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Hybrid Tabu search-simulated annealing method to solve optimal reactive power problem

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ABSTRACT

Reactive power optimization problem has a substantial inspiration on secure and economic operation of power system. In this work we utilized Hybridized Tabu Search-Simulated Annealing (HTSSA) algorithm to solve reactive power problem. At first both the algorithm separately solved the reactive power problem, then hybridization has been done and the hybridized algorithm has been utilized to solve the reactive power problem. Detailed comparisons have been done between three modes. The validity of the proposed algorithm has been tested in standard IEEE 30 bus system. And the results show the proposed algorithm HTSSA efficiently solved the reactive power problem. Simulation results clearly show that real power loss considerably reduced and voltage profiles also within the limits.

Introduction

The key objective of reactive power dispatch problem is to reduce the real power loss and to keep the voltage profiles within the specified limits. Various numerical methods like the gradient method [1,2], Newton method [3] and linear programming [4–7] have been utilized to solve the optimal reactive power dispatch problem. The problem of voltage stability and collapse play a key role in power system planning and operation [8]. In [9], an improved evolutionary programming is used to solve the optimal reactive power dispatch problem. In [10], the optimal reactive power flow problem is solved by integrating a genetic algorithm with a nonlinear interior point method. In [11], a programming based approach is used to solve the optimal reactive power dispatch problem. In [12], A. Kargarian et al present a probabilistic algorithm for optimal reactive power provision in hybrid electricity markets with uncertain loads. This paper weights hybridization of both the algorithms to obtain better results. Goodness of the algorithms is used for proposed HTSSA. The results of all three algorithms are obtained and analyzed. These algorithms are tested on standard IEEE30-bus system and results obtained from HTSSA show better performance than the parent algorithms. Simulation study show the better performance of the proposed algorithm in reducing the real power loss and also profiles are within the limits.

Problem formulation

Reactive power problem has been formulated in two modes. In first mode of problem formulation penalty has not been included and the second mode of problem formulation includes penalty. Both the cases have different augmented objective function. But the equality constraints, inequality constraints and control variables remains the same.

Objective function

The objective function of this problem is to find the optimal settings for reactive power control variables which minimize the function.

(a) Without penalty [13]:

The objective function without penalty is expressed as,

$$f = (w * P_l) + (1 - W) * VD \tag{1a}$$

P_l – real power loss of the system,
VD – load bus voltage deviations,
W – Weighting factor and is set to 0.69.

(b) With penalty [14]:

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The objective function describes the fitness value of the system with quadratic penalties. Where k_1, k_2, k_3, k_4 are chosen to be around 10 (from trial and error method),

$$f = (w * P_l) + (1 - w) * VD + k_1 \sum_{i=1}^{nl} L_i^2 + k_2 \sum_{i=1}^{npq} V_i^2 + k_3 \sum_{i=1}^{npv} Q_i^2 + k_4 P_{sl}^2 \tag{1b}$$

where
w – Weighing factor and is set to 0.7,
P_l – real power losses,
VD – voltage deviation of the load buses,
L_i – sum of thermal limit violation of all lines,
V_i – sum of voltage limit violation of all load buses,
Q_i – sum of reactive power limit violation of all generating buses,
P_{sl} – slack bus real power limit violation,
nl – total number of branches (lines),
npq – total number of load buses,
npv – total number of generator buses.

$$L_i = \begin{cases} L_i - L_i^{max}, & if\ L_i > L_i^{max}; \\ L_i^{min} - L_i, & if\ L_i < L_i^{min}; \\ else & 0; \end{cases}$$

$$V_i = \begin{cases} V_i - V_i^{max}, & if\ V_i > V_i^{max}; \\ V_i^{min} - V_i, & if\ V_i < V_i^{min}; \\ else & 0; \end{cases}$$

$$Q_i = \begin{cases} Q_i - Q_i^{max}, & if\ Q_i > Q_i^{max}; \\ Q_i^{min} - Q_i, & if\ Q_i < Q_i^{min}; \\ else & 0; \end{cases}$$

$$P_{sl} = \begin{cases} P_{sl} - P_{sl}^{max}, & if\ P_{sl} > P_{sl}^{max}; \\ P_{sl}^{min} - P_{sl}, & if\ P_{sl} < P_{sl}^{min}; \\ else & 0; \end{cases}$$

