A GA/SA/TS-based reactive power optimization

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Reactive power optimization in power systems solved by adjusting generator voltages, transformer taps, and capacitors/reactors is a mixed integer nonlinear programming problem. Genetic Algorithm (GA), Simulated Annealing (SA) and Taboo Search (TS) are widely used to combinatorial optimization in recent years. Combining the advantages of individual algorithms, a hybrid GA/SA/TS algorithm to solve the reactive power optimization problem is proposed in this paper. An IEEE 30-bus power system has been used to test the proposed algorithm. Comparing the results of the proposed algorithm with GA, and GA/SA show that the proposed GA/SA/TS hybrid method has the strongest capability of finding global optimal solution within reasonable computing time.

ان آمثلة القدرة غير الفعالة في نظم القوى التي تعرف بعملية ضبط جهود المولدات ومغايرات الجهد بالمحولات وعدد وأماكن مكثفات القدرة أو ملفات الحث المضافة تعتبر إحدى صور البرمجة اللاخطية. وفي السنوات الأخيرة، استخدم في حل مثل هذه المشكلات كلا من الخوارزم الجيني(GA) ومحاكي التخمي(SA) والبحث المحّرم (TS). وفي هذا البحث قد أخذنا مزايا كل طريقة من هذه الطرق الثلاث بحيث نقدم طريقة مختلطة (TS/SA/GA) لحل مشكلة آمثلة القدرة غير الفعالة في منظومات القوى واختبرنا الطريقة على النظام القياسي ذو ٣٠ عقدة. كما نقدم في هذا البحث النتائج المقارنة للطرق المقترحة مثل الخوارزم الجيني وطريقة تجمع بين الخوارزم الجيني ومحاكي التخمير معا وطريقة أخرى نجمع بين الثلاث طرق وبهذا قد تمكنا من الحصول على الحل الأمثل لمشكلة القدرة غير الفعالة في نظم القوى الكهربية.

Keywords: Power system analysis, reactive power optimization, Genetic Algorithm, Simulated Annealing, Taboo Search, and Hybrid technique

1. Introduction

The application of optimization techniques to power system planning and operation problems has been an area of active research in the recent past. A wide variety of operational programming techniques such as nonlinear programming, quadratic programming, Newton-based solution of optimality conditions, linear programming, hybrid versions of linear programming and integer programming and interior point methods have been applied to solve the power system Optimal Power Flow (OPF) problems [1]. Reactive power optimization in power system solved by adjusting generator voltages, transformer taps and capacitor/reactors is a mixed integer nonlinear programming problem. Global optimization techniques, such as Genetic Algorithm (GA), Simulated Annealing (SA), Taboo Search (TS), evolutionary programming and evolutionary strategy, have recently been applied to reactive power optimization [2-5] leading to improved solutions but with relatively slow performance.

In the middle of last decade, modified GA was applied to optimal reactive power planning in practical power systems [2]. Some comparative results of evolutionary programming, evolutionary strategy, genetic algorithm, and linear programming using the IEEE 30-bus system demonstrated that GA could give good solutions [3]. In [4], a modified GA as an upper stage and successive linear programming at a lower lever stage have been used in practical optimal reactive power planning. TS has also been introduced to large scale var optimization [5].

GA, SA and TS have different features and their combination may become more effective to find the global optimal solutions and some promising results have been reported on unit commitment [6]. Combining the advantages of individual algorithms, hybrid GA/SA/TS algorithm to solve the reactive power optimization problem is proposed in this paper. The IEEE 30 bus system has been tested.

