Optimizing reactive power flow of HVDC systems using genetic algorithm

Ulaş Kılıç a,⇑, Kürsat Ayan b, Uğur Arifoğlu c

⇑Corresponding author. Address: Department of Mechatronics Engineering, Celal Bayar University, Manisa, Turkey.
E-mail addresses: ulas.kilic@cbu.edu.tr (U. Kılıç), kayan@sakarya.edu.tr (K. Ayan), arifoglu@sakarya.edu.tr (U. Arifoğlu).

ARTICLE INFO

Article history:
Received 2 August 2012
Received in revised form 16 July 2013
Accepted 8 August 2013

Keywords:
Optimal reactive power flow
Integrated AC–DC system
Heuristic method
Genetic algorithm
Evolutionary

ABSTRACT

Due to the usage of high voltage direct current (HVDC) transmission links extensively in recent years, it requires more studies in this issue. Two-terminal HVDC transmission link is one of most important elements in electrical power systems. Generally, the representation of HVDC link is simplified for optimal reactive power flow (ORPF) studies in power systems. ORPF problem of purely AC power systems is defined as minimization of power loss under equality and inequality constraints. Hence, ORPF problem of integrated AC–DC power systems is extended to incorporate HVDC links taking into consideration power transfer control characteristics. In this paper, this problem is solved by genetic algorithm (GA) that is an evolutionary-based heuristic algorithm for the first time. The proposed method is tested on the modified IEEE 14-bus test system, the modified IEEE 30-bus test system, and the modified New England 39-bus test system. The validity, the efficiency, and effectiveness of the proposed method are shown by comparing the obtained results with that reported in literature. Thus, the impact of DC transmission links on the whole power systems is shown.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

ORPF is an energy system problem that the scientists try to solve for a long time [1–5]. The problem is minimization of the power loss in an energy network. In other words, the aim is minimization of objective function which is power loss in an energy system. At the same time, the objective function of whole system is minimized under equality and inequality constraints. The equality and inequality constraints in purely AC system are power equalities defined for all the buses and physical constraints of the energy system, respectively. All the constraints have been to be satisfied while the power loss of whole the system is being minimized.

The scientists have used many different methods for solving ORPF problem of purely AC power systems [1–13]. These methods are numerical and heuristic methods. According to the results reported in literature, it can be seen that heuristic methods are superior from the numerical methods [4–13]. One important advantage of heuristic methods is that they convergence to the optimum solution in shorter time than others and without reaching local minimums.

Because of the energy consumption increasing rapidly in recent years, it is required to increase the power generation capacity. This causes to over load the transmission lines. Thus, even small perturbations can cause a part of the energy system to leave the synchronization even if it is subjected to the small perturbations. It is needed to reschedule energy systems to avoid such undesirable situations like these and to maintain the continuity of the operating. So in recent years, the power system planners try to reschedule the energy systems to transfer the power through HVDC links in recent years. There are many advantages of the power transmission through HVDC links. For examples, reactive power is not transferred through HVDC links and energy loss of HVDC links is lesser than long AC system transmission lines. Additionally, the instantaneous power in neighboring AC systems can be controlled by HVDC links. Furthermore, HVDC links is used to stabilize electric power systems [14]. Recently, many researches are performed on realization of HVDC models for power flows studies [15–19]. The formulation for the basic model of two-terminal HVDC link is given in Ref. [20].

In ORPF problem of the integrated AC–DC power systems, DC link constraints are included in the problem. In the literature, there are two basic approaches for solving the power flow equations. The first is the sequential approach [19,21,22]. In this method, AC and DC equations are solved separately by successive iterations. Although the implementation of the sequential method is simple, it has convergence problems associated with certain situations.
Furthermore, the state vector does not contain explicitly DC variables. The second approach is known as the unified approach [23]. In this study, the first method is used.

GA is a heuristic algorithm based on native selection. The basic logic of this algorithm is based on the living of strong individuals in nature and the dying of others. This algorithm consists of stages as initial population, fitness scaling, selection, crossover, mutation, and stopping. GA has been used successfully for solution of the engineering problem for a long time [24–29]. In this paper, GA is used for solution of ORPF problem in integrated AC–DC power systems for the first time.

After this introduction, the modeling of DC transmission link is represented in Section 2. The methodology of GA is explained in Section 3. GA based optimal reactive power flow solution of HVDC systems is explained in Section 4. In order to demonstrate validity, efficiency and effectiveness of the proposed method, simulation results of the modified IEEE 14-bus test system, the modified IEEE 30-bus test system and the modified New England 39-bus test system are given and the obtained results are extensively evaluated and compared to that reported in the literature in section 5. Finally, the conclusions are discussed in section 6.

2. The modeling of DC transmission link

Before analyzing DC transmission system, it is necessary to model DC transmission link and the converters. The modeling is made based on accepted assumptions in the literature. The assumptions are as follows [23]:

- The main harmonic values of current and voltage in AC system is balanced.
- The other harmonics except the main harmonic are ignored.
- The ripples in the form of DC current and voltages are ignored.
- The thyristors used in the converters are accepted as ideal switch and it is supposed to be short circuit in the direction of transmission and open circuit in the direction of plugging.
- No load current of the converter transformers and the losses are ignored.

