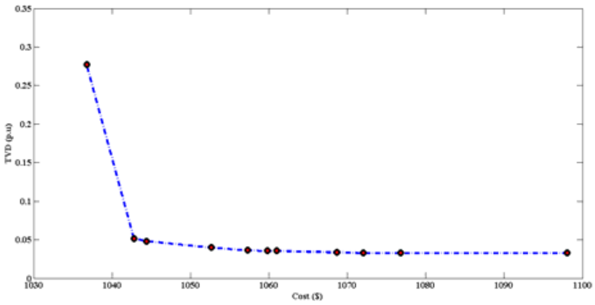

Fig. 1 The Pareto optimal front of case 1.

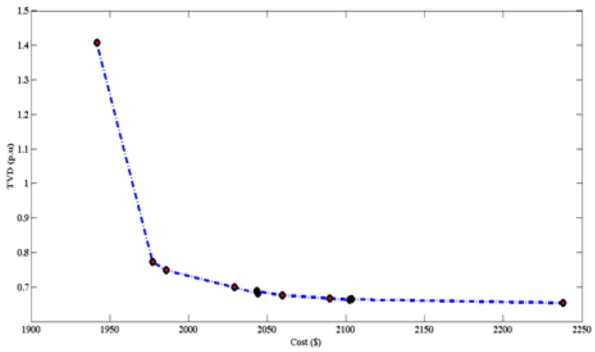

Fig. 2 The Pareto optimal front of case 2.

The set of solutions for f_1, f_2 and its membership functions (μ_1, μ_2) are presented in Table 1. The minimum value of the membership function for each of the functions f_1 and f_2, for changes in w are located in the last column (min (μ_1, μ_2)). With using fuzzy satisfying method, the reported maximum value for min (μ_1, μ_2) in last column Table.1 is chosen as Pareto optimal solutions. In this case, the optimal solution is obtained for w = 0.9. The optimal solution for f_1, f_2 and its related control variables such as generator voltage, transformers tap, shunt capacitor are presented in Table 2. If the goal is to optimize the function f_1, the optimal value is 1036.793 $ for the control variables listed in the first column of Table 2.

If the goal is to optimize the function f_2, the optimal value is 0.032853 for the control variables listed in the third column of Table 2. In latest column, the optimal solutions are presented for multi objective function. According this table, the obtained best solutions for f_1 and f_2 are 1042.776 $ and 0.051624, respectively.

4.2 IEEE 57-Bus System

The standard IEEE 57-bus system consists of seven generators (at the buses 1, 2, 3, 6, 8, 9, 12), eighty transmission lines and fifteen branches under load tap setting transformer branches. The possible reactive power compensation buses are 18, 25 and 53. In this case, f_{1base} and f_{2base} are 2290.5 $ and 1.23358 p.u, respectively.

The PSO is used for solving the proposed multi-objective function and the Pareto optimal front of the solutions is obtained as depicted in Fig. 2. The selection of final solution using fuzzy satisfying approach is the next step after finding the Pareto optimal front. The attributes of Pareto optimal front solutions are described in Table 3. The set of solutions for f_1, f_2, its membership functions (μ_1, μ_2) and min (μ_1, μ_2) for different value of w are presented in Table 3. With using fuzzy satisfying method, the optimal solution is obtained in $w = 0.8$. The simulation results for best solution are shown in Table 4. In Table 4, if the goal is to optimize the function f_1, the optimal value is 1941.883 $ and if the goal is to optimize the function f_2, the optimal value is obtained 0.654755. The optimum values for the functions f_1, f_2 for reported control variables are presented in columns 2 and 3, respectively. In latest column for $w = 0.8$, the optimal solutions are presented for multi objective function.

Table 2 Simulation results for best solutions.

