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Minimization of Active Power Loss and Voltage Profile Fortification by Using Differential Evolution – Harmony Search Algorithm

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Abstract

This paper presents DEHS (Differential Evolution-harmony Search) algorithm for solving the multi-objective reactive power dispatch problem .Harmony Search is a new heuristic algorithm, which mimics the procedure of a music player to search for an ideal state of harmony in music playing. Harmony Search can autonomously mull over each component variable in a vector while it generates a new vector. These features augment the flexibility of the Harmony Search algorithm and produce better solutions and overcome the disadvantage of Differential Evolution. Improved Differential Evolution method based on the Harmony Search Scheme, which we named it DEHS (Differential Evolution-harmony Search). The DEHS method has two behaviors. On the one hand, DEHS has the flexibility. It can adjust the values lightly in order to get a better global value for optimization. On the other hand, DEHS can greatly boost the population's diversity. It not only uses the DE's strategies to search for global optimal results, but also utilize HS's tricks that generate a new vector by selecting the components of different vectors randomly in the harmony memory and its outside. In order to evaluate the proposed algorithm, it has been tested on IEEE 30 bus system and compared to other algorithms.

Key words: Modal analysis, optimal reactive power, Transmission loss, differential evolution, harmony.

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1. Introduction

Optimal reactive power dispatch problem is one of the complex optimization problems in power system. The sources of the reactive power are the generators, synchronous condensers, capacitors, static compensators and tap changing transformers. Here the reactive power dispatch problem involves best operation of the existing generator bus voltage magnitudes, transformer tap setting and the output of reactive power sources so as to minimize the real power loss and to boost the voltage stability of the system. Various arithmetical techniques have been adopted to solve this optimal reactive power dispatch problem. These include the gradient method [1-2], Newton method [3] and linear programming [4-7].The gradient and Newton methods experience from the difficulty in handling inequality constraints. To apply linear programming, the input- output function is to be expressed as a set of linear functions which may lead to loss of accurateness. Newly Global Optimization techniques such as genetic algorithms have been planned to solve the reactive power flow problem [8, 9]. To boost the voltage stability, voltage magnitudes alone will not be a reliable indicator of how far an operating point is from the collapse point [10]. The reactive power support and voltage problems are intrinsically related. Hence, this paper formulates the reactive power dispatch as a multi-objective optimization problem with loss minimization and maximization of static voltage stability margin (SVSM) as the objectives. Global optimization has received extensive research attention, and a great number of methods have been applied to solve this problem. Evolutionary algorithm is a heuristic approach for minimizing possibly nonlinear and non-differentiable continuous space functions. For many decades, evolutionary algorithms range from the first algorithm Genetic Algorithm (GA) [11] to Evolutionary Strategies (ES) [12], Genetic Programming (GP) [13], Evolutionary Programming (EP) [14], Differential Evolution (DE) [15], and other methods, such as Simulated Annealing (SA) [16], Particle Swarm Optimizer (PSO) [17, 18], and Neural Networks [19]. All of these have been successfully applied to a wide range of optimization problems, such as, image processing, pattern recognition, scheduling, engineering design, and others [20]. DE algorithm as a novel version of GA is a population-based stochastic direct search method for global optimization. Unlike GA that uses binary coding to represent problem parameters, DE uses real valued parameters, which is easily applied to experimental minimization where the cost value is derived from a physical experiment rather than a computer simulation. DE has four advantages: ability to handle non-differentiable, nonlinear and multi-modal cost functions; ability to parallel cope with computation intensive cost functions; ease of use; and good convergence properties. It has been successfully applied to various benchmark and real-world problems, including a travelling salesman problem [21], design centring [22], digital filter design [21, 23], and noisy objection functions [24], and so on. Harmony Search (HS) is a new heuristic algorithm mimics the improvisation of music players, which was proposed by Geem [25]. HS is optimization algorithms that seek a best state (global optimum-minimum cost or maximum benefit or efficiency) determined by objective function assessment. It has been successfully used into various benchmark and real-world problems, includes a travelling salesman problem [26], parameter optimization of river flood model [27], design of pipeline network [28, 29], and design of truss structures [30]. In this paper, we propose an improved DE combined with HS named DEHS, not only uses the DE's strategies to search for global optimal results, and utilize HS's tricks that generate a new vector by selecting the components of different vectors randomly in the harmony memory and its outside, but also uses the pitch adjustment method to adjust the variables left or right in population of one generation. Our algorithm is more flexible and greatly enhancements population's diversity, which totally different from Liao [31] proposed MDE-IHS method, which use the current Number of Function Evaluations (NFE) to replace the parameter t in improvisation step [32-33]. As a result, DEHS avoided the optimal function falling into local minimal. The proposed algorithm DEHS been evaluated in standard IEEE 30 bus test system & the results analysis shows that our proposed approach outperforms all approaches investigated in this paper.