2. Problem fomulation

The real power loss can be reduced and voltage profiles can be improved by adjusting control variables, such as generator bus voltages (continuous), transformer taps (integer) and capacitors/reactors (integer). Constraints include the power flow equations, limits on control variables, the reactive power generation limits, load bus voltage limits and branch (transformer and transmission line) power limits. It is a mixed integer nonlinear programming problem. The following fitness or objective function is used in this paper:

$$f = P_\ell + \lambda_1 \sum_{\alpha} \Delta V_i^2 + \lambda_2 \sum_{\beta} \Delta Q_{ij}^2 \quad , \qquad (1)$$

where, P_ℓ is the real power loss; λ_1, λ_2 are punishment factors; α denotes a set of bus i whose voltage deviates ΔV_i from its upper or lower limit, and β represents a set of branch ij whose reactive power deviates ΔQ_{ij} from its upper or lower limit.

Power constrains, i.e. power flow equations are:

$$P_i = V_i \sum_{j \in i} V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta ij) \ , \qquad (2)$$

$$Q_i = V_i \sum_{j \in i} V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta ij), \qquad (3)$$

and the variable constrains are:

$$V_{G\,min} \le V_G \le V_{G\,max}, \qquad (4)$$

$$K_{T\,min} \le K_T \le K_{T\,max}, \qquad (5)$$

$$Q_{C\,min} \le Q_C \le Q_{C\,max}, \qquad (6)$$

$$V_{L\,min} \le V_L \le V_{L\,max}, \qquad (7)$$

$$Q_L \le Q_{L\,max}, \qquad (8)$$

$$Q_{G\,min} \le Q_G \le Q_{G\,max}, \qquad (9)$$

where, V_G , K_T and Q_C are vectors of generator voltages, transformer ratios and var compensations, respectively; V_L , Q_G and Q_L represent vectors of load bus voltages, reactive power generations and branch powers, respectively.

Minimizing f subject to eqs. (4) to (9) is the reactive power optimization problem in this paper. In the hybrid algorithms to be introduced in section III, the first three constrains (control variable) given as in eqs. (4 to 6) can be easily satisfied by creating feasible solutions. The fourth and fifth constraints, eqs. (7) and (8), have already been combined into the fitness function. The last one, eq. (9), is checked by the power flow calculation.

3. GA/SA/TS hybrid algorithms

3.1. Genetic algorithm

GA has become increasingly popular in recent year in science and engineering disciplines and there are many modified versions since it was originally proposed in 1970's. Starting from the simple to more advanced forms of reproduction, crossover and mutation, better solutions can be found rapidly with little relationship to the original population. It is quite simple, robust, but difficult to avoid tending to local optimal solutions.

3.2. Simulated annealing

SA is a powerful technique for solving combinatorial optimization problems. It has the ability of escaping local optimum by incorporating a probability function in accepting or rejecting new solutions. The annealing process needs enough time so as to find the global optimal solution.

The system to be optimized starts at a high temperature, and is cooled down, until the system freezes, and reaches the global optimum in a similar manner to the annealing of a crystal during growth to reach a perfect structure. The frozen structure will be close to the lowest objective.

At each temperature, the system is simulated in the neighborhood N(s) of the current solution and a set of moves is then selected randomly. This means that the search space N(s) can alter from one solution to another. If

the move decreases the value of the objective function then the new solution is retained. On the other hand, if the move increases the objective function, acceptance is treated probabilistically and the Boltzman's factor $e^{(-\Delta f/kT)}$ is calculated, where Δf is the change in the objective function due to the move, the parameter T is the temperature and k is Boltzman's constant whose dimension depends on f and T. A random number r that is uniformly distributed in the interval [0,1] is chosen. If $r < e^{(-\Delta f/kT)}$, the new solution is retained. Otherwise, the move is discarded and the solution before this step is used for the next step. This process is equivalent to accepting all the moves at very high temperatures and moving freely in the solution space. Whereas, at low temperatures only moves with decreased objective are accepted. The algorithm stops when no significant improvement in the objective function is found for a number of consecutive iterations.
SA pseudo-code is shown below:

```
Simulated Annealing ($s \in S$):
Begin
    $t=T(0), n=1$
    Best solution $s_{best}=s$;
    Repeat until (termination criterion fulfilled) Do
        Generate $s_{new} \in N(s)$;
        $\Delta f=f(s)-f(s_{new})$;
        If (($\Delta f \geq 0$) or ($e^{-\Delta f/kt}$>random[0,1]))then
$s=s_{new}$;
        If($f(s_{new})<f(s_{best})$)then $s_{best}=s_{new}$;
        $t=T(n)$
        $n=n+1$;
    Return $s_{best}$;
End.
```