(i) Real power loss minimization (P_l)

The total real power of the system is given in Eq. (2)

$$P_l = \sum_{k=1}^{N_l} G_k (V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)) \tag{2}$$

where N_l – total number of transmission lines in the system; G_k – conductance of the line k; V_i and V_j are the magnitudes of the sending end and receiving end voltages of the line; δ_i and δ_j are angles of the end voltages.

(ii) Load bus Voltage deviation minimization (VD)

Bus voltages magnitudes are maintained within the allowable limit to ensure quality service. As shown in Eq. (3) below, voltage profile is improved by minimizing the deviation of the load bus voltage from the reference value and it is taken as 1.0 p.u.

$$VD = \sum_{k=1}^{N_{pq}} |(V_k - V_{ref})| \tag{3}$$

Constraints

The minimization problem is subjected to the equality and inequality constraints as follows.

Equality constraints:

Load flow constraints:

The real and reactive power constraints are according to Eqs. (4) and (5) respectively as given below:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \cos(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{4}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_{ij} Y_{ij} \sin(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{5}$$

Inequality constraints:

Generator bus voltage (V_{Gi}) inequality constraint:

$$V_{Gi}^{min} \leqslant V_{Gi} \leqslant V_{Gi}^{max}, i\varepsilon ng \tag{6}$$

Load bus voltage (V_{Li}) inequality constraint:

$$V_{Li}^{min} \leqslant V_{Li} \leqslant V_{Li}^{max}, i\varepsilon nl \tag{7}$$

Switchable reactive power compensation (Q_{Ci}) inequality constraint:

$$Q_{Ci}^{min} \leqslant Q_{Ci} \leqslant Q_{Ci}^{max}, i\varepsilon nc \tag{8}$$

Reactive power generation (Q_{Gi}) inequality constraint:

$$Q_{Gi}^{min} \leqslant Q_{Gi} \leqslant Q_{Gi}^{max}, i\varepsilon ng \tag{9}$$

Transformer tap setting (T_i) inequality constraint:

$$T_i^{min} \leqslant T_i \leqslant T_i^{max}, i\varepsilon nt \tag{10}$$

Description of algorithms

Tabu search

Tabu search (TS), which was firstly developed by Glover [15–17]. Neighborhood explorations take a potential solution to a problem and authenticate its instantaneous local opportunities, which is, solutions that are similar except for one or two minor details to recognize a better-quality solution. Local search methods incline to become stuck in suboptimal regions. Tabu search takes advantage of the performance of these tactics by using memory structures, which elucidate the visited solutions. If a potential solution has been already visited within a certain short-term period or if it has already violated a rule, it is marked as "tabu" (forbidden) so that the algorithm would not reconsider that possibility.

1. Arbitrarily develop an initial solution.
2. Calculate neighborhood.
3. Choose a candidate move.
4. Is candidate tabu? If yes then go to step 4a or go to step 5.
   4a. Will solution be the absolute best? Or go to step 4b.
   4b. Reject candidate move and adjust the neighborhood then go to step 3.
5. Update solution by incorporating the candidate move, set z value
6. Have we reached the stopping criteria?
   6a. if yes – Stop and report the best solution found during search.
   6b. if no – go to step 2.

Tabu search Algorithm for reactive power problem

Step 1. Let S be the preliminary feasible solution and Z its objective function value; then, set $S^* = S$, $Z^* = Z$, max short-term memory (STM) = 5, and max iteration = 1000; iter = 1. Best O value = O value.