An AC bus having generators, AC lines, shunt compensators and converters is represented in Fig. 1[30]. The active and reactive power equalities at such a bus are given by Eqs. (1) and (2).

\[
P_{gk} = P_k + P_{dk} + P_k
\]

\[
Q_{gk} + Q_{sk} = Q_{rk} + Q_{sk} + Q_k
\]

where \( P_{gk} \) is the active power generation of the \( k \)th bus; \( P_k \) the active power transferred to dc line from the \( k \)th bus; \( P_{dk} \) the active power transferred to ac line from the \( k \)th bus; \( P_{sk} \) the active load of the \( k \)th bus; \( Q_{gk} \) the reactive power generation of the \( k \)th bus; \( Q_{rk} \) the reactive load of the \( k \)th bus; \( Q_{sk} \) the reactive power absorbed by the converter in the \( k \)th bus; \( Q_{dk} \) the reactive power transferred to ac line from the \( k \)th bus; \( Q_{sk} \) the shunt compensator in the \( k \)th bus. For rectifier bus,

\[
P_{dk} = p_i
\]

(3)

\[
q_{dk} = q_i
\]

(4)

For inverter bus,

\[
P_{dk} = -p_i
\]

(5)

\[
q_{dk} = q_i
\]

(6)

A basic schematic diagram of a two-terminal HVDC transmission link interconnecting buses “r” (rectifier) and “f” (inverter) is illustrated in Fig. 2. The basic converter equations describing the relationship between AC and DC variables were expressed in Ref. [31].

The variables shown in Fig. 2 are defined as follows:

- \( V_r \) is the primary line-to-line ac voltage (rms) of the rectifier side.
- \( V_f \) the primary line-to-line ac voltage (rms) of the inverter side.
- \( \phi_r \) the phase angle of the rectifier side.
- \( \phi_f \) the phase angle of the inverter side.
- \( i_r \) ac current of the rectifier side.
- \( i_f \) ac current of the inverter side.
- \( v_{gk} \) the rectifier side voltage of DC link.
- \( v_{qk} \) the inverter side voltage of DC link.
- \( i_d \) the direct current.
- \( t \) the transformer tap ratio.

2.1. The equations for rectifier side of DC transmission link

The equations related to the rectifier operation of a converter can be expressed as follows:

\[
v_{dar} = k_t v_r
\]

(7)

\[
v_{di} = v_{far} \cos \alpha - r_{cr} i_d
\]

(8)

where \( r_{far} \) is the ideal no-load direct voltage, \( k = 3 \sqrt{2} / \pi \) and \( \alpha \) is the ignition delay angle; \( r_{cr} \) the so called equivalent commutation resistance, which accounts for the voltage drop due to commutation overlap and is proportional to the commutation reactance, \( r_{cr} = \sqrt{3} x_{cr} / \pi \). The active power for the rectifier side is determined by:

\[
p_r = v_{di} i_d
\]

(9)

\[fig1.png\]

Fig. 1. The representation of the ac bus which is connected dc transmission link [30].
Since losses at the converter and transformer can be ignored \( ( p_r = p_{dc} ) \), the reactive power at the rectifier side is determined as follows:

\[
q_r = [ p_r \tan \phi_r ]
\]  \hspace{1cm} (10)

where \( \phi_r \) is the phase angle between the AC voltage and the fundamental AC current and is calculated by neglecting the commutation overlap as follows:

\[
\phi_r = \cos^{-1} \left( \frac{V_{dc}}{V_{ac}} \right)
\]  \hspace{1cm} (11)

The equivalent circuit of a two-terminal HVDC link is shown in Fig. 3[32] and the related relationships are given by Eqs. (8), (13), and (17).

2.2. The equations for inverter side of DC transmission link

The equations related to the inverter operation of a converter can be expressed as follows:

\[
v_{dci} = k t_i v_i
\]  \hspace{1cm} (12)

\[
v_{di} = v_{dci} \cos \gamma - r_{di} i_d
\]  \hspace{1cm} (13)

\[
p_i = v_{di} i_d
\]  \hspace{1cm} (14)

\[
q_i = [ p_i \tan \phi_i ]
\]  \hspace{1cm} (15)

\[
\phi_i = \cos^{-1} \left( \frac{v_{di}}{v_{dci}} \right)
\]  \hspace{1cm} (16)

where \( \gamma \) is the extinction advance angle.

2.3. DC link equation

The relationship between the voltages of both sides of DC link voltages can be expressed by Eq. (17):
where \( r_{dc} \) is DC link resistance.

3. Illustration of GA

GA is a heuristic algorithm based on natural selection. GA’s were firstly utilized by Holland in 1975 for solving optimization problems [33]. The base logic of the algorithm is that genes of powerful individuals are based to be carried over next generation and others are based to be detached in next generation. In natural selection, a human born, grows, and dies. These stages of human life correspond to the different operators in the algorithm. GA operators related these stages can be explained as the following.

3.1. Initial population

Initial population is determined in two ways. One of them is to form random individuals as initial population size within their limits. The second way is to form initial population of the certain individuals. The fitness values of individuals within population are obtained to be put in objective function the formed individuals. The individual number within initial population is randomly determined by Eq. (18).

\[
 w_{ij} = w_{\text{min},j} + \text{rand}(0,1) \times \frac{w_{\text{max},j} - w_{\text{min},j}}{C_0}
\]

where the parameters \( w_{\text{min},j} \) and \( w_{\text{max},j} \) show the minimum and maximum of the variable \( w_j \).