3.3. Hybrid GA/SA

GA combined with SA, called as GA/SA for short which apply SA to test the members of the new population produced by the reproduction, crossover and mutation of GA, can avoid entrapment in local optimum to some extent since the solution variety is increased. However, with the temperature becoming low, the probability of trapping in local optimum increases.

3.4. Taboo Search

TS is another powerful optimization procedure that has been successfully applied to a number of combinatorial problems. It has the ability to avoid entrapment in local minima by employing a flexible memory system [7]. TS consists of move, Taboo list and aspiration criterion.

Among the finite candidate solutions of the neighborhood of the current solution, the solution, which has the best fitness function value, is selected as the new trial solution. This mapping, from the current solution to new trial one in neighborhood, is called a move. To prevent the cycling and escape from the local optimum, a Taboo list is utilized in the selection of the best move.

Because of the Taboo list, TS can find the global optimal solution with fairly good probability. But since TS starts from a single point, its convergence speed and the final solution may depend on the original point [7].

A very basic pseudo-code of TS can be seen below:

```
Taboo Search ($s \in S$);
Begin
  Taboo list $T=\emptyset$;
  Best solution $s_{best}=s$;
  Repeat until (Termination criterion fulfilled) Do
        Find best solution $s_{new} \in N(s)$, $s_{new} \notin T$;
        $T=T \cup \{s_{new}\}$
        if($f(s_{new})<f(s_{best})$)then $s_{best}=s_{new}$;
    Return $s_{best}$;
End
```

3.5. Hybrid GA/SA/TS algorithm

GA, SA and TS are of individual features. Reasonably combining local and global searching ability of GA and TS, and adopting the acceptance probability of SA, the following GA/SA/TS hybrid algorithm is proposed to improve the efficiency of problem solving.

At first a middle solution is obtained by GA/SA, then with this solution as a starting point, carry out TS until stopping criterion is satisfied. This algorithm tries to combine multi-point search of GA with good convergent characteristics of TS. It can simply be described as:

Read power system data and algorithm parameters, create an initial population X_{10}, X_{20}, ..., X_{n0} by randomly generating a set of feasible solutions (chromosomes);
ii. Start GA/SA, after given number of iterations arrive at a middle population X_{1m}, X_{2m},..., X_{nm};
iii. Select the best solution X_{km} from X_{1m}, X_{2m},..., X_{nm}, execute TS from this point till a stopping criterion.

As for the stopping or terminating criteria, both of the following are applied in the paper.
i. The number of iterations performed since the best solution last changed is greater than a re-specified maximum number of iterations;
ii. Maximum allowable number of iterations is reached.

4. Numerical results

The IEEE 30-bus power system, shown in fig. 1, has been tested using MATLAB-R12 on PC-Pentium 600 MHz. The IEEE 30-bus power system [8] consists of 6 generator buses, 22 load buses, and 41 branches. The data of the system is given in Appendix A. The control variables, which are shown in Table 1, include 6 generator voltages, 4 transformer taps and 4 capacitor banks. In table 1, "(4, 12)" represents a transformer connected between buses 4 and 12, "1.0-1.1/20" means that 20 possible values of generator voltages, "0.95-1.05/5" means that 5 values of tap positions including 0.95 and 1.05 are taken evenly from 0.95 to1.05 p.u., and "0-0.5/10" gives 10 equidistant levels between 0 and 0.5 p.u. of the capacitor ratings.

