A new approach for optimal reactive power flow of MTDC systems using the ABC algorithm

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Abstract: This paper presents a new approach to optimize reactive power flow of multiterminal high voltage direct current (HVDC) systems. Successful application of two-terminal DC systems worldwide makes the use of multiterminal direct current (MTDC) systems more attractive. Due to the economic and technical advantages of HVDC technology, MTDC systems have been used extensively in recent years. In this study, the artificial bee colony (ABC) algorithm is used for solution of the optimal reactive power flow problem of MTDC systems. In opposition to the current-balancing method used in the literature, this study represents a new approach for DC system power flow calculations. The proposed approach is tested on a sample IEEE MTDC test system. The results by the proposed approach are compared with those reported in the literature. Thus, the applicability and the efficiency of this approach used together with the ABC algorithm are shown.

Key words: Optimal reactive power flow, high voltage direct current system, multiterminal direct current system, artificial bee colony algorithm

1. Introduction

There are some advantages of power transmission by using high voltage direct current (HVDC) systems. One of them is the ability to rapidly control the power transmitted over HVDC systems. This possibility creates a considerable effect on the stability of the associated AC systems. Secondly, DC links do not transmit reactive power and thus the performance of HVDC systems increases considerably. In addition, recent advances in semiconductor technology have reduced size of the conversion equipment and also improved its reliability. However, these systems have some disadvantages. First, the converters, which are among the fundamental components of HVDC systems, absorb reactive power, and second, they also generate harmonic currents and voltages. They can cause overheating of capacitances and nearby generators. For this reason, it is necessary to use AC and DC filters on both sides. When HVDC systems contain three or more DC links, they are called multiterminal direct current (MTDC) systems.

Many numerical methods have been used for the power flow solution of MTDC systems so far. Essentially they are divided into two categories [1]:

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Sequential method
Simultaneous or unified method

Newton–Raphson-based power flow analysis using the Norton equivalent circuit for multiterminal AC-DC systems was given in [1]. Here the converters on both sides are simulated by a commutation resistance in parallel with a current source. The active powers at all the buses except the slack bus, where the voltage is specified, are considered as being specified. While previous approaches use six variables for each converter on both sides of the DC link, this approach uses three variables. Thus, we have lower storage requirements and the algorithm converges rapidly. In [2], a sequential power flow algorithm was proposed for a balanced and unbalanced multiterminal bipolar AC-DC system. The proposed algorithm has two advantages. One of them is that we have less convergence time and storage requirements, as DC system variables are not included in the Jacobian matrix. The other is that this algorithm can be developed for balanced and unbalanced situations and run with current, voltage, and power controlled terminals without changing anything. A new technique for power flow analysis of integrated AC-DC systems was proposed in [3]. Here a fast decoupled load flow technique is used, and entire AC-DC system equations are handled simultaneously. This technique is applied to two systems, one with a point-to-point DC transmission and the other with a 3-terminal mesh HVDC subsystem. An optimal power flow solution using a sequential quadratic programming technique for an AC-DC power system having one or more MTDC systems was proposed in [4]. Here, as the power transmitted over DC systems can be controlled easily, the economic advantage of this is explained by numerical results obtained from the test systems. A generalized DC power flow software for multiterminal HVDC systems was developed in [5]. This can be implemented together with any AC power flow software. A new approach for power flow of AC-DC systems was presented in [6]. Here, the converters on both sides of the DC link are considered as voltage-dependent loads and the power flow equations are arranged without considering DC variables. Therefore, the method developed in [6] is reliable and simple. Thus, the power flow equations of each area can be solved separately for nonsynchronous interconnections.

Many numerical and heuristic methods such as quadratic programming [7], linear programming [8], the genetic algorithm [9], particle swarm optimization [10], and the artificial bee colony (ABC) algorithm [11] have been applied to solve the optimal reactive power flow (ORPF) problem of purely AC systems so far. As seen from the results reported in the literature, heuristic methods are superior to numerical methods [9–11].