Step 2. Arbitrary (i, j) = rand/Long-term memory (LTM) (i, j), $(n1, n2)$ = the indices of maximum value in arbitrary.

Step 3. If there is none $(n1, n2)$ in STM matrix, alter $n1$ and $n2$ locations; or else, repeat step 2.

Step 4. Inset $n1$ and $n2$ in STM and release the last indices from STM (e.g., $m1$, $m2$); and LTM($m1$, $m2$) = LTM($m1$, $m2$) + 1.
Step 5. Compute the objective function value (Z) of the new permutation.
Step 6. If $Z \leqslant Z^*$, then $Z^* = Z$, $S^* = S$, and iter = iter + 1.
Step 7. If iter $\leqslant$ max iteration, then replicate step 2; or else, print Z^* and S^*.

Simulated annealing

Simulated annealing (SA) is a standard probabilistic meta-heuristic for combinatorial optimization problem of locating a good guesstimate to the global optimum of a given function in an attractive great exploration space. For certain problems, SA may be more competent than exhaustive enumeration rather than the finest possible solution. Paul [18] reported that for a number of varied problem instances, SA could perform better for higher quality targets while TS performs better for lower quality targets.

1. Set initial temperature; arbitrarily develop an initial solution.
2. Arbitrarily choose unit and period of harvest to change in current solution.
3. Is proposed solution better than current solution?
   3a. If yes – then iterations = iterations + 1; total iterations = total iterations + 1.
   3b. If no – then calculate acceptance value – if solution accepted, Then move to step 3a or go to step 2.
4. Current solution = proposed solution.
5. Is Time to change temperature?
   5a. if yes then – new temperature = old temperature x temperature reduction factor.
   5b. if no then go to step – 2.
6. Have we reached the stopping criteria?
   6a. if yes – Stop and report the best solution found during search.
   6b. if no – go to step 2.

Simulated annealing algorithm for reactive power problem

$s \leftarrow$ Create Initial Solution()
$T \leftarrow T_0$
while end conditions not met **do**
$s' \leftarrow$ Pick At Arbitrary ($N(s)$)
if (f (s') < f (s)) **then**
$s \leftarrow s'$
else
Admit s' as new-fangled solution with possibility p (T, s', s)
end if
Modernize (T)
end while

Hybridized Tabu Search – Simulated Annealing Algorithm (HTSSA) for solving reactive power problem

Both the simulated annealing and tabu search algorithms has been hybridized. Step 1 to step 6 main part of hybridization to handle the reactive power problem.

step 1:
Set S as preliminary solution and z-evaluate objective function
step 1. 3: $S^* = S$ and $Z^* = Z$;
STM = 5;// max short-term memory
Max iteration = 1000; iter = 1; best value O = O value
step 2: randomize
step 2.1: for i = 1 to n do
for j = 1 to n do
ARBITRARY (i,j) = rand/LTM;
step 2.2: (i,j) and ($n1$,$n2$) = index of (ARBITRARY $\in$ STM);
step 3: T = 0;
for i = 1 to size(STM,1) do
for j = 1 to size(STM,2) do;
if(($n1$,$n2$) == STM(i,j))
T = 1; reiterate Step 2
if(T = 0)
{
temp = n1;
n1 = n2;
n2 = temp
}
step 4:
$m1$ = size(STM,1);
$m2$ = size(STM,2);
($n1$,$n2$) = STM($m1$,$m2$);
LTM($m1$,$m2$) = LTM($m1$,$m2$) + 1;
step 5: z = calculate objective function;
step 6:
if(z <= z^*); $z^* = z$
{
$S^* = S$;
iter = iter + 1
}
step7: if (iter <= max iteration); repeat step 2; else print z^* and S^*

Simulation study

All the three algorithms are tested on a standard IEEE 30 bus system using MATLAB. MATPOWER [19] is open-source Matlab power system simulation software. And the results are proposed. The system has 6 generating buses 1, 2, 5, 8, 11 and 13. The transformer tap settings were made at 4 lines and shunt capacitors are added at 9 buses. The limits for the generator voltages are (0.9–1.1) p.u, tap settings are (0.9–1.1) p.u and shunt capacitors are (0–10) MVARs. The test is performed with 50 agents and maximum number of iterations is set to 500. The initial value settings are listed below in Table 1.