Four methods, the previous SGA, and GA/SA, and the proposed D-GA/SA/TS (decimal coding TS), called as TSD for short, and B-GA/SA/TS (binary coding TS), called TSB for short, are applied to the optimization of the tested system. In SGA the population is 50, and the crossover and mutation probabilities are 0.6 and 0.002, respectively. In SA, the initial temperature is 100 and the decent rate is 0.999. Both SGA and GA/SA terminate after 100 iterations. The TS table size is 40 in the TSB and 20 in the TSD. The number of trial solutions (neighborhood searching) is 30 in both TSB and TSD. Both TSB and TSD terminate after 50 iterations.

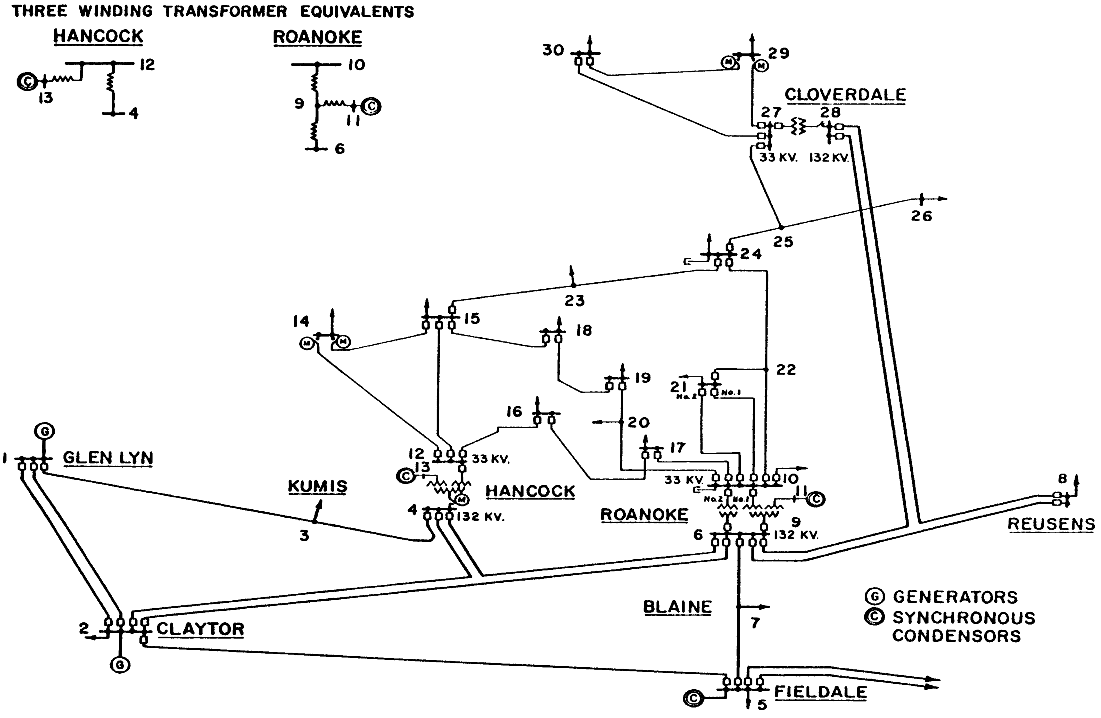

Fig. 1. IEEE 30-bus system.

Table 1
Regulating facilities in 30-bus system

Type	No.	Position	Range/Stage
Generator	6	1,2, 5, 8, 11, 13	1.0-1.1/ 20
Trans.	4	(4,12), (6,9), (6,10),(28,27)	0.95-1.05/ 5
Capacitor	4	10, 19, 24, 15	0-0.5/ 10

From table 1, it can be shown that the search space is 20^6 x 5^4 x10^4 states each of which is represented by 58 and 24 bits, as shown in tables 2 and 3, in the binary and decimal codes, respectively. Only TSD adopts the decimal coding.