The ABC algorithm is a population-based heuristic optimization algorithm proposed by Karaboga [12]. As the ABC algorithm is effective in determining the global minimum points of nonlinear and nonconvex problems, it has been applied to optimal power flow problems of AC and AC-DC power systems successfully in recent years [13–21]. In addition to this, up to now, a current-balancing approach has been used for solving the reactive power flow problem of MTDC systems. In this approach, the sum of the currents absorbed by DC terminals in the MTDC system is tried to be made zero by using all the current-voltage relationships in a calculation process. Herein, the variables are sensitive to their initial conditions, and when they exceed their limits, the computation time increases. In opposition to this, this paper proposes a new approach for solving this problem. The proposed approach overcomes the disadvantages of the current-balancing approach by selecting the currents transmitted from two DC links as the control variables. Finally, in this study, the ABC algorithm is used together with the proposed approach for the first time.

The rest of the paper is organized as follows: the DC system model is illustrated in Section 2. An overview of the ABC algorithm is introduced in Section 3. Application of the proposed approach to the ORPF problem of MTDC systems is explained in Section 4. In Section 5, the proposed approach is applied to the modified
IEEE 14-bus test system and the obtained simulation results are given in tables. They are then discussed by comparison with those reported in the literature. Finally, the validity and effectiveness of this approach used together with the ABC algorithm are presented based on comparative results and the superiority of this approach over the other methods is demonstrated in Section 6.

2. DC system model

The DC system model, consisting of a DC link and converters, is based on the accepted assumptions in the literature [6]. A general bus representation having generators, AC lines, shunt compensators, and converters is given in Figure 1 [4].

In Figure 1, $P$, $Q$, $V$, and $\delta$ represent active power outputs, reactive powers, bus voltage magnitudes, and bus voltage angles, respectively. The subscripts $g$, $l$, $s$, and $dc$ also represent the generator, load, shunt reactive compensator, and DC link, respectively. The active and reactive power balances at bus $k$ can be also expressed by the following equations:

\begin{align}
P_{gk} & = P_{lk} + P_{dck} + P_k, \quad (1) \\
Q_{gk} + Q_{sk} & = Q_{lk} + Q_{dck} + Q_k, \quad (2)
\end{align}

where $P_{gk}$ and $Q_{gk}$ represent the output active and reactive powers of the generator connected to the $k$th bus, $P_{lk}$ and $Q_{lk}$ represent the active and reactive loads of the $k$th bus, $Q_{sk}$ represents the reactive power of the shunt reactor connected to the $k$th bus, $P_{dck}$ represents the active power given to the DC transmission link connected to the $k$th bus, $Q_{dck}$ represents the reactive power absorbed by the converter at the $k$th bus, and $P_k$ and $Q_k$ represent the active and reactive powers transferred through the AC transmission line connected to the $k$th bus. $P_k$ and $Q_k$ are also given by the following equations:

\begin{align}
P_k & = V_k \sum_{j=1}^{N} V_j (G_{kj} \cos \delta_{kj} + B_{kj} \sin \delta_{kj}), \quad (3) \\
Q_k & = V_k \sum_{j=1}^{N} V_j (G_{kj} \sin \delta_{kj} - B_{kj} \cos \delta_{kj}), \quad (4)
\end{align}
where $V_j$ and $V_k$ are the voltage magnitudes of the $j$th and $k$th buses, $G_{kj}$ and $B_{kj}$ are transfer conductance and susceptance between buses $k$ and $j$ of the bus admittance matrix $Y_{bus}$, $\delta_{kj}$ is the voltage angle difference between buses $k$ and $j$, and $N$ is the bus number in the power system.

2.1. DC system equations

The DC voltage of an $m$-pulse rectifier in a monopolar HVDC system can be expressed by the following equation [22]:

$$V_{dck} = nmt_{dck} \frac{\sqrt{2}V_k}{\pi} \sin\left(\frac{\pi}{m}\right) \cos \alpha_k - \frac{nmX_{ck}}{2\pi} I_{dck},$$

(5)

where $n$ is the converter number in series, $m$ is peak number on load voltage per period, $t_{dck}$ is the tap ratio of the transformer at the DC side, $V_k$ is the secondary effective voltage of the transformer, $\alpha_k$ is the gating delay angle for the rectifier operation (or the extinction advance angle for inverter operation), $X_{ck}$ is the commutation reactance, and $I_{dck}$ is the DC current.