3.2. Fitness scaling

The scaling stage is one of GA operators. The scaling prevents algorithm to get stuck on a local point. There are different scaling methods as rank scales, top scales, and shift linear scales. In this study, the better individuals than individual having average fitness value are selected and can be formulated as follows:

\[
 w_f = w_{\text{min},j} + \text{rand}(0,1) \times (w_{\text{max},j} - w_{\text{min},j})
\]

where the parameters \( w_{\text{min},j} \) and \( w_{\text{max},j} \) show the minimum and maximum of the variable \( w_j \).

Table 2

<table>
<thead>
<tr>
<th>DC link characteristics for the modified 14-bus test system.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rectifier</strong></td>
</tr>
<tr>
<td>Bus number</td>
</tr>
<tr>
<td>Commutation reactance (p.u.)</td>
</tr>
<tr>
<td>DC link resistance (p.u.)</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Cases</th>
<th>Minimum fitness value</th>
<th>Maximum fitness value</th>
<th>Average fitness value</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.4413</td>
<td>50260.7</td>
<td>25132.57</td>
<td>13.66</td>
</tr>
<tr>
<td>2</td>
<td>3.8589</td>
<td>22681.4</td>
<td>11342.63</td>
<td>26.77</td>
</tr>
<tr>
<td>3</td>
<td>3.6099</td>
<td>4.4261</td>
<td>4.01800</td>
<td>37.43</td>
</tr>
<tr>
<td>4</td>
<td>3.6062</td>
<td>4.4092</td>
<td>4.00770</td>
<td>54.82</td>
</tr>
<tr>
<td>5</td>
<td>3.5476</td>
<td>4.1244</td>
<td>3.83600</td>
<td>67.65</td>
</tr>
<tr>
<td>6</td>
<td>3.5349</td>
<td>4.0601</td>
<td>3.79750</td>
<td>81.05</td>
</tr>
<tr>
<td>7</td>
<td>3.5045</td>
<td>4.0024</td>
<td>3.75345</td>
<td>94.72</td>
</tr>
<tr>
<td>8</td>
<td>3.4648</td>
<td>3.9056</td>
<td>3.68520</td>
<td>107.88</td>
</tr>
<tr>
<td>9</td>
<td>3.4631</td>
<td>3.8399</td>
<td>3.65150</td>
<td>121.54</td>
</tr>
<tr>
<td>10</td>
<td>3.4372</td>
<td>3.7769</td>
<td>3.60705</td>
<td>135.95</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Comparative DC system results obtained by GA and Ref. [36] of the modified IEEE 14-bus test system for the case 5.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>( p_{\mu} )</td>
</tr>
<tr>
<td>( p_{\mu} )</td>
</tr>
<tr>
<td>( q_{\mu} )</td>
</tr>
<tr>
<td>( q_{\alpha} )</td>
</tr>
<tr>
<td>( \tau )</td>
</tr>
<tr>
<td>( \tau )</td>
</tr>
<tr>
<td>( \alpha )</td>
</tr>
<tr>
<td>( \gamma )</td>
</tr>
<tr>
<td>( r_{\mu} )</td>
</tr>
<tr>
<td>( r_{\alpha} )</td>
</tr>
<tr>
<td>( i_{\mu} )</td>
</tr>
</tbody>
</table>
Table 5

<table>
<thead>
<tr>
<th>Variables (p.u.)</th>
<th>Limits</th>
<th>Results</th>
<th>GA</th>
<th>Ref. [36]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{r1}$</td>
<td>0.0000</td>
<td>3.3240</td>
<td>0.5458</td>
<td>–</td>
</tr>
<tr>
<td>$P_{r2}$</td>
<td>0.0000</td>
<td>2.0000</td>
<td>1.0803</td>
<td>–</td>
</tr>
<tr>
<td>$q_{r1}$</td>
<td>-0.1000</td>
<td>0.5000</td>
<td>0.0003</td>
<td>-0.0838</td>
</tr>
<tr>
<td>$q_{r2}$</td>
<td>-0.1000</td>
<td>0.5000</td>
<td>0.0548</td>
<td>-0.0081</td>
</tr>
<tr>
<td>$q_{r3}$</td>
<td>-0.1000</td>
<td>1.0000</td>
<td>0.17</td>
<td>0.2873</td>
</tr>
<tr>
<td>$q_{r4}$</td>
<td>-0.1000</td>
<td>1.0000</td>
<td>0.51</td>
<td>0.1815</td>
</tr>
<tr>
<td>$q_{r5}$</td>
<td>-0.1000</td>
<td>0.8000</td>
<td>0.09</td>
<td>0.327</td>
</tr>
<tr>
<td>$q_{r6}$</td>
<td>0.0000</td>
<td>0.2000</td>
<td>0.18</td>
<td>0.00</td>
</tr>
<tr>
<td>$q_{r7}$</td>
<td>0.0000</td>
<td>0.2000</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>$P_{r8}$</td>
<td>1.0000</td>
<td>1.1500</td>
<td>1.0600</td>
<td>1.0707</td>
</tr>
<tr>
<td>$P_{r9}$</td>
<td>1.0000</td>
<td>1.1500</td>
<td>1.0564</td>
<td>1.0618</td>
</tr>
<tr>
<td>$P_{r10}$</td>
<td>1.0000</td>
<td>1.1500</td>
<td>1.0426</td>
<td>1.0124</td>
</tr>
<tr>
<td>$q_{r11}$</td>
<td>0.9500</td>
<td>1.0500</td>
<td>1.0364</td>
<td>1.0495</td>
</tr>
<tr>
<td>$q_{r12}$</td>
<td>0.9500</td>
<td>1.0500</td>
<td>1.0236</td>
<td>1.0236</td>
</tr>
<tr>
<td>$q_{r13}$</td>
<td>0.9500</td>
<td>1.0500</td>
<td>1.0124</td>
<td>1.0124</td>
</tr>
<tr>
<td>$q_{r14}$</td>
<td>0.9500</td>
<td>1.0500</td>
<td>1.0286</td>
<td>1.0286</td>
</tr>
<tr>
<td>$P_{r15}$</td>
<td>0.9000</td>
<td>1.1000</td>
<td>1.0716</td>
<td>1.0618</td>
</tr>
<tr>
<td>$P_{r16}$</td>
<td>0.9000</td>
<td>1.1000</td>
<td>1.0564</td>
<td>1.0618</td>
</tr>
<tr>
<td>$q_{r17}$</td>
<td>0.9000</td>
<td>1.1000</td>
<td>0.93</td>
<td>0.0162</td>
</tr>
<tr>
<td>Power loss (p.u.)</td>
<td>0.035476</td>
<td>0.0425</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**3.3. Selection**

