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AN EVOLUTIONARY PROGRAMMING APPLICATION TO OPTIMAL REACTIVE POWER DISPATCH

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This paper presents an application of evolutionary programming (EP) to optimal reactive power dispatch (ORDP). The objective of ORDP is to minimize the real power losses and keep the voltages and reactive power generations in their operating limits. In this matter the control variables are generator bus voltages and transformer taps.

The proposed EP approach was evaluated on the modified IEEE-30 bus system.

Keywords: Evolutionary Programming, Optimal Reactive Power Dispatch, Minimizing the Real Power Losses.

List of Symbols

N_B	– set of number of total buses;
N_{PQ}, N_{PU}	– set of number of PQ and PU buses;
$N_{B\text{-}S}$	– set of number of total buses excluding slack bus;
L ,T	– set of number of transmission lines and transformers;
$\underline{U}_i = U_i e^{j\theta_i}$	– voltage at bus i;
$\underline{Y}_{ik} = G_{ik} + jB_{ik}$	– (i,k) element of nodal admittance matrix;
P_i^{sch} , Q_i^{sch}	– scheduled active and reactive power at bus i;
$\Delta P_{i,k}$	– active power loss in branch i-k;
Q_{gi}	– reactive power generation at bus i;
$N_{i,k}$	– turn ration of (i,k) transformer ;
$U_i^{\min}$, $U_i^{\max}$	– lower and upper voltage limits;
$Q_{gi}^{\min}$, $Q_{gi}^{\max}$	– lower and upper reactive power generation limits;
$N_{ik}^{\min}$, $N_{ik}^{\max}$	– lower and upper turn ratio limits;

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1. Introduction

Power system economical operation consists of two aspects: active power regulation and reactive power dispatch. In a real large scale power system this is a complex problem and is considered conventionally as two separate problems [1-6].

The purpose of optimal reactive power dispatch (ORDP) is to control the generator bus voltages and tap-settings of the under-load tap changing (ULTC) to minimize the network power loss and improve voltage profiles. Solving this problem is subject to a number of constraints such as limits on bus voltages, ULTC settings, reactive power of the generators, etc. Many methods based on linear and non-linear programming have been proposed to solve this problem. These optimization methods are based on successive linearization and use the first and second derivatives of objective function and its constraint equations as the search directions. Such treatments quite often lead to a local minimum point and sometimes result in divergence.

Some new methods based on artificial intelligence have recently been used in ORDP and reactive power planning to solve local minimum problems and uncertainties [7,8,9].

This paper presents an application of evolutionary programming (EP), instead of the conventional methods, to solve an optimization reactive power dispatch problem. EP does not require the mathematical assumptions applied in the conventional methods and offers a powerful global search over the control variables space.

2. Problem formulation

The objective of ORPD is to minimize the network real power loss in the transmission network witch can be described as follows:

$$MIN\left[P_{LOSS}\right] = \sum_{(i,k)\in L\cup T} \Delta P_{i,k} \tag{1}$$

with equality constraints:

$$\begin{aligned} P_i^{sch} &= U_i \sum_{k=1}^{n} U_k \left(G_{ik}\cos\left(\theta_i-\theta_k\right)+B_{ik}\sin\left(\theta_i-\theta_k\right)\right) \;\; i\in N_{B-S} \\ Q_i^{sch} &= U_i \sum_{k=1}^{n} U_k \left(G_{ik}\sin\left(\theta_i-\theta_k\right)-B_{ik}\cos\left(\theta_i-\theta_k\right)\right) \;\; i\in N_{PQ} \end{aligned} \tag{2}$$

and inequality constrains:

$$
\begin{aligned}
&Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} && i \in N_{PU} \\
&N_{ik}^{\min} \leq N_{ik} \leq N_{ik}^{\max} && (i,k) \in T \\
&U_{i}^{\min} \leq U_{i} \leq U_{i}^{\max} && i \in N_{B}
\end{aligned}
\tag{3}
$$

For implementing the evolutionary programming algorithm the inequality constrains are added as a quadric penalty terms to the objective function and the active power losses are expressed from the equation of active power balance:

$$P_{LOSS} = \sum_{i \in N_B} P_{gi} - \sum_{i \in N_B} P_{li} = P_S(\mathbf{U}, \boldsymbol{\theta}) - P_{const} \tag{4}$$

where $P_S(\mathbf{U}, \boldsymbol{\theta})$ is the injected active power at slack-bus and P_{const} includes all unchanged generated and load active power in the system. Thus the optimization problem can be redefined as follows:

$$MIN\left[f_q\right] = P_S(\mathbf{U}, \boldsymbol{\theta}) + \sum_{i \in N_{U\,\lim}} \lambda_{U_i} \left(U_i - U_i^{\lim}\right)^2 + \sum_{i \in N_{Qg\,\lim}} \lambda_{Q_{gi}} \left(Q_{gi} - Q_{gi}^{\lim}\right)^2 \tag{5}$$