2. Voltage Stability Evaluation

2.1.Modal analysis for voltage stability evaluation

Modal analysis is one of the methods for voltage stability enhancement in power systems. The linearized steady state system power flow equations are given by.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix} J_{p\theta} & J_{pv} \\ J_{q\theta} & J_{QV} \end{bmatrix} \quad (1)$$

Where

ΔP = Incremental change in bus real power.

ΔQ = Incremental change in bus reactive

Power injection

$\Delta\theta$ = incremental change in bus voltage angle.

ΔV = Incremental change in bus voltage Magnitude

$J_{p\theta}$, J_{PV} , $J_{Q\theta}$, J_{QV} jacobian matrix are the sub-matrixes of the System voltage stability is affected by both P and Q. However at each operating point we keep P constant and evaluate voltage stability by considering incremental relationship between Q and V.

To reduce (1), let $\Delta P = 0$, then.

$$\Delta Q = \left[J_{QV} - J_{Q\theta} J_{P\theta^{-1}} J_{PV}\right]\Delta V = J_R \Delta V \quad (2)$$

$$\Delta V = J^{-1} - \Delta Q \quad (3)$$

Where

$J_R = (J_{QV} - J_{Q\theta} J_{P\theta^{-1}} JPV)$ (4)

J_R is called the reduced Jacobian matrix of the system.

2.2.Modes of Voltage instability:

Voltage Stability characteristics of the system can be identified by calculating the Eigen values and Eigen vectors

Let

$J_R = \xi \eta$ (5)

Where,

ξ = right eigenvector matrix of J_R

η = left eigenvector matrix of J_R

Λ = diagonal eigenvalue matrix of J_R and

$J_{R^{-1}} = \xi \Lambda^1 \eta$ (6)

From (5) and (8), we have

$\Delta V = \xi \Lambda^1 \eta \Delta Q$ (7)

or

$\Delta V = \sum_I \frac{\xi_i \eta_i}{\lambda_i} \Delta Q$ (8)

Where ξ_i is the ith column right eigenvector and η the ith row left eigenvector of J_R.

λ_i is the ith Eigen value of J_R.

The ith modal reactive power variation is,

$\Delta Q_{mi} = K_i \xi_i$ (9)

where,

$K_i = \sum_j \xi_{ij^2} - 1$ (10)

Where

ξ_{ji} is the jth element of ξ_i

The corresponding ith modal voltage variation is

$\Delta V_{mi} = [1/\lambda_i]\Delta Q_{mi}$ (11)

It is seen that, when the reactive power variation is along the direction of ξ_i the corresponding voltage variation is also along the same direction and magnitude is amplified by a factor which is equal to the magnitude of the inverse of the ith eigenvalue.

In (10), let $\Delta Q = e_k$ where e_k has all its elements zero except the kth one being 1. Then,

$$\Delta V = \sum_i \frac{\eta_{1k}\ \xi_1}{\lambda_1} \quad (12)$$

η_{1k} k th element of η_1

V –Q sensitivity at bus k

$$\frac{\partial V_K}{\partial Q_K} = \sum_i \frac{\eta_{1k}\ \xi_1}{\lambda_1} = \sum_i \frac{P_{ki}}{\lambda_1} \quad (13)$$

3. Problem Formulation

The objectives of the reactive power dispatch problem considered here is to reduce the system real power loss and maximize the static voltage stability margins (SVSM).