Some average results of 100 trials are shown in table 4. The optimal power loss are demonstrated in table 4. It can be seen that the average power loss found by TSD is the least and by GA/SA is the most centralized. GA/SA is better than SGA. Since the short coding length enlarges the searching space, TSD leads to better solutions than TSB.

The first 50 iteration curves of SGA, GA/SA, TSB, and TSD are also shown in fig. 2. From fig. 2, it can be seen that TSD is of the best convergence performance among the four methods. In other words, TSD is the best.

Table 2
Binary code in the 30-bus

6 gen*5 bits		4 trans*3 bits		4 cap*4 bits	
10100	...	101	..	1010	..

Table 3
Decimal code in the 30-bus

6 gen*2 bits		4 trans*1bit		4 cap*2 bits	
20	...	5	..	10	..

Table 4
Average Results of the 30-bus system

Method	Power loss (pu)	% Decrease	Time (sec)
SGA	0.05268	1.745	35.7
GA/SA	0.05099	4.910	36.9
TSB	0.05109	4.712	16.2
TSD	0.04970	7.302	1.9

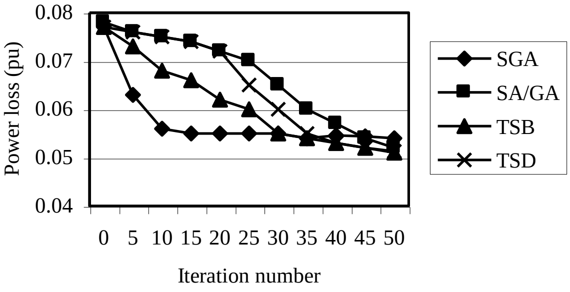

Fig. 2. Convergent characteristics of four algorithms.

5. Conclusions

GA, SA and TS, each having its own characteristics, are cooperatively used to power system reactive power optimization in this paper. A hybrid GA/SA/TS search method is proposed to combine local search and global search. Combining the advantages of individual

Appendix A

Table A-1
IEEE 30-bus system's data

Bus	V	P	Q	Bus	V	P	Q	Bus	V	P	Q
1*	1.060	0.0	0.0	11*	1.082	0.0	0.0	21	1.0	-17.5	-11.2
2*	1.043	18.3	-12.7	12	1.0	-11.2	-7.5	22	1.0	0.0	0.0
3	1.0	-2.4	-1.2	13*	1.071	0.0	0.0	23	1.0	-3.2	-1.6
4	1.0	-7.6	-1.6	14	1.0	-6.2	-1.6	24	1.0	-8.7	-6.7
5*	1.010	-94.2	-19.0	15	1.0	-8.2	-2.5	25	1.0	0.0	0.0
6	1.0	0.0	0.0	16	1.0	-3.5	-1.8	26	1.0	-3.5	-2.3
7	1.0	-22.8	-10.9	17	1.0	-9.0	-5.8	27	1.0	0.0	0.0
8*	1.010	-30.0	-30.0	18	1.0	-3.2	-0.9	28	1.0	0.0	0.0
9	1.0	0.0	0.0	19	1.0	-9.5	-3.4	29	1.0	-2.4	-0.9
10	1.0	-5.8	-2.0	20	1.0	-2.2	-0.7	30	1.0	-10.6	-1.9