In this stage, the parents to be crossed for producing a child are selected. There are different selection methods as stochastic uniform, remainder, uniform, shift linear, roulette and tournament. In this study, the tournament method is preferred and can be formulated as follows:

$$
\tau_i = \frac{F_i}{\sum_{j=1}^{N_k} F_j}
$$

(20)

where $\tau_i$ represents the weight of $i$th individual within population. Furthermore, the sum of the elective probabilities of all the individuals within population is 1 as given by Eq. (21).

$$
\sum_{i=1}^{N_k} \tau_i = 1
$$

(21)

The twice individual of the children number determined in the beginning of the algorithm is selected from individuals within population for crossover. The percentage distribution of the individuals within population is proportional to its fitness value. The best individuals are shown by the high-level percentage distributions in roulette selection. After all the individuals are shown as the percentage distribution between 0 and 1, the roulette selection in the definite number is performed. Thus, the individuals are selected for crossover.

**3.4. Crossover**

In this stage, a child is produced to be crossed the parents. New individuals same as the determined number are produced to be used the crossing method with the scattered parameter from parents selected via the tournament method explained in selection stage. The value of 1 and 0 as gen number of an individual is randomly produced. If the value is 1, then gen is taken from mother, the value is 0, then gen is taken from father and thus the child is produced.

Cross: 1 0 1 1 0
Mother: a b c d e
Father: x y z u w
Child: a y c d w

**3.5. Mutation**

In mutation stage, new individuals are produced to be changed all or some gens of the selected individuals within population. The number of individual undergo mutation has to be determined in the beginning of the algorithm. The individuals undergo mutation are reproduced to be formed all the gens of the selected individuals within algorithm. Thus, new individuals as the number determined by Eq. (18) are randomly produced.

**3.6. The stopping criterion of algorithm**

There are many criterions for stopping algorithm. Some of these are the fitness value, time, and iteration number. In this study, iteration number is preferred as the stopping criterion. More information related to GA operators is available in Ref. [34]. Final population is formed to be included the reproduced individuals in stages above to initial population. After the individuals within final population are classified according to fitness value, the individual same as initial population is carried over the next iteration. A simple flow scheme of GA is shown in Fig. 4 [35].
4. Optimizing reactive power flow of HVDC systems using GA

In order to solve ORPF problem of HVDC systems, we have to determine the control and the variables. The control variables...
should be the same as those of the problem to be optimized. The control variables of the AC–DC system are:

$$U = [U_{AC}, U_{DC}]$$  \hspace{1cm} (22)

$$U_{AC} = [p_{23}, \ldots, p_{PN}, v_{g1}, \ldots, v_{gN}, q_{1}, \ldots, q_{N}]$$ \hspace{1cm} (23)

$$U_{DC} = [\vec{p}, \vec{q}, \vec{q}, \vec{I}]$$ \hspace{1cm} (24)

where $p_{gi}$ except the slack unit $p_{slack}$ is the generator active power outputs, $v_{gi}$ the generator voltage, $N_g$ the number of generator buses, $N_s$ the number of shunt compensators and $N_t$ the number of transformers, respectively.

The state variables of the AC–DC system are:

$$X = [X_{AC}, X_{DC}]$$ \hspace{1cm} (25)

$$X_{AC} = [p_{g1}, \ldots, p_{gN}, v_{1}, \ldots, v_{N}]$$ \hspace{1cm} (26)

$$X_{DC} = [\vec{r}, \vec{r}, \vec{\alpha}, \vec{\gamma}, \vec{V}_{dr}, \vec{V}_{dv}]$$ \hspace{1cm} (27)

where $p_{gslack}$ is the slack bus active power output, $q_{dr}$ the reactive power output, $v_{load}$ the load bus voltage, $N_l$ the number of load buses, respectively.