The equivalent representation of a converter terminal and converter circuit model is given in Figures 2 and 3 [4], respectively. Rearranging Eq. (5) for $m = 6$ and $n = 1$,

$$V_{dck} = \frac{3}{\pi} X_c I_{dck},$$

(6)
The expression $V_{dcok} = 3\sqrt{2}V_kt_{dc}k/\pi$ in the first term of Eq. (6) is defined as the open circuit direct voltage. Thus, for the actual quantities of the HVDC system, the direct voltage, the phase shifted the active power, and the reactive power expressions can be given as follows, respectively.

$$V_{dc} = V_{dcok} \cos \alpha_k - \frac{3}{\pi} X_{ck} I_{dck}$$  \hspace{1cm} (7)

$$V_{dc} = V_{dcok} \cos \gamma_k - \frac{3}{\pi} X_{ck} I_{dck}$$  \hspace{1cm} (8)

$$\varphi_k = \cos^{-1} \left( \frac{V_{dc}}{V_{dcok}} \right)$$  \hspace{1cm} (9)

$$P_{dc} = V_{dc} I_{dc}$$  \hspace{1cm} (10)

$$Q_{dc} = |P_{dc} \tan \varphi_k|$$  \hspace{1cm} (11)

Here, $\varphi_k$ represents phase shifted.

2.2. Per unit transformation

After defining the base active power $P_{ACbase}$ and the base voltage $V_{ACbase}$ of the AC side, the base current $I_{ACbase}$ and base impedance $Z_{ACbase}$ for the AC side can be determined as follows:

$$P_{ACbase} = P_{DCbase},$$ \hspace{1cm} (12)

$$I_{ACbase} = \frac{P_{ACbase}}{\sqrt{3}V_{ACbase}},$$ \hspace{1cm} (13)

$$Z_{ACbase} = \frac{V_{ACbase}}{\sqrt{3}I_{ACbase}}.$$ \hspace{1cm} (14)

After defining the base active power $P_{DCbase}$, the expressions of $V_{DCbase}$, $I_{DCbase}$, and $Z_{DCbase}$ for the DC side can be determined by defining $C_b = \sqrt{2}nm\sin \left( \frac{\pi}{m} \right) / \pi$ as follows:

$$V_{DCbase} = C_b V_{ACbase},$$ \hspace{1cm} (15)

$$I_{DCbase} = \frac{\sqrt{3}I_{ACbase}}{C_b},$$ \hspace{1cm} (16)

$$Z_{DCbase} = C_b^2 Z_{ACbase},$$ \hspace{1cm} (17)

where $V_{DCbase}$, $I_{DCbase}$, and $Z_{DCbase}$ show active base power, DC base voltage, DC base current, and base impedance of DC side. The expressions in per unit are given by dividing the actual AC and DC expressions into their base expressions as follows:

$$v_k = \frac{V_k}{V_{ACbase}},$$ \hspace{1cm} (18)
where $v_k$, $x_{ck}$, $r_{ck}$, $v_{dck}$, and $i_{dck}$ show AC voltage, commutation reactance, commutation resistance, DC voltage, and DC current in per unit, respectively. According to these, the others are determined by the following equations:

\[
V_{dck} = \frac{nmt_{dck} \sqrt{V_k}}{V_{DCbase}} \sin \left( \frac{\pi}{m} \right) \cos \alpha_k - \frac{nmx_{ck}I_{dck}}{V_{DCbase}},
\]

\[
V_{dck} = \frac{nmt_{dck} \sqrt{V_k}}{\sqrt{2}nm \sin \left( \frac{\pi}{m} \right) V_{ACbase}/\pi} - \frac{nmx_{ck}I_{dck}}{Z_{DCbase}I_{DCbase}},
\]

\[
v_{dck} = v_k t_{dck} \cos \alpha_k - r_{ck} i_{dck},
\]

\[
p_{dck} = v_{dck} i_{dck},
\]

\[
v_{dcek} = v_k t_{dck},
\]

\[
\varphi_k = \cos^{-1} \left( \frac{v_{dck}}{v_{dcek}} \right),
\]

\[
q_{dck} = |p_{dck} \tan \varphi_k|.
\]

3. Overview of the ABC algorithm

The ABC algorithm proposed by Karaboga in 2005 can be explained by the concept of swarm intelligence for real bees [12]. The algorithm has been applied to various engineering problems successfully since 2005 [23–30]. The algorithm consists of four major steps: initialization, worker bees, onlooker bees, and scout bees. Following the initialization step, the other three steps are repeated respectively until completing the algorithm.