Case 1:

The values obtained for the first objective function without penalty are tabulated below and HTSSA shows the best optimal solution. Hence, in this case it is proved from Table 2 that the values obtained from hybrid HTSSA have best results when compared to TS and SA.

Table 1
Initial Parameter Settings.

S. no	Control variables	Initial value
1.	VG1	1.04
2.	VG2	1.05
3.	VG5	1.01
4.	VG8	1.01
5.	VG11	1.04
6.	VG13	1.04
7.	T6-9	1.074
8.	T6-10	1.060
9.	T4-12	1.029
10.	T27-28	1.061
11.	Q10	0
12.	Q12	0
13.	Q15	0
14.	Q17	0
15.	Q20	0
16.	Q21	0
17.	Q23	0
18.	Q24	0
19.	Q29	0

Table 2
Comparative results for case without penalty.

S. no	Control Variables	TS	SA	HTSSA
1.	VG1	1.10	1.0540	1.0989
2.	VG2	1.0960	1.0452	1.0909
3.	VG5	1.0668	1.0217	1.0712
4.	VG8	1.0719	1.0260	1.0720
5.	VG11	1.0069	1.0090	0.9860
6.	VG13	1.0171	1.0205	0.9919
7.	T6-9	0.9350	1.0116	1.0789
8.	T6-10	1.0789	0.9909	1.10
9.	T4-12	1.0209	1.0019	1.0972
10.	T27-28	1.0025	0.9982	1.0070
11.	Q10	2.2550	5.0831	6.5192
12.	Q12	5.7681	4.8110	6.4310
13.	Q15	9.5011	5.0361	6.5252
14.	Q17	5.6932	5.2111	6.2979
15.	Q20	3.5626	5.4534	6.5414
16.	Q21	5.8532	5.7186	6.5428
17.	Q23	10	6.2461	6.3896
18.	Q24	5.9091	4.7716	6.5343
19.	Q29	3.1204	6.1471	6.4932
20.	Fitness	3.6901	3.6449	3.3779
21.	Power loss	4.9820	5.2069	4.8259
22.	*VD*	0.67501	4.42e−07	0.0012
23.	Time	8.30	485	321

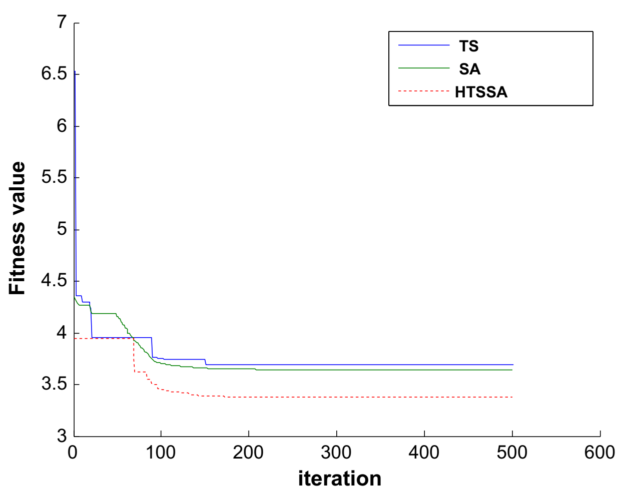

Fig. 1. Fitness value convergence characteristics.