where λ_{U_i} and $\lambda_{Q_{gi}}$ are the penalty factors that can be increased in the optimization procedure and $U_i^{\lim}$, respectively $Q_{gi}^{\lim}$ are defined in the following equations:

$$
\begin{aligned}
U_i^{\lim} &= \begin{cases} U_i^{\min} & if \quad U_i < U_i^{\min} \\ U_i^{\max} & if \quad U_i > U_i^{\max} \end{cases} \\
Q_{gi}^{\lim} &= \begin{cases} Q_{gi}^{\min} & if \quad Q_{gi} < Q_{gi}^{\min} \\ Q_{gi}^{\max} & if \quad Q_{gi} > Q_{gi}^{\max} \end{cases}
\end{aligned}
\tag{6}
$$

It can be seen that the generalized objective function f_q is a non-linear and non-continuous function. Gradient based conventional methods are not good enough to solve this problem.

3. Evolutionary Programming Algorithm for solving the minimization problem

Evolutionary Programming (EP) is different from conventional optimization methods. It does not need to differentiate cost functions and constraints. It uses probability transition rules to select generations [8-11]. Each individual competes with some other individuals in a combined population of the old generation and the mutated old generation. The competition results are valued using a probabilistic rule. Winners are selected to constitute the next generation and the number of winners is the same as that of individuals in the old generation.

The procedure of EP for ORDP is briefly listed as follows [8,10]:

- **Initialization**

The initial control variable population is selected by randomly selecting $p_i = \left[U^i_{PV}, N_{ik}\right]$, *i=1,2,…,m*, where *m* is the population size, from the sets of uniform distributions ranging over $\left[U_i^{\min}, U_i^{\max}\right]$ and $\left[N_{ik}^{\min}, N_{ik}^{\max}\right]$. The fitness value, $f_i = \dfrac{1}{1+P_S(\mathbf{U},\boldsymbol{\theta})}$, of each individual, p_i, is obtained by running the Newton-Raphson method.

- **Statistics**

The values of the maximum fitness, minimum fitness, sum of fitness and average fitness of this generation are calculated as follows:

$$\begin{aligned} f_{\max} &= \left\{ f_i \mid f_i \geq f_j \; \forall f_j, j = 1,2,\ldots,m \right\} \\ f_{\min} &= \left\{ f_i \mid f_i \leq f_j \; \forall f_j, j = 1,2,\ldots,m \right\} \\ f_{\Sigma} &= \sum_{i=1}^{m} f_i \\ f_{avg} &= \frac{f_{\Sigma}}{m} \end{aligned} \tag{7}$$

- **Mutation**

Each p_i is mutated and assigned to p_{i+m} in accordance with the following equation:

$$p_{i+m,j} = p_{i,j} + N\left(0, \beta\left(x_{j\max} - x_{j\min}\right)\frac{f_i}{f_{\max}}\right), j = 1, 2, ..., n \tag{8}$$

In practical applications a small fixed mutation probability can only result in a premature convergence, while a search with a large fixed mutation probability will not converge. To solve this problem an adaptive mutation scale is given to change the mutation probability:

$$\beta(\mathrm{k}+1) = \begin{cases} \beta(\mathrm{k}) - \beta_{\mathrm{step}} & \text{if } \mathrm{f}_{\min}(\mathrm{k}) - \text{unchanged} \\ \beta(\mathrm{k}) & \text{if } \mathrm{f}_{\min}(\mathrm{k}) - \text{decresed} \\ \beta_{\mathrm{final}} & \text{if } \beta(\mathrm{k}) - \beta_{\mathrm{step}} < \beta_{\mathrm{final}} \end{cases} \quad ; \beta(0) = \beta_{\mathrm{init}} \tag{9}$$

- **Competition**

Each individual p_i in the combined population has to compete with some other individuals to get its chance to be transcribed to the next generation. After all individuals had competed with some others individuals, they will be ranked in descending order of their corresponding fitness value. The first *m* individuals of the *2m* individuals formed are transcribed along with their corresponding fitness value f_i to be the basis of the next generation.

5. Numerical Results

5.1. IEEE 30-bus system

In this section the modified IEEE 30-bus system (Figure 1) is used to show the effectiveness of the EP algorithm. The network consists of six generator-buses, 21 load-buses and 43 branches, of witch four branches are ULTC transformer (6,9), (6,10), (4,12), (28,27). The branch parameters and loads are given in [3] while the parameters and variable limits are listed in Table 1.

5.2.Initial conditions

The initial conditions are defined as follows:

- generator bus voltages and transformer taps are set to 1.0 p.u.;
- total active and reactive loads are P_{LOAD}=2.834 p.u. and Q_{LOAD}=1.262 p.u. respectively.