The following assumptions shall be noted before getting to other steps: only one bee can enter each nourishment source, a failure value is saved for each nourishment source, and the bees that are sent to nourishment sources at the initialization step are considered as worker bees after this step.

Initialization: At this step, nourishment sources within the search area are randomly identified. In order to identify a nourishment source, a random value between the lower limit and the upper limit of the parameters can be deduced by the equation below:

\[
w_{ij}^{new} = w_{min,j} + \text{rand}(0,1) \left( w_{max,j} - w_{min,j} \right),
\]
where \( i = 1, \ldots, SN \), \( SN \) is the size of the nourishment source, \( j = 1, \ldots, D \), \( D \) is the number of optimization parameters, \( w_{\min,j} \) and \( w_{\max,j} \) are the limits of the nourishment source position, and \( \text{rand}(0,1) \) varies between 0 and 1.

Step 1. Worker bees: The worker bees identify a new source neighboring the nourishment source they work on; if the nourishment amount in a specified source is abundant, the newly detected source gets memorized. The worker bee then informs the other bees in the hive about which source is the best one. The identification process of a new nourishment source can be defined as below:

\[
w_{ij}^{\text{new}} = w_{ij}^{\text{old}} + \lambda_{ij} (w_{ij}^{\text{old}} - w_{kj}^{\text{old}}) \quad i = 1, \ldots, SN; \quad k = 1, \ldots, SN; \quad i \neq k \text{ and } j = 1, \ldots, D,
\]

where \( w_{ij} \) is the nourishment source position and \( \lambda_{ij} \) is a random number between {1 and 1.}

Step 2. Onlooker bees: Each one of the worker bees informs the scout bees about the nourishment source they have used. The scout bees then choose a source in proportion with the nourishment amount in the source. The probability of choosing a particular source is determined by the ratio of nourishment amount in a specified source to total nourishment amount in all resources. This ratio is given by Eq. (32). This operation is called the “roulette wheel”. In this way, all the nourishment sources are given a chance to be chosen, while the sources with a larger amount of nourishment are given a higher chance of being chosen.

\[
s_{pi} = \frac{fit_{i}}{\sum_{j=1}^{SN} fit_{j}} \quad i = 1, \ldots, SN,
\]

where \( fit_{i} \) represents nourishment amount in the \( i \)th source, which is proportional to the fitness value of the \( i \)th nourishment source.

The efficiency of a nourishment source is calculated by Eq. (33) [23–25]. The selection probability of a nourishment source with high efficiency is higher in the roulette wheel selection.

\[
fit_{i} = \frac{1}{F_{i}} \quad i = 1, \ldots, SN
\]

Step 3. Scout bees: At the end of each cycle when all the worker bees and scout bees finish their quest for sources, they share the information they have collected with the other bees in the beehive. This sharing of information also includes the failure value of each nourishment source as well. This measurement technique shows whether the source with the largest nourishment amount in a given region is depleted or not. If the source with the larger nourishment amount is depleted, the search for nourishment around that source discontinues. In that case, the worker bee leaves that given nourishment source and the scout bees discontinue their search around that source. If a worker bee leaves a particular source, then that bee becomes a scout bee. In each cycle, only one bee among all worker bees can become a scout bee. When a worker bee becomes a scout bee, then the new scout bee randomly identifies a new nourishment source in the search area using Eq. (30). The value to which a particular source is depleted is referred as the “limit”.

4. Application of the proposed approach to the problem

The control variables of the optimization problem are given by the following equations:

\[
u = [u_{AC}, u_{DC}],
\]
\[
U_{AC} = [p_{g2}, ..., p_{gN_g}, v_{g1}, ..., v_{gN_g}, t_1, ..., t_{N_T}, q_{c1}, ..., q_{N_c}],
\]
\[
U_{DC} = [p_{dc1}, q_{dc1}, q_{dc2}, q_{dc3}, i_{dc12}, i_{dc13}],
\]

where \(p_{gi}\) except for the slack bus is the generator active power outputs, \(v_{gi}\) is the generator voltage magnitudes, \(t\) is the transformer tap setting, and \(q_c\) is the shunt compensation. \(N_g\), \(N_T\), and \(N_c\) are the number of generator buses, transformers, and shunt VAR compensators, respectively. The state variables are also given by the following equations:

\[
x = [x_{AC}, x_{DC}],
\]

\[
x_{AC} = [p_{gslack}, q_{g1}, ..., q_{gN_g}, v_{L1}, ..., v_{LN_l}],
\]

\[
x_{DC} = [v_{dc1}, v_{dc2}, v_{dc3}, t_{dc1}, t_{dc2}, t_{dc3}, \alpha_1, \alpha_2, \alpha_3],
\]

where \(p_{gslack}\) is the slack bus active power output, \(q_{gi}\) is the reactive power outputs, \(v_{Li}\) is the load bus voltage magnitudes, and \(N_l\) is the number of load buses.

The representation of a multiterminal HVDC system is given in Figure 4.

**Figure 4.** The representation of the multiterminal HVDC system.

The power flow calculation is performed by the proposed approach and a fitness value \(F_i\) for each individual is calculated to evaluate its quality as follows:

Step 1: The initial conditions of the control variables are obtained by the ABC algorithm.

Step 2: \(i_{dc1}\) is obtained by the following equation:

\[
i_{dc1} = i_{dc12} + i_{dc13}.
\]
Step 3: $v_{dc1}$ is obtained by the following equation:

$$v_{dc1} = p_{dc1}/i_{dc1}. \quad (41)$$

Step 4: $v_{dc2}$ is obtained by the following equation:

$$v_{dc2} = v_{dc1} - i_{dc12}r_{dc12}. \quad (42)$$

Step 5: $v_{dc3}$ is obtained by the following equation:

$$v_{dc3} = v_{dc1} - i_{dc13}r_{dc13}. \quad (43)$$

Step 6: $i_{dc23}$ is obtained by the following equation:

$$i_{dc23} = (v_{dc2} - v_{dc3})/r_{dc23}. \quad (44)$$

Step 7: $i_{dc2}$ is obtained by the following equation:

$$i_{dc2} = i_{dc23} - i_{dc12}. \quad (45)$$

Step 8: $i_{dc3}$ is obtained by the following equation:

$$i_{dc3} = -i_{dc23} - i_{dc13}. \quad (46)$$

Step 9: $p_{dc2}$ is obtained by the following equation:

$$p_{dc2} = v_{dc2}i_{dc2}. \quad (47)$$

Step 10: $p_{dc3}$ is obtained by the following equation:

$$p_{dc3} = v_{dc3}i_{dc3}. \quad (48)$$

Step 11: The active and reactive powers of DC links are considered as load and then the powers at these buses are updated by the following relationships:

$$p_{l_{update}}^{ij} = p_{ij} + p_{dcj}$$
$$q_{l_{update}}^{ij} = q_{ij} + q_{dcj}$$

$$j = 1, 2, 3. \quad (49)$$

Step 12: Power flow analysis is realized by the Newton–Raphson method. Whole state variables at the AC side are specified and the unknown state variables at the DC side are calculated step by step as follows.

Step 13: $\varphi_j$ is obtained by the following equation:

$$\varphi_j = \tan^{-1} \left( \frac{q_{dcj}}{p_{dcj}} \right)$$

$$j = 1, 2, 3. \quad (50)$$
Step 14: \( t_{dcj} \) is obtained by the following equation:

\[
t_{dcj} = \frac{v_{dcj}}{v_j \cos \varphi_j}
\]

\( j = 1, 2, 3 \).

(51)

Step 15: \( v_{doj} \) is obtained by the following equation:

\[
v_{doj} = v_{dcj} + |i_{dcj} r_{cj}| \quad j = 1, 2, 3.
\]

(52)

Step 16: \( \alpha_j \) or \( \gamma_j \) is obtained by the following equation:

\[
\alpha_j, \gamma_j = \cos^{-1} \left( \frac{v_{dcj}}{v_{doj} t_{dcj}} \right) \quad j = 1, 2, 3.
\]

(53)

Step 17: Power loss is obtained by the following equation:

\[
p_{loss} = \sum_{i=1}^{N_g} p_{gi} - \sum_{j=1}^{N_l} p_{lj}.
\]

(54)