3.1.Minimization of Real Power Loss

Minimization of the real power loss (Ploss) in transmission lines is mathematically stated as follows.

$$P_{loss} = \sum^{n}_{\substack{k=1\\ k=(i,j)}} g_{k(V_i^2+V_j^2-2V_i\,V_j\,\cos\,\theta_{ij})} \quad (14)$$

Where n is the number of transmission lines, g_k is the conductance of branch k, V_i and V_j are voltage magnitude at bus i and bus j, and θ_{ij} is the voltage angle difference between bus i and bus j.

3.2.Minimization of Voltage Deviation

Minimization of the Deviations in voltage magnitudes (VD) at load buses is mathematically stated as follows.

Minimize $VD = \sum_{k=1}^{nl} |V_k - 1.0|$ (15)

Where nl is the number of load busses and V_k is the voltage magnitude at bus k.

3.3.System Constraints

Objective functions are subjected to these constraints shown below.

Load flow equality constraints:

$$P_{Gi} - P_{Di} - V_{i \sum_{j=1}^{nb} V_j} \begin{bmatrix} G_{ij} & \cos\theta_{ij} \\ +B_{ij} & \sin\theta_{ij} \end{bmatrix} = 0, i = 1,2 \dots., nb \quad (16)$$

$$Q_{Gi} - Q_{Di} - V_{i \sum_{j=1}^{nb} V_j} \begin{bmatrix} G_{ij} & \cos\theta_{ij} \\ +B_{ij} & \sin\theta_{ij} \end{bmatrix} = 0, i = 1,2 \dots., nb$$

(17)

where, *nb* is the number of buses, P_G and Q_G are the real and reactive power of the generator, P_D and Q_D are the real and reactive load of the generator, and G_{ij} and B_{ij} are the mutual conductance and susceptance between bus *i* and bus *j*.

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

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}, i \in ng \quad (18)$$

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

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max}, i \in nl \quad (19)$$

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

$$Q_{Ci}^{min} \leq Q_{Ci} \leq Q_{Ci}^{max}, i \in nc \quad (20)$$

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

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, i \in ng \quad (21)$$

Transformers tap setting (T_i) inequality constraint:

$$T_i^{min} \leq T_i \leq T_i^{max}, i \in nt \quad (22)$$

Transmission line flow (S_{Li}) inequality constraint:

$$S_{Li}^{min} \leq S_{Li}^{max}, i \in nl \quad (23)$$

Where, nc, ng and nt are numbers of the switchable reactive power sources, generators and transformers.

4. Standard Differential Evolution

The DE algorithm was originally introduced by Price and Storn about fifteen years ago [21]. At present, there are a number of variants of DE. The particular variant used throughout this investigation is the DE/rand/1/bin scheme, *rand* means randomly chosen population vector, *1* is the number of difference vectors used, *bin* means crossover due to independent binomial experiments [39]. This scheme will be discussed here briefly.

$$P_{x,g} = \left(x_{i,g}\right), i = 0,1,..,N_P - 1; g = 0,1,..,G_{max} \tag{24}$$

$$x_{i,g} = \left(x_{j,i,g}\right), j = 0,1,..,D - 1. \tag{25}$$

Where N_p denotes the number of population vectors, g defines the generation counter, and D stands for the dimensionality, i.e. the number of parameters. In case a preliminary solution is available, the initial population might be generated by adding normally distributed random deviations to the nominal solution $x_{nom;0}$.

DE generate new parameter vectors by adding the weighted difference between two population vectors to a third vector. Let this operation be called mutation.

$$v_{i,g+1} = x_{r1,g} + F.\left(x_{r2,g} - x_{r3,g}\right) \tag{26}$$

Where random indexes r1, r2, $r3 \in 1, 2, ..., N_p$, cross rate F $\in [0, 2]$.