After running the power flow program for the initial conditions we can see that:

- there are six buses with voltages less then minimum admissible value (see also Figure 2): U_1=0.9223 p.u.; U_{19}=0.9498 p.u.; U_{24}=0.9467 p.u.; U_{25}=0.9467 p.u.; U_{26}=0.9276 p.u.; U_{29}=0.9346 p.u.;
- generated active and reactive power and network power losses are: P_G=2.8942 p.u. ; Q_G=1.3096 p.u. ; P_{LOSS}=0.0602 p.u.

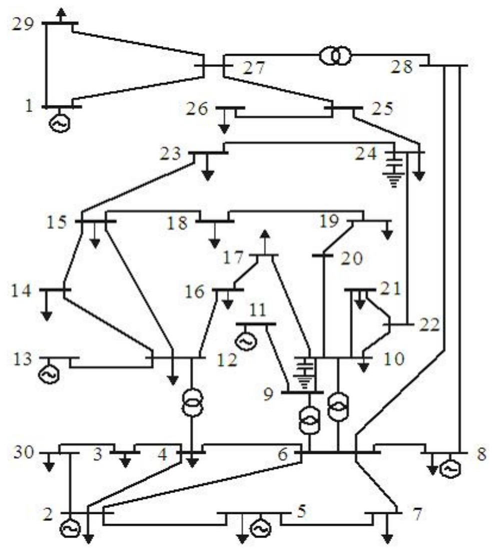

Fig. 1. The modified IEEE 30-bus test system.

Table 1

Parameters and variable limits

Reactive Power Generation Limits						
Bus	2	5	8	11	13	30
$Q_g^{\min}$	-0.20	-0.15	-0.15	-0.10	-0.15	-0.20
$Q_g^{\max}$	1.00	0.80	0.60	-0.50	0.60	2.00
Voltage and Tap – Settings Limits						
$U_{PU}^{\min}$	$U_{PU}^{\max}$	$U_{PQ}^{\min}$	$U_{PQ}^{\max}$	$N_{ik}^{\min}$	$N_{ik}^{\max}$	
0.90	1.10	0.95	1.05	0.90	1.10	

5.3. Optimal solution obtained using EP

In order to use EP for ORDP problem the control variables of the transmission network (voltages at *PU* – buses and turn ratio of ULTC) are arranged as elements of an individual in populations used during evolutionary search.

$p_i =$

U_{g2}	U_{g5}	U_{g8}	U_{g11}	U_{g13}	U_{g30}	$N_{6,9}$	$N_{6,10}$	$N_{4,12}$	$N_{28,27}$

The lower and upper limits are considered as follows:

- $U_i^{\min} = 0.9$ p.u. and $U_i^{\max} = 1.1$ p.u. for PU – buses and slack – bus;
- $U_i^{\min} = 0.95$ p.u. and $U_i^{\max} = 1.05$ p.u. for PQ – buses;
- $N_{ik}^{\min} = 0.9$ p.u and $N_{ik}^{\max} = 1.1$ p.u.

The population size is chosen to be 50, while the number of competitors is 20. In the initial population each element $p_{ij}^{(0)}$ of individuals $p_i^{(0)}$, $i = \overline{1,50}$ is initialized with a random value between the lower and upper limit.

The fitness values f_i used for mutation, competition, and reproduction are obtained for each individual by running the power flow program based on Newton – Raphson method.

After successful search using the EP, we obtain the optimal values of control variables (PU – bus voltages, slack – bus voltage and transformer tap N_{ik}). These are the elements of the best individual in the last population:

$p_{opt} =$

U_{g2}	U_{g5}	U_{g8}	U_{g11}	U_{g13}	U_{g30}	$N_{6,9}$	$N_{6,10}$	$N_{4,12}$	$N_{28,27}$
1.0655	1.0471	1.0421	1.0485	1.0461	1.0720	0.9782	1.0286	0.9566	0.9412

After computation of power flow with these optimal values, voltages at PU – buses and turn ratio of ULTC we obtain the new values for bus voltages (Figure 2), total active end reactive generated power and active power loses as follows: P_G=2.8856 p.u. ; Q_G=1.2523 p.u. and P_{LOSS}=0.0516 p.u.

To be noted that after the optimization process we obtain a better reactive power dispatch in the system (Figure 3) and a power saving of:

$$P_{save}\% = \frac{P_{LOSS}^{initial} - P_{LOSS}^{opt}}{P_{LOSS}^{initial}} \times 100 = \frac{0.0602 - 0.0516}{0.0602} \times 100 = 14.28\% \qquad (10)$$

Also as a consequence of ORPD in optimal operation condition all voltage values are in their limits unlike the initial condition where there are some buses with voltage values less then the lower limit (Figure 2).