For updating active and reactive power at rectifier and inverter bus, we use the following formulas:

For rectifier bus:

$$\text{P}_{\text{update}}^\text{load} = \text{P}_{\text{load}} + p_i$$

$$\text{Q}_{\text{update}}^\text{load} = \text{Q}_{\text{load}} + q_i$$ \hspace{1cm} (28)

For inverter bus:

$$\text{P}_{\text{update}}^\text{load} = \text{P}_{\text{load}} - p_i$$

$$\text{Q}_{\text{update}}^\text{load} = \text{Q}_{\text{load}} + q_i$$ \hspace{1cm} (29)

The fitness value for each individual is obtained by Eq. (30) as follows:

$$\text{Fitness} = \frac{1}{\text{P}^2 + \text{Q}^2} \cdot \left(\text{P}^2 + \text{Q}^2\right)$$ \hspace{1cm} (30)

where $\text{P}^2 + \text{Q}^2$ is the power loss of the modified IEEE 30-bus test system for the case 5.

![Fig. 14. For Case B, the power loss variations of the best, the worst and average individuals against iteration number of the modified IEEE 30-bus test system for the case 5.](image)

![Fig. 15. For Case A, the reactive power variations at rectifier and inverter sides against iteration number for the modified IEEE 30-bus test system.](image)
for each individual is calculated to evaluate its quality as follows:

\[ p_{loss} = \sum_{i=1}^{N_s} p_{l0} - \sum_{j=1}^{N_t} p_{j0} \]  

\[ p_{load} = \sum_{i=1}^{N_s} p_{l0} - \sum_{j=1}^{N_t} p_{j0} \]  

where \( p_{loss} \) represents the real power transmission line losses, \( p_{load} \) represents the active load of the bus.

The flowchart of genetic algorithm is defined as follows:

Step 1: Read system data and GA parameters.
Step 2: Generate initial population of \( n \) individuals via control variable \( u \).
Step 3: Calculate the fitness value \( F_i \) of each chromosome in the population.

\[ F_i = \frac{1}{C_0} \sum_{k=1}^{n} F_{k,i} \]

Step 4: Create a new population by repeating the following steps until the new population is completed.
Step 5: Select the parents by tournament selection.
Step 6: Crossover the parent chromosomes to form a new child with scattered.
Step 7: Mutate new child with a mutation probability.
Step 8: Calculate the fitness \( F_i \) of each new child.
Step 9: Include new child to the population.
Step 10: Classify the all individuals from minimum to maximum.
Step 11: Carry over the individual same as initial population to the next iteration.
Step 12: If the stopping criterion is satisfied, stop algorithm and show the best solution in current population else, go to Step 4.

5. Application of GA on test systems and the simulation results

In this study, the proposed method is applied to four different test systems those are the modified IEEE 14-bus test system, the modified IEEE 30-bus test system and the modified New England 39-bus test system. The simulations are performed for different population sizes given in Table 1. For these systems, minimum, maximum, average fitness values and the computational times obtained by GA are given in the bottom. It can be seen from results that the optimum solution is not obtained by increasing the population size and the computational times of the software increase as the population size increases. The optimum solution is obtained by trials. The crossover rate and the mutation rate inside of the algorithm are taken into account as a constant such as the population size and the computational times obtained by GA are given in the bottom. Furthermore, the results obtained by the proposed method are compared to those reported in literature. The proposed algorithm is run on a computer with I3 CPU 2.4 GHz, 2 GB RAM. In order to test the validity, the effectiveness, and the efficiency of the proposed method, the test systems mentioned above are used. The algorithm proposed in this study is developed via real GA codes without using GA tool on Matlab.

In this study, the transformer tap ratios and the switchable shunt capacitor/reactor banks are taken into consideration as discrete variables. The transformer tap-step and the bank/unit capacity-step are also selected as being 0.01 p.u.

5.1. The modified IEEE 14-bus test system

The modified IEEE 14-bus test system is shown in Fig. 5[36]. A two-terminal HVDC link is included to between buses 4 and 5 in the original IEEE 14-bus test system. This system has 20 ac transmission lines, 2 generators, 3 transformers, 3 synchronous condensers and 2 switchable VAR compensators. The bus 4 is selected as rectifier and then the bus 5 is selected as inverter bus.

The characteristics of DC transmission link are given in Table 2.

For all the cases, minimum, maximum, average fitness values and the computational times obtained by GA for the modified IEEE 14-bus test system are given Table 3. Although the computational times of the software are very low for the population sizes in cases 1, and 2 minimum, maximum and average fitness values are so much and the variables exceed their limits. The variables do not exceed their limits for the population sizes in cases 3–10. For these cases, it can be seen from Table 3 that the computational times increase considerably, as the average fitness values decrease from case 3 to case 10. In order to show the superiority of the proposed method, the population size which obtains better than solution reported in literature is determined as best one. Therefore optimum population size for this test system is taken into account as case 5.
For the case 5, the fitness values variations of the best, the worst and average individuals against iteration number of the modified IEEE 14-bus test system are shown in Fig. 6.

The power loss variations of the best, the worst and average individuals against iteration number of the modified IEEE 14-bus test system for the case 5 are shown in Fig. 7.

For the case 5, comparative DC system results obtained by GA and Ref. [36] of the modified IEEE 14-bus test system are given in Table 4.

Comparative AC system results obtained by GA and Ref. [36] of the modified IEEE 14-bus test system for the case 5 are given in Table 5. As can be evidently seen from Table 5, the power loss obtained by GA is lesser than that reported in Ref. [36] by 16.32%.

The reactive power variations at rectifier and inverter sides against iteration number for the modified IEEE 14-bus test system are shown in Fig. 8.