In order to increase the diversity of the perturbed parameter vectors, crossover is operated.

$$u_{ji,g+1} = \begin{cases} v_{ji,g+1} if(rand(j) \leq CR) or j = rand(i) \\ x_{ji,g} if(rand(j) > CR) or j \neq rand(i) \end{cases} \tag{27}$$

where rand(j) is the jth evaluation of a uniform random number generator with outcome ∈ [0, 1], rand(i) is a randomly chosen index ∈ 1, 2, ...,D which endures that $u_{i;g+1}$ gets at least one parameter from $v_{i;g+1}$. CR is the crossover constant ∈ [0, 1]. If the trial vector yields a lower cost function value than the target vector, the trial vector replaces the target vector in the following generation. This last operation is called selection. Each population vector has to serve once as the target vector so that N_p competitions take

Place in one generation. However, due to the limitation of $N_p \cdot (N_p - 1)$ potential perturbation possibilities for base vector, there is a limited possibility to find regions of improvement and hence stagnation [40] can be the price to pay for the low number of N_p. In order to increase the number of potential points to be searched while still maintaining a low number of N_p gives rise to the various strategies for diversity enhancement, of which research on DE's mutation is one method.

5. Harmony Search

Harmony Search (HS) algorithm was newly developed in an analogy of music creativeness process where music players manage the pitches of their instruments to obtain better harmony [31]. The Harmony Memory Size (HMS) determines the number of vectors to be stored. Then, through the Harmony Memory Considering Rate (HMCR) choose any one value from the HM, utilize the Pitch Adjusting Rate (PAR) choose an neighbouring value of one value from the HM, and choose totally random value from the possible value range. The steps in the process of HS are as follows:

Step 1: Initialize the algorithm parameters and optimization operators. Such as HM, HMS, HMCR, PAR.

Step 2: Improvise a new harmony from HM. A New Harmony vector is generated from HM, based on memory considerations, pitch adjustments, and randomization. The HMCR is the probability of choosing one value from the historic values stored in the HM, and (1-HMCR) is the probability of randomly choosing one feasible value not limited to those stored in the HM.

$$x_{i,g+1} = \begin{cases} x_{ji,g} \; if(rand(0,1) \leq HMCR, \\ l_i + rand(0,1)(u_i - l_i) with\; probability\; (1 - HMCR) \end{cases}$$

(28)

$$x_{i,g+1} = \begin{cases} x_{i,g+1} - rand(0,1) * BANDif(rand(0,1) \leq 0.5, \\ x_{i,g+1} + rand(0,1) * BANDif(rand(0,1) > 0,5. \end{cases}$$

(29)

Step 3: Update HM. If a New Harmony vector is better than the worst harmony in HM, judged in terms of the objective function value, the New Harmony is included in HM and the existing worst harmony is excluded from HM.

Step 4: Repeat Steps 2 and 3 until the terminating criterion is satisfied.

6. An Improved Differential Evolution Based on Harmony Search for solving reactive power dispatch problem.

In this paper, we suggest a new way to improve the DE, through combining the DE and HS, to improve the population's diversity. HS algorithm generates the new vector not only from the Harmony Memory, but also from the outside of Harmony Memory. The complete algorithm of DEHS is as follows.

6.1.Initialization

In order to unite DE and HS successfully, we assume the DE's general method DE/rand/1/bin strategy to generate a point X, if some dimension values of the point are located beyond the constraint of the variables, i.e. we use the following rules to adjust it:

$$x_i = \begin{cases} l_i + U_i(0,1)(u_i - l_i) if x_i < l_i \\ u_i - U_i(0,1)(u_i - l_i) if x_i > u_i \end{cases} \qquad (30)$$

Where $U_i(0, 1)$ is the uniform random variable from [0, 1] in each dimension i, and $1 \leq i \leq N$, which is also suit for initializing HS's harmony memory. The improvement includes four steps as follows,