* Generator bus

Table A-2
IEEE 30-bus system's parameters

Link	I	j	r_{ij}	x_{ij}	$y_b/2$	Link	i	j	r_{ij}	x_{ij}	$y_b/2$
1	1	2	0.0192	0.0575	0.0528	22	15	18	0.1073	0.2185	0.0
2	1	3	0.0452	0.1652	0.0408	23	18	19	0.0639	0.1292	0.0
3	2	4	0.0570	0.1737	0.0368	24	19	20	0.0340	0.0680	0.0
4	3	4	0.0132	0.0379	0.0084	25	10	20	0.0936	0.2090	0.0
5	2	5	0.0472	0.1983	0.0418	26	10	17	0.0324	0.0845	0.0
6	2	6	0.0581	0.1763	0.0374	27	10	21	0.0348	0.0749	0.0
7	4	6	0.0119	0.0414	0.0090	28	10	22	0.0727	0.1499	0.0
8	5	7	0.0460	0.1160	0.0204	29	21	22	0.0116	0.0236	0.0
9	6	7	0.0267	0.0820	0.0170	30	15	23	0.1000	0.2020	0.0
10	6	8	0.0120	0.0420	0.0090	31	22	24	0.1150	0.1790	0.0
11*	6	9	0.0	0.2080	0.0	32	23	24	0.1320	0.2700	0.0
12*	6	10	0.0	0.5560	0.0	33	24	25	0.1885	0.3292	0.0
13	9	11	0.0	0.2080	0.0	34	25	26	0.2544	0.3800	0.0
14	9	10	0.0	0.1100	0.0	35	25	27	0.1093	0.2087	0.0
15*	4	12	0.0	0.2560	0.0	36*	28	27	0.0	0.3960	0.0
16	12	13	0.0	0.1400	0.0	37	27	29	0.2198	0.4153	0.0
17	12	14	0.1231	0.2559	0.0	38	27	30	0.3202	0.6027	0.0
18	12	15	0.0662	0.1304	0.0	39	29	30	0.2399	0.4533	0.0
19	12	16	0.0945	0.1987	0.0	40	8	28	0.0636	0.2000	0.0428
20	14	15	0.2210	0.1997	0.0	41	6	28	0.0169	0.0599	0.0130
21	16	17	0.0524	0.1923	0.0						

*Transformer element

algorithms, they adopt the acceptance probability of SA to improve the convergence of the SGA, and TS is introduced to find a more accurate solution. An IEEE 30-bus power system has been used to test the proposed algorithm.

Comparing the results of the proposed algorithm with those obtained by GA, and GA/SA show that the proposed GA/SA/TS hybrid method has the strongest capability of finding global optimal solution within reasonable computing time.

References

[1] J.A. Momoh, et. al., "A Review of selected Optimal Power Flow Literature to 1993, Part I and Part II", IEEE Transactions on Power System, Vol. 14 (1), pp. 96-111(1999).

[2] K. Iba, "Reactive power optimization by genetic algorithm", IEEE Transactions on Power System, Vol. 9 (2), pp. 685-692 (1994).

[3] Y.K. Lee and F.F. Yang, "Optimal reactive Power Planning Using Evolutionary Algorithm, Evolutionary Strategy, Genetic Algorithm, and Linear Programming", IEEE Transactions on Power System, Vol. 13 (1), pp. 101-108 (1998).

[4] A. J. Urdancta, et. al., "A Hybrid Genetic Algorithm for Optimal Reactive Power Planning Based Upon Successive Linear Programming", IEEE Transactions on Power System, Vol. 14 (4), pp. 1292-1298 (1999).

[5] D. Gan, et. al., "Large Scale Var Optimization and Planning by Taboo Search", Electric Power Systems Research, Vol. 39 (3), pp. 195-204 (1996).

[6] A. Mantawy, et. al., "Integrating Genetic Algorithm, Taboo Search, and Simulated Annealing for the Unit Commitment Problem", Ieee Trans. On Power Systems, Vol. 14 (3), pp 829-836 (1999).

[7] R. Gallego, A. Monticelli, and R. Romero, "Taboo Search Algorithm for Network Synthesis", IEEE Transactions on Power Systems, vol. 15 (2), pp. 490-495 (2000).

[8] L.L. Freris, and A. M. Sasson, "Investigation of the Load Flow Problem", Proceedings of IEE, Vol. 115 (10), pp. 1459-1470 (1968).

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