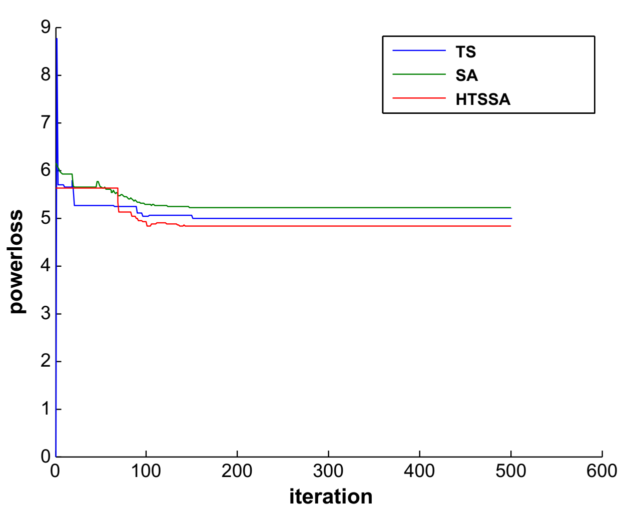

Fig. 2. Real power loss characteristics.

The below graph in Fig. 1 shows the convergence of the fitness values with respect to number of iterations. The HTSSA has the best convergence criteria.

The real power loss for the given case is shown in the below graph Fig. 2. It also proves that the HTSSA algorithm converges at lesser real power loss providing reactive power optimization.

The voltage deviation (*VD*) seems to be reduced for the hybrid algorithm and provides a good voltage profile in all load buses. Fig. 3 shows the voltage deviation characteristics of all three algorithms.

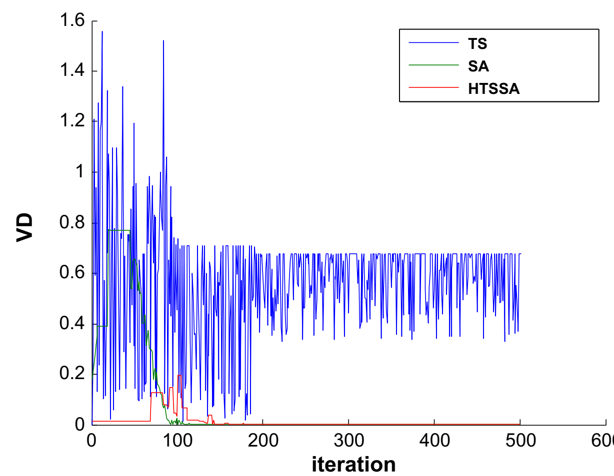

Fig. 3. Voltage deviation characteristics.

Case 2:

For the second case objective function with penalties considered the following Table 3 shows the same results proving that the hybrid algorithm is the best. Since it converges with minimum

Table 3
Comparative results for case with penalty.

S. no	Control variables	TS	SA	HTSSA
1.	VG1	0.9279	1.0169	1.0981
2.	VG2	0.9320	1.0104	1.0911
3.	VG5	0.9651	0.9864	1.0706
4.	VG8	0.9691	0.9961	1.0724
5.	VG11	0.9943	1.0485	1.0336
6.	VG13	1.0061	1.0433	1.0114
7.	T6-9	1.0561	0.9872	1.1001
8.	T6-10	0.9810	0.9822	1.0341
9.	T4-12	1.0901	0.9924	1.0711
10.	T27-28	0.9720	0.9930	1.0081
11.	Q10	1.0971	5.0722	3.8733
12.	Q12	5.5104	4.7569	3.7028
13.	Q15	9.2729	4.9742	2.5676
14.	Q17	5.0224	5.1915	2.8843
15.	Q20	3.6782	5.3684	3.5076
16.	Q21	5.7611	5.6145	3.1192
17.	Q23	9.6331	6.0504	3.4102
18.	Q24	5.0891	4.7984	3.1935
19.	Q29	2.3169	6.0770	3.6931
20.	Fitness	9.5654^{e+03}	3.9960	3.3791
21.	Power loss	8.2068	5.6461	4.8265
22.	*VD*	1.6611	0.1170	0.0020
23.	Time	6.6769	235.969	244.08
24.	Penalty line	0	0	0
25.	Penalty volt	0.0269	3.1440^{e-04}	0
26.	Penalty reactive	954.9137	0	0
27.	Penalty slack	0	0	0