6.2.Improve the Generation

Step 1: produce the initial population randomly and compute the fitness of each individual;

Input:DEHS algorithm parameters: CR, F, HMCR, PAR;

Initialization:Generate the initial population of N_p as HM with vectors satisfying lower and

upper bounds;

for $t \in 1, ..., G_{max}$ do

repeat

The halting criterion is not satisfied

for i ∈ 1, ...,Np do

//r0! = r1! = r2! = i

r0 = floor(rand(0, 1) ∗ N_p); while(r0==i);

r1 = floor(rand(0, 1) ∗ N_p); while(r1==r0 or r1==i);

r2 = floor(rand(0, 1) ∗ N_p); while(r2==r1 or r2==r0 or r2==i);

jrand = floor(D ∗rand(0, 1));

end for

for j ∈ 1, ...,D do

if rand(0, 1) ≤ CR or j==jrand) then

$u_j = x_{j;r0} + F* (x_{j;r1} - x_{j;r2});$

else

$u_j = x_{j;i};$

end if

end for

//Improvise a new harmony

for j ∈ 1, ...,D do

// Harmony memory considering:randomly select any variable-i pitch in HM

if (rand(0, 1) ≤ HMCR then

if (round(0, 1) ≤ PAR then

//Pitch adjusting: randomly adjust u_j within a small bandwidth,

±rand(0, 1) ∗ BAND

if (round(0, 1) ≤ 0.5 then

$v_j = u_j + rand(0, 1) * BAND$

else

$v_j = u_j - rand(0, 1) * BAND$

end if

end if

else

//Random playing: randomly select any pitch within upper u_j and lower bounds l_j

$v_j = l_j + rand(0, 1) * (u_j - l_j)$

end if

end for

if v_j is better than the worst harmony in HM, x_{worst}, then

Replace x_{worst} with v_j in HM, then sort HM

end if

until $|f(best) - f(worst)| < \varepsilon$

end for

Step 2: discover the best and the worst individuals in the existing population in HM;

Step 3: manage a new harmony: first, generated a new vector by DE's operation; secondly, adjust the vector through HS;

Step 4: revise harmony memory, which is same to selection. If the fitness which is measured by the objective function of the generated harmony vector (trail vector) $u_{i;g}$ is better than or equal to the worst harmony vector(target vector) $x_{i;j}$, it replaces the worst harmony vector in the next generation; otherwise, the target retains its place in the population for at least one more generation.

$$x_{i,g+1} = \begin{cases} u_{i,g} if \ \left(u_{i,g} \leq f(x_{i,g})\right), \\ x_{i,g} \ otherwise \ . \end{cases} \quad (31)$$

Step 5: confirm the stopping criterion: $|f(best) - f(worst)| < \varepsilon = 1 \times 10^{-16}$. This halting criterion is used to make the algorithm stop earlier when the results satisfy the precision of the problems .

7. Simulation Results

The soundness of the proposed DEHS Algorithm method is demonstrated on IEEE-30 bus system. The IEEE-30 bus system has 6 generator buses, 24 load buses and 41 transmission lines of which four branches are (6-9), (6-10) , (4-12) and (28-27) - are with the tap setting transformers. The lower voltage magnitude limits at all buses are 0.95 p.u. and the upper limits are 1.1 for all the PV buses and 1.05 p.u. for all the PQ buses and the reference bus. The simulation results have been presented in Tables 1, 2, 3 &4. And in the Table 5 shows clearly that proposed algorithm powerfully reduce the real power losses when compared to other given algorithms. The optimal values of the control variables along with the minimum loss obtained are given in Table 1. Equivalent to this control variable setting, it was found that there are no limit violations in any of the state variables.