Step 18: A fitness value \( F_i \) for each individual is calculated by the following equation:

\[
F_i = p_{loss} + \left( p_{gslack} - p_{gslack}^{lim} \right)^2 + \sum_{i=1}^{N_g} \left( q_{gi} - q_{gi}^{lim} \right)^2 + \sum_{i=1}^{N_l} \left( v_{li} - v_{li}^{lim} \right)^2 + \sum_{j=1}^{3} \left( v_{dcj} - v_{dcj}^{lim} \right)^2
\]

\[
+ \sum_{j=1}^{3} \left( t_{dcj} - t_{dcj}^{lim} \right)^2 + \sum_{j=1}^{3} \left( \alpha_j - \alpha_j^{lim} \right)^2,
\]

where \( p_{gslack}^{lim}, q_{gi}^{lim}, v_{li}^{lim}, v_{dcj}^{lim}, \) and \( \alpha_j^{lim} \) show the limits of the related variables, respectively.

(55)

5. Discussion of the simulation results

AC transmission lines among buses 5, 4, and 2 in the original IEEE 14-bus test system are replaced to the MTDC system and the modified IEEE 14-bus test system is obtained as shown in Figure 5 [31]. Many experimental runs were performed with different iteration and population sizes. When the iteration number is higher than 1000 and the population size is larger than 200, the computation time needed for reaching an optimum solution increases; thus, they need to be restricted by these values. Therefore, several experiments for different population sizes with reasonable iterations are performed. According to the experimental results, the optimum population size is determined as 60 for the ABC algorithm. Convergence time of the algorithm for the test system is obtained as 48.24 s.
The variation of fitness value and power loss versus iteration is shown in Figure 6. As seen in the figure, the algorithm converges on an optimum point within 13 iterations in terms of fitness value. It is clear that there is no increase in power loss after 6 iterations.

The variation of the effective transformer tap ratios versus iteration for each converter is given in Figure 7. The figure shows that the effective transformer tap ratios in the first and second converters exceed their limits in the first few iterations and then stay within the limits.

DC and AC system results by the proposed approach are given in Tables 1 and 2, respectively. Furthermore, $t_{47}$, $t_{49}$, $t_{53}$, $q_{c6}$, and $q_{c8}$ are obtained as 1.0761, 1.0324, 1.0267, 0.5111, and 0.4443 in p.u., respectively. In Table 3, the power losses by the proposed approach are given and compared with those reported in the literature. As seen in Table 3, the power loss obtained by the proposed approach is less than those of [22,31–33], namely 39.54%, 22.31%, 3.22%, and 14.80%.
Table 1. DC system results.

<table>
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<th>Variable</th>
<th>Limits (p.u.)</th>
<th>Value (p.u.)</th>
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Table 2. AC system results.

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<th>Value (p.u.)</th>
<th>Variable</th>
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<td>-1.513</td>
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<td>-0.0604</td>
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<td>( p_{g1} )</td>
<td>0.3 2.0</td>
<td>0.3909</td>
<td>( q_{g2} )</td>
<td>-0.6 0.6</td>
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<td>( q_{g3} )</td>
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<tr>
<td>( p_{g3} )</td>
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<td>( q_{g6} )</td>
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<td>0.5111</td>
<td>( t_{47} )</td>
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<td>1.0761</td>
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<td>( q_{g8} )</td>
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<td>0.4443</td>
<td>( t_{49} )</td>
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<td>1.0324</td>
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Table 3. Comparative power losses.

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<td>Power loss (p.u.)</td>
<td>0.051581</td>
<td>0.08532</td>
<td>0.06640</td>
<td>0.05330</td>
<td>0.060545</td>
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6. Conclusion
In this study, a new approach is used to solve the ORPF problem of a multiterminal HVDC system using the ABC algorithm without using the current-balancing method. The proposed approach is realized by taking into consideration DC currents transferred via DC transmission links as the control variables and the sum of these currents as zero. Thus, a new approach is proposed for solving this kind of problem of multiterminal HVDC systems. The power losses reported in the previous section show that this approach is better than the others and can also be applied effectively for optimum power flow and ORPF solutions of large-scale HVDC systems. In ideal operating conditions and in this study, the ratios of reactive powers absorbed by converters to active powers transferred by the DC link for each DC transmission link are taken into account as being 0.5 during the simulation time. In future works, the transformer tap ratios and shunt reactive compensators can be considered as discrete.

References