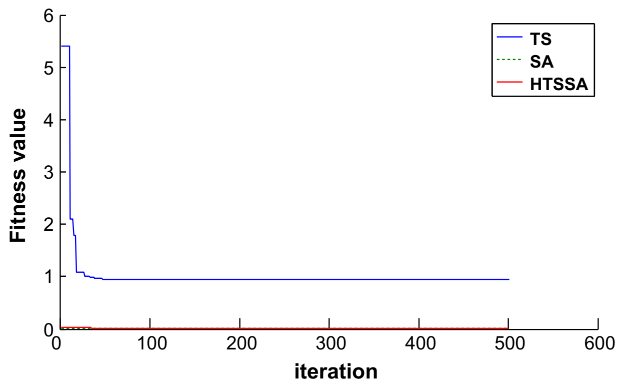

Fig. 4. Fitness value convergence.

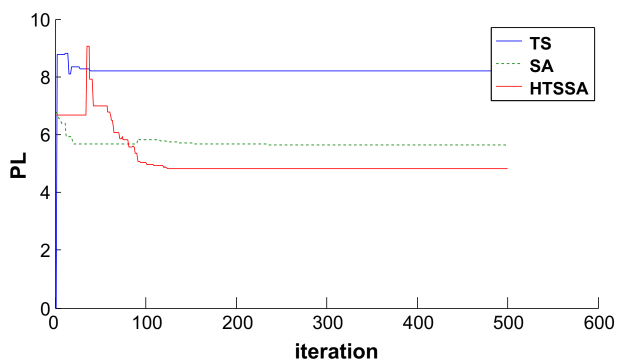

Fig. 5. Power loss curves.

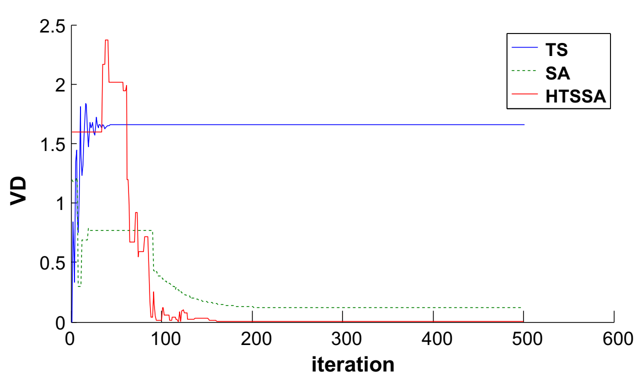

Fig. 6. Voltage deviation characteristics.

values of fitness value, power loss and voltage deviations. Zero penalty of the algorithm proves its reliability.

The following graph in Fig. 4 is the fitness value convergence characteristics. Here the TS algorithm has higher value of reactive power penalty and the other algorithms have less penalty or zero penalty.

The power loss (PL) curves for the case is shown in Fig. 5 and hybrid algorithm shows the best optimal results.

The voltage deviations (*VD*) for the case are also low for hybrid algorithm as shown in Fig. 6.

Thus on the whole by the analyzing the results it is obvious that the hybrid algorithm is the best for both the cases of the ORPD problems.

Conclusion

Thus both the objective functions are successfully tested over the standard IEEE 30 bus system. This paper has hence achieved the following conclusions-proposed HTSSA algorithm has the best results than TS and SA algorithms. And also it converges at a faster rate. Global best optimal values are obtained from the HTSSA algorithm. Mainly real power losses are minimized to the maximum. Voltage profile of the system is well maintained within the limits. All the above results are proved using zero penalty values. Hence, reactive power problem is best solved using HTSSA algorithm and reactive power optimization is achieved. Future works may include the implementation of the algorithm for several other test systems and problems.

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