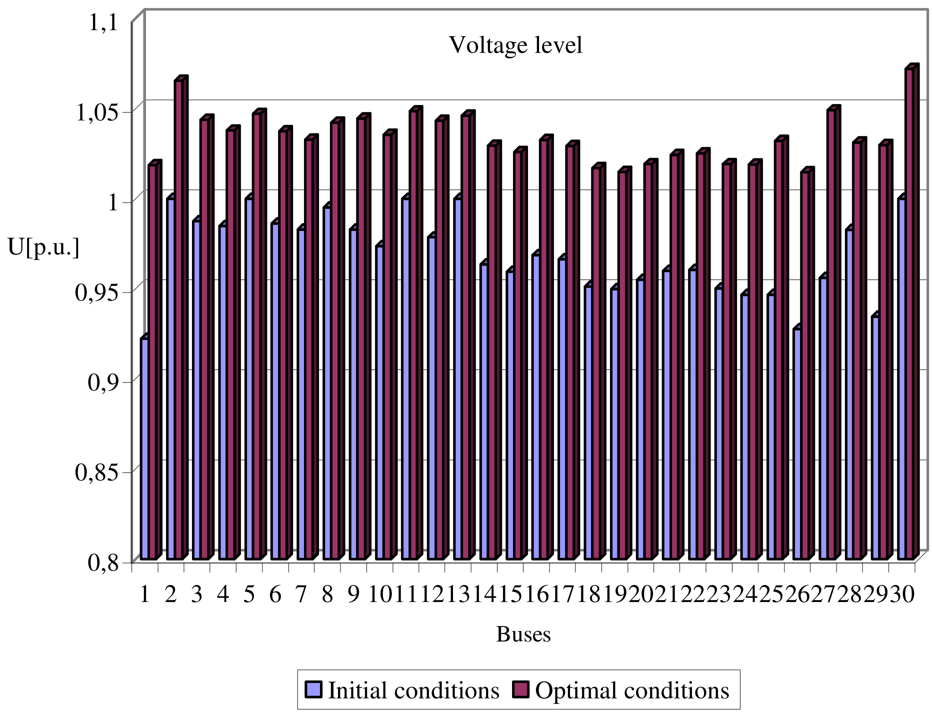

Fig.2. Voltage level – Initial conditions / Optimal Conditions

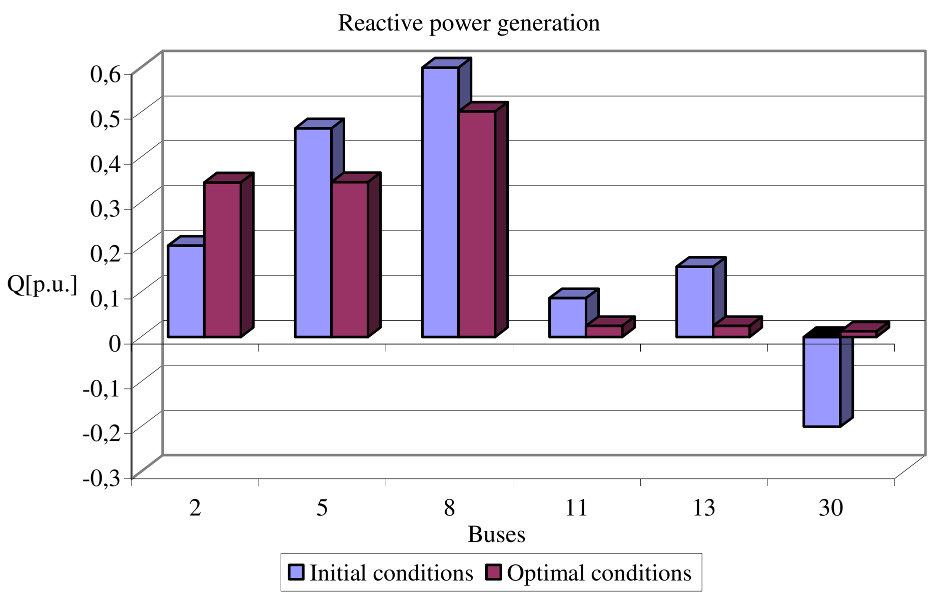

Fig.3. Reactive power generation – Initial conditions / Optimal Conditions

4. Conclusions

Optimal Reactive Power Dispatch is an optimization problem of a non-continuous and non-linear function with uncertainties arising from large-scale power systems. Evolutionary Programming with the techniques developed in this paper is a suitable algorithm to solve such a problem. The EP does not require the mathematical assumption applied in the conventional methods and offers a powerful global search over the control variable space. Simulation studies were carried out on the modified IEEE-30-bus system. The simulation results shows that the application of EP to ORPD could achieve very attractive power savings and better operating conditions, cheeping the voltages and reactive generated powers into their limits.

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