Transformer tap ratio variations at rectifier and inverter sides against iteration number for the modified IEEE 14-bus test system are shown in Fig. 9.

Table 9

<table>
<thead>
<tr>
<th>Cases</th>
<th>Minimum fitness value</th>
<th>Maximum fitness value</th>
<th>Average fitness value</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44.5042</td>
<td>51.9933</td>
<td>256.989</td>
<td>23.3</td>
</tr>
<tr>
<td>2</td>
<td>40.8734</td>
<td>46.6905</td>
<td>196.732</td>
<td>51.1</td>
</tr>
<tr>
<td>3</td>
<td>39.546</td>
<td>46.0505</td>
<td>196.732</td>
<td>72.3</td>
</tr>
<tr>
<td>4</td>
<td>38.4464</td>
<td>47.4534</td>
<td>180.654</td>
<td>99.6</td>
</tr>
<tr>
<td>5</td>
<td>37.1844</td>
<td>47.4534</td>
<td>180.654</td>
<td>121.4</td>
</tr>
<tr>
<td>6</td>
<td>36.1538</td>
<td>46.3185</td>
<td>180.654</td>
<td>130.6</td>
</tr>
<tr>
<td>7</td>
<td>35.5116</td>
<td>46.3185</td>
<td>180.654</td>
<td>178.9</td>
</tr>
<tr>
<td>8</td>
<td>35.4762</td>
<td>45.0288</td>
<td>180.654</td>
<td>209.6</td>
</tr>
<tr>
<td>9</td>
<td>35.0795</td>
<td>43.6327</td>
<td>180.654</td>
<td>229.8</td>
</tr>
<tr>
<td>10</td>
<td>34.8669</td>
<td>42.5273</td>
<td>180.654</td>
<td>250.4</td>
</tr>
</tbody>
</table>

For the case 5, the fitness values variations of the best, the worst and average individuals against iteration number of the modified IEEE 14-bus test system are shown in Fig. 6.


Fig. 19. The modified New England 39-bus system [38].

Fig. 20. The fitness values variations of the best, the worst and average individuals against iteration number of the modified New England 39-bus test system for the case 5.

Fig. 21. The power loss variations of the best, the worst and average individuals against iteration number of the modified New England 39-bus test system for the case 5.
5.2. The modified IEEE 30-bus test system

The data of the modified IEEE 30-bus test system is given in Ref. [37]. The study is realized for different cases of the modified IEEE 30-bus test system. These are:

**HVDC Case A:** A two-terminal HVDC link is included between buses 2 (rectifier bus) and 14 (inverter bus) in the original IEEE 30-bus test system.

**HVDC Case B:** A two-terminal HVDC link is included between buses 2 (rectifier bus) and 16 (inverter bus) in the original IEEE 30-bus test system.

For both HVDC cases, the modified IEEE 30-bus test system is shown in Fig. 10.

For both HVDC cases, the maximum, minimum and average fitness values and the computational times obtained for different population sizes are given in Table 6.

As can be evidently seen from Table 6, for some trials in the population cases of 1–4, the minimum fitness values are within the normal range whereas the maximum fitness values exceed the normal range.

**Table 10**

DC system results for the modified New England 39-bus test system.

<table>
<thead>
<tr>
<th>Control angles (°)</th>
<th>Tap-ratio</th>
<th>Active power (p.u.)</th>
<th>Reactive power (p.u.)</th>
<th>DC current (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>9.364390</td>
<td>0.93</td>
<td>0.910674</td>
<td>0.317602</td>
</tr>
<tr>
<td>Rec.</td>
<td>10.979469</td>
<td>0.94</td>
<td>0.908758</td>
<td>0.286124</td>
</tr>
<tr>
<td>Inv.</td>
<td>9.737835</td>
<td>0.99</td>
<td>0.911674</td>
<td>0.319752</td>
</tr>
<tr>
<td>1</td>
<td>9.462326</td>
<td>0.98</td>
<td>0.908758</td>
<td>0.286124</td>
</tr>
<tr>
<td>2</td>
<td>10.043390</td>
<td>0.95</td>
<td>0.908758</td>
<td>0.286124</td>
</tr>
<tr>
<td>3</td>
<td>10.623789</td>
<td>0.97</td>
<td>0.908758</td>
<td>0.286124</td>
</tr>
<tr>
<td>4</td>
<td>11.204239</td>
<td>0.96</td>
<td>0.908758</td>
<td>0.286124</td>
</tr>
</tbody>
</table>

**Table 11**

AC system results for the modified New England 39-bus test system.