ORPD including voltage stability constraint problem was handled in this case as a multi-objective optimization problem where both power loss and maximum voltage stability margin of the system were optimized concurrently. Table 2 indicates the optimal values of these control variables. Also it is found that there are no limit violations of the state variables. It indicates the voltage stability index has increased to 0.2472 from 0.2488, an advance in the system voltage stability. To determine the voltage security of the system, contingency analysis was conducted using the control variable setting obtained in case 1 and case 2. The Eigen values equivalents to the four critical contingencies are given in Table 3. From this result it is observed that the Eigen value has been improved considerably for all contingencies in the second case.

Table 1. Results of DEHS – ORPD optimal control variables

Control variables	Variable setting
V1	1.040
V2	1.041
V5	1.042
V8	1.030
V11	1.010

V13	1.040
T11	1.03
T12	1.03
T15	1.0
T36	1.0
Qc10	3
Qc12	2
Qc15	2
Qc17	0
Qc20	3
Qc23	4
Qc24	4
Qc29	3
Real power loss	4.4045
SVSM	0.2472

Table 2.Results of DEHS -Voltage Stability Control Reactive Power Dispatch Optimal Control Variables

Control Variables	Variable Setting
V1	1.042
V2	1.041
V5	1.040
V8	1.033
V11	1.009
V13	1.034
T11	0.090
T12	0.090
T15	0.090
T36	0.091
Qc10	4

Qc12	3
Qc15	2
Qc17	4
Qc20	0
Qc23	4
Qc24	4
Qc29	3
Real power loss	4.9861
SVSM	0.2488

Table 3. Voltage Stability under Contingency State

Sl.No	Contingency	ORPD Setting	VSCRPD Setting
1	28-27	0.1410	0.1430
2	4-12	0.1658	0.1661
3	1-3	0.1774	0.1783
4	2-4	0.2032	0.2041

Table 4. Limit Violation Checking Of State Variables

State variables	limits		ORPD	VSCRPD
	Lower	upper		
Q1	-20	152	1.3422	-1.3269
Q2	-20	61	8.9900	9.8232
Q5	-15	49.92	25.920	26.001
Q8	-10	63.52	38.8200	40.802
Q11	-15	42	2.9300	5.002
Q13	-15	48	8.1025	6.033
V3	0.95	1.05	1.0372	1.0392
V4	0.95	1.05	1.0307	1.0328
V6	0.95	1.05	1.0282	1.0298
V7	0.95	1.05	1.0101	1.0152

V9	0.95	1.05	1.0462	1.0412
V10	0.95	1.05	1.0482	1.0498
V12	0.95	1.05	1.0400	1.0466
V14	0.95	1.05	1.0474	1.0443
V15	0.95	1.05	1.0457	1.0413
V16	0.95	1.05	1.0426	1.0405
V17	0.95	1.05	1.0382	1.0396
V18	0.95	1.05	1.0392	1.0400
V19	0.95	1.05	1.0381	1.0394
V20	0.95	1.05	1.0112	1.0194
V21	0.95	1.05	1.0435	1.0243
V22	0.95	1.05	1.0448	1.0396
V23	0.95	1.05	1.0472	1.0372
V24	0.95	1.05	1.0484	1.0372
V25	0.95	1.05	1.0142	1.0192
V26	0.95	1.05	1.0494	1.0422
V27	0.95	1.05	1.0472	1.0452
V28	0.95	1.05	1.0243	1.0283
V29	0.95	1.05	1.0439	1.0419
V30	0.95	1.05	1.0418	1.0397

Table 5. Comparison of Real Power Loss

Method	Minimum loss
Evolutionary programming[34]	5.0159
Genetic algorithm[35]	4.665
Real coded GA with Lindex as SVSM[36]	4.568
Real coded genetic algorithm[37]	4.5015
Proposed DEHS method	4.4045

8. Conclusion

In this paper a novel approach DEHS algorithm used to solve optimal reactive power dispatch problem.The performance of the proposed algorithm has been demonstrated through its voltage stability assessment by using modal analysis method and is effective at various instants following system contingencies. Also this method has a good performance for voltage stability Enhancement of large, complex power system networks. The effectiveness of the proposed method is demonstrated on IEEE 30-bus system.

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