Variable	Best Solution f_1	Best Solution f_2	Best Solution f_1, f_2
V_{g1}	1.06	1.052664	1.06
V_{g2}	1.033868	1.025698	1.031676
V_{g3}	1.001915	0.99792	0.997176
V_{g6}	1.052732	1.01617	1.015255
V_{g8}	1.06	1.040474	1.027915
Q_{C-9}	20	19.90485	19.99998
T_{4-7}	1.012405	1.052156	1.05129
T_{4-9}	0.917797	0.955883	0.935949
T_{5-6}	0.97071	0.941708	0.995997
f_1 ($)	**1036.793**	1072.025	**1042.776**
f_2	0.276999	**0.032853**	**0.051624**

5 Conclusions

In the study of the reactive power marginal price in this paper, the reactive power production costs of generators and capital cost of capacitors and improvement of voltage profile are considered in the objective function of power flow problem. In this paper, interactive fuzzy satisficing method using the completed max (min) problems has proposed in order to deal with the fuzzy goals of the decision maker in the nonlinear multi-objective function. In this interactive scheme, after determining the membership functions, the satisficing solution of the decision maker can be derived by updating desire membership values based on the current values of the membership functions together with the trade-off rates between the membership functions. In this way the satisficing solution for the decision maker can be derived efficiently from among a Pareto optimal solution set by updating desire membership values. The PSO algorithm is used to find the optimal solution of multi-objective function. The validity and effectiveness of the proposed method is verified by using standard IEEE 14-bus and IEEE 57-

bus test systems. In case 14 bus IEEE, the optimal solution for f_1 and f_2 are 1036.793 $ and 0.032852, respectively and in case 57 bus IEEE, the optimal solution for f_1 and f_2 are 1941.883 $ and 0.654755, respectively.

Table 3 Degree of optimization satisfaction for each solution.

W	F_1	F_2	μ_1	μ_2	Min (μ1,μ2)	F
0	2237.93	0.654755	0	1	0	0.5308
0.1	2103.719	0.664024	0.453345	0.987681	0.453345	0.5765
0.2	2102.351	0.663245	0.457965	0.988717	0.457965	0.6137
0.3	2089.698	0.667233	0.500706	0.983416	0.500706	0.6523
0.4	2059.707	0.676571	0.60201	0.971006	0.60201	0.6888
0.5	2043.271	0.68815	0.657529	0.955618	0.657529	0.7250
0.6	2043.994	0.682094	0.655084	0.963665	0.655084	0.7566
0.7	2029.248	0.699465	0.704894	0.94058	0.704894	0.7903
0.8	1985.919	0.748531	0.851254	0.87537	0.851254	0.8150
0.9	1977.081	0.773094	0.881106	0.842725	0.842725	0.8395
1	1941.883	1.407192	1	0	0	0.8478

Table 4 Simulation results for best solutions.

Variable	best solution f_1	best solution f_2	best solution f_1,f_2	Variable	best solution f_1	best solution f_2	best solution f_1,f_2
V_{g1}	1.06	1.022514	1.059988	T_{24-26}	1.017409	1.022796	1.014052
V_{g2}	1.046039	1.012991	1.044811	T_{7-29}	0.96838	0.972687	0.990876
V_{g3}	1.031246	1.009927	1.024266	T_{34-32}	0.955393	0.914785	0.920572
V_{g6}	1.03262	1.003644	1.02303	T_{11-41}	0.9	0.900045	0.900011
V_{g8}	1.048799	1.024095	1.04425	T_{15-45}	0.963377	0.928063	0.960362
V_{g9}	1.018029	1.000171	1.012185	T_{14-46}	0.941262	0.974093	0.963993
V_{g12}	1.029363	1.027875	1.021856	T_{10-51}	0.948651	0.991565	0.982757
Q_{C-18}	9.999947	0.651221	9.999946	T_{13-49}	0.914764	0.900006	0.930357
Q_{C-25}	9.999907	9.829612	9.99997	T_{11-43}	0.944944	0.960299	0.949666
Q_{C-53}	9.999558	9.999987	9.999796	T_{40-56}	1.002773	0.981544	1.018516
T_{4-18}	0.995282	0.918137	0.978692	T_{39-57}	0.967004	0.907058	0.934752
T_{4-18}	0.948161	1.02145	1.019304	T_{9-55}	0.958117	0.970306	0.983156
T_{21-20}	1.008664	0.976592	0.985388	f_1 (\$)	**1941.883**	2237.93	**1985.919**
				f_2	1.407192	**0.654755**	**0.748531**

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