<table>
<thead>
<tr>
<th>Bus number</th>
<th>$v_1$ (p.u.)</th>
<th>Angle (°)</th>
<th>$p_g$ (p.u.)</th>
<th>$q_g$ (p.u.)</th>
<th>Transformer tap ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
<td>-10.043</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.022</td>
<td>-8.1610</td>
<td>-</td>
<td>-</td>
<td>$t_{12-11}$</td>
</tr>
<tr>
<td>3</td>
<td>1.014</td>
<td>-11.703</td>
<td>-</td>
<td>-</td>
<td>$t_{10-11}$</td>
</tr>
<tr>
<td>4</td>
<td>0.987</td>
<td>-12.288</td>
<td>-</td>
<td>-</td>
<td>$t_{10-12}$</td>
</tr>
<tr>
<td>5</td>
<td>0.999</td>
<td>-10.166</td>
<td>-</td>
<td>-</td>
<td>$t_{10-13}$</td>
</tr>
<tr>
<td>6</td>
<td>1.003</td>
<td>-9.270</td>
<td>-</td>
<td>-</td>
<td>$t_{10-14}$</td>
</tr>
<tr>
<td>7</td>
<td>0.991</td>
<td>-11.463</td>
<td>-</td>
<td>-</td>
<td>$t_{10-15}$</td>
</tr>
<tr>
<td>8</td>
<td>0.990</td>
<td>-11.957</td>
<td>-</td>
<td>-</td>
<td>$t_{10-16}$</td>
</tr>
<tr>
<td>9</td>
<td>1.008</td>
<td>-10.824</td>
<td>-</td>
<td>-</td>
<td>$t_{10-17}$</td>
</tr>
<tr>
<td>10</td>
<td>1.018</td>
<td>-6.395</td>
<td>-</td>
<td>-</td>
<td>$t_{10-18}$</td>
</tr>
<tr>
<td>11</td>
<td>1.012</td>
<td>-7.368</td>
<td>-</td>
<td>-</td>
<td>$t_{10-19}$</td>
</tr>
<tr>
<td>12</td>
<td>1.024</td>
<td>-7.284</td>
<td>-</td>
<td>-</td>
<td>$t_{10-20}$</td>
</tr>
<tr>
<td>13</td>
<td>1.015</td>
<td>-7.071</td>
<td>-</td>
<td>-</td>
<td>$t_{10-21}$</td>
</tr>
<tr>
<td>14</td>
<td>1.013</td>
<td>-8.619</td>
<td>-</td>
<td>-</td>
<td>$t_{10-22}$</td>
</tr>
<tr>
<td>15</td>
<td>1.006</td>
<td>-10.84</td>
<td>-</td>
<td>-</td>
<td>$t_{10-23}$</td>
</tr>
<tr>
<td>16</td>
<td>1.015</td>
<td>-10.161</td>
<td>-</td>
<td>-</td>
<td>$t_{10-24}$</td>
</tr>
<tr>
<td>17</td>
<td>1.024</td>
<td>-11.302</td>
<td>-</td>
<td>-</td>
<td>$t_{10-25}$</td>
</tr>
<tr>
<td>18</td>
<td>1.019</td>
<td>-11.896</td>
<td>-</td>
<td>-</td>
<td>$t_{10-26}$</td>
</tr>
<tr>
<td>19</td>
<td>1.013</td>
<td>-5.601</td>
<td>-</td>
<td>-</td>
<td>$t_{10-27}$</td>
</tr>
<tr>
<td>20</td>
<td>1.007</td>
<td>-6.683</td>
<td>-</td>
<td>-</td>
<td>$t_{10-28}$</td>
</tr>
<tr>
<td>21</td>
<td>1.005</td>
<td>-8.032</td>
<td>-</td>
<td>-</td>
<td>$t_{10-29}$</td>
</tr>
<tr>
<td>22</td>
<td>1.009</td>
<td>-3.671</td>
<td>-</td>
<td>-</td>
<td>$t_{10-30}$</td>
</tr>
<tr>
<td>23</td>
<td>1.012</td>
<td>-4.078</td>
<td>-</td>
<td>-</td>
<td>$t_{10-31}$</td>
</tr>
<tr>
<td>24</td>
<td>1.020</td>
<td>-10.172</td>
<td>-</td>
<td>-</td>
<td>$t_{10-32}$</td>
</tr>
<tr>
<td>25</td>
<td>1.036</td>
<td>-7.359</td>
<td>-</td>
<td>-</td>
<td>$t_{10-33}$</td>
</tr>
<tr>
<td>26</td>
<td>1.057</td>
<td>-10.783</td>
<td>-</td>
<td>-</td>
<td>$t_{10-34}$</td>
</tr>
<tr>
<td>27</td>
<td>1.038</td>
<td>-12.186</td>
<td>-</td>
<td>-</td>
<td>$t_{10-35}$</td>
</tr>
<tr>
<td>28</td>
<td>1.051</td>
<td>-9.64</td>
<td>-</td>
<td>-</td>
<td>$t_{10-36}$</td>
</tr>
<tr>
<td>29</td>
<td>1.049</td>
<td>-7.576</td>
<td>-</td>
<td>-</td>
<td>$t_{10-37}$</td>
</tr>
<tr>
<td>30</td>
<td>1.016</td>
<td>-4.48</td>
<td>3.28362</td>
<td>-0.28788</td>
<td>$t_{10-38}$</td>
</tr>
<tr>
<td>31</td>
<td>1.000</td>
<td>0.00</td>
<td>6.24765</td>
<td>2.366</td>
<td>$t_{10-39}$</td>
</tr>
<tr>
<td>32</td>
<td>1.014</td>
<td>1.747</td>
<td>7.02286</td>
<td>2.28483</td>
<td>$t_{10-40}$</td>
</tr>
<tr>
<td>33</td>
<td>1.059</td>
<td>-1.524</td>
<td>5.60843</td>
<td>0.20751</td>
<td>$t_{10-41}$</td>
</tr>
<tr>
<td>34</td>
<td>0.973</td>
<td>-0.699</td>
<td>5.41427</td>
<td>1.24117</td>
<td>$t_{10-42}$</td>
</tr>
<tr>
<td>35</td>
<td>1.059</td>
<td>0.893</td>
<td>6.25942</td>
<td>-0.037</td>
<td>$t_{10-43}$</td>
</tr>
<tr>
<td>36</td>
<td>1.050</td>
<td>2.904</td>
<td>4.86081</td>
<td>0.90016</td>
<td>$t_{10-44}$</td>
</tr>
<tr>
<td>37</td>
<td>1.009</td>
<td>0.541</td>
<td>6.07412</td>
<td>-0.02089</td>
<td>$t_{10-45}$</td>
</tr>
<tr>
<td>38</td>
<td>1.024</td>
<td>-2.228</td>
<td>6.34158</td>
<td>-1.7428</td>
<td>$t_{10-46}$</td>
</tr>
<tr>
<td>39</td>
<td>0.963</td>
<td>-9.777</td>
<td>11.80329</td>
<td>-2.43789</td>
<td>$t_{10-47}$</td>
</tr>
</tbody>
</table>

Power loss (p.u.) 0.37184

**Fig. 22.** The reactive power variations at rectifier and inverter sides against iteration number for the modified New England 39-bus test system.

**Fig. 23.** Transformer tap ratio variations at rectifier and inverter sides against iteration number for the modified New England 39-bus test system.

HVDC Case A: A two-terminal HVDC link is included between buses 2 (rectifier bus) and 14 (inverter bus) in the original IEEE 30-bus test system.

HVDC Case B: A two-terminal HVDC link is included between buses 2 (rectifier bus) and 16 (inverter bus) in the original IEEE 30-bus test system.

For both HVDC cases, the modified IEEE 30-bus test system is shown in Fig. 10.

For both HVDC cases, the maximum, minimum and average fitness values and the computational times obtained for different population sizes are given in Table 6.

As can be evidently seen from Table 6, for some trials in the population cases of 1–4, the minimum fitness values are within the normal range whereas the maximum fitness values exceed the normal range.
The minimum and maximum fitness values are within the normal range in the population cases of 5–10. Although the computational time difference between population cases 5 and 10 is great, the fitness value difference between cases 5 and 10 is low. On this account, acceptable population size is determined as case 5 for both HVDC cases.

For both HVDC cases, the fitness value variations of the best, the worst and average individuals against iteration number are shown in Figs. 11 and 12, respectively.

For both HVDC cases, the power loss variations of the best, the worst and average individuals against iteration number are shown in Figs. 13 and 14, respectively.

Comparative DC system results obtained by GA and Ref. [37] are given in Table 7.

Comparative AC system results obtained by GA and Ref. [37] are given in Table 8. As can be evidently seen from Table 8, the power losses obtained by GA and the numerical method in Ref. [37] for HVDC Case A are 0.1240 and 0.2841, respectively. The power losses obtained by GA and the numerical method in Ref. [37] for HVDC Case B are also 0.1201 and 0.2811, respectively. For both HVDC cases, the results obtained by GA are lesser than those reported in Ref. [37] by 56.35% and 57.27%, respectively.

For both HVDC cases, the reactive power variations at rectifier and inverter sides against iteration number are shown in Figs. 15 and 16, respectively.

For both HVDC cases, transformer tap ratio variations at rectifier and inverter sides against iteration number are shown in Figs. 17 and 18, respectively.

For both HVDC cases, as can be evidently seen from Figs. 17 and 18 that the transformer tap ratios are within limits at the end of the iteration.

5.3. The modified New England 39-bus test system

AC transmission line between buses 4 and 14 in the original New England 39-bus test system is replaced with a two terminal HVDC link and the modified New England 39-bus test system shown in Fig. 19 is obtained [38]. The upper and lower limits of the transformer tap ratios in power system are 1.1 p.u. and 0.9 p.u., respectively. DC link data for this test system is the same as that of the modified 14-bus test system.

The simulation results obtained by the trials are given in Table 9.

By reason of comparison of the fitness values and the computational times, the optimum solution is determined as case 5. For case 5, the variations of the best, the worst, and the average fitness values against iteration number is shown in Fig. 20.

The power loss variations of the best, the worst and average individuals against iteration number for case 5 of the modified New England 39-bus test system are shown in Figs. 11 and 12.

The reactive power variations at rectifier and inverter sides against iteration number for the modified New England 39-bus test system are shown in Fig. 22.

Transformator tap ratio variations at rectifier and inverter sides against iteration number for the modified New England 39-bus test system are shown in Fig. 23.

6. Conclusion and discussion

In this study, ORPF problem of an integrated AC–DC power system is firstly solved by GA. In order to show the validity, the efficiency, and the effectiveness of GA, ORPF problem of an integrated AC–DC power system is tested on three test systems which are the modified IEEE 14-bus test system, the modified IEEE 30-bus test system and the modified New England 39-bus test system. As can be evidently shown from Tables 5 and 8, ORPF results obtained by GA for the modified IEEE 14-bus test system and the modified IEEE 30-bus test system is lesser than those obtained by the numerical method in Ref. [36,37]. As can be evidently seen GA is also faster than the numerical methods in terms of the convergence times. In comparison with other methods, GA converges reliably and rapidly to the true optimal point. In future, this algorithm and the other heuristic algorithms can be applied to ORPF of the large-scale multi-terminal HVDC systems.

As a result, it can be seen that the size of the system is not proportional to the population size and it is needed to make trials with respect to different population sizes for each system.

References


