

Optimal reactive power flow solution in multiterminal AC-DC systems based on artificial bee colony algorithm

Faruk YALÇIN^{1,*}, Uğur ARİFOĞLU²

¹Department of Mechatronics Engineering, Sakarya University, Sakarya, Turkey

²Department of Electrical-Electronics Engineering, Sakarya University, Sakarya, Turkey

Received: 29.11.2012 • Accepted: 03.01.2013 • Published Online: 15.08.2014 • Printed: 12.09.2014

Abstract: Active power loss optimization is one of the important goals in electrical power systems and it is provided by optimal reactive power flow (ORPF). In this study, a new approach for the solution of the ORPF in multiterminal AC-DC systems is proposed. This approach provides 3 main contributions. First, the convergence problem in the AC-DC power flow is solved. Second, the problem of getting stuck in local minima during the optimization process is overcome. Third, a better global optimum point is obtained for the ORPF. Active power loss optimization is implemented through the artificial bee colony (ABC) algorithm, which is a heuristic optimization method, by considering the system constraints. This study is the first to use the ABC algorithm for the solution of the ORPF in multiterminal AC-DC systems. The proposed approach is tested on the modified IEEE 14-bus AC-DC test system and the obtained results from this and other studies are given. Comparative results prove that this approach is more efficient and reliable in reaching a global optimum while satisfying all of the system constraints.

Key words: Optimal reactive power flow, AC-DC, artificial bee colony algorithm, genetic algorithm

1. Introduction

In electrical power systems, system overloading related to a constantly increasing demand is extremely important for both the supply of the existing and future demands and the reliability of the power system. Due to high costs and inconvenient terrain circumstances economically, there are difficulties in allocating new energy transmission lines. Hence, existing power systems must be used efficiently. Therefore, active power loss minimization in power systems is vastly important for system efficiency, reliability, and economic profit. Active power loss minimization is provided by the optimal reactive power flow (ORPF). Dynamic and static reactive power compensators, shunt capacitors and reactors, generator voltage amplitude values, and tap changers in power systems are the main factors of the ORPF because of their ability to change the reactive power flow [1].

High-voltage direct current (HVDC) systems have been used in integrated AC-DC power systems for a long time. HVDC applications started in the 1950s. Even though investment costs related to HVDC systems are high, they are more economic than AC transmission lines for very long distances. Additionally, efficient conductor intersection, flexible control, system reliability and consistency, efficient implementation, lack of a reactive power problem, and continuously increasing development in semiconductor technology are the advantageous characteristics of HVDC systems [2]. For these reasons, researchers have been working on integrated AC-DC systems for a long time. Many methods have been proposed for AC-DC power flow. These

*Correspondence: farukyalcin@sakarya.edu.tr

methods in the literature can be separated into 2 main parts: sequential and simultaneous methods. In the sequential method, AC and DC power flow are implemented separately and convergence can be provided by going backwards and forwards [3,4]. In the simultaneous method, all of the equations regarding the AC-DC system are one within the other and the equations are solved together [5,6]. Today, there are plenty of commercial real-life applications of HVDC systems around the world. Sweden, Russia, Canada, Brazil [7], the United States, and Italy [8] are some of the countries that utilize HVDC systems in their power grids.

Although there are many significant studies about AC-DC power flow in this area, there are not enough substantial studies on the optimal power flow of 2-terminal or multiterminal AC-DC systems in the literature. Existing optimal power flow studies on AC-DC systems have been implemented using quadratic programming, linear programming, mixed-integer nonlinear programming, the gradient-restoration algorithm, and the steepest descent algorithm [9–14]. However, problems such as convergence and getting stuck in local minima exist in these conventional methods [15]. These conventional methods are based on derivative calculation techniques and convergence is very dependent on the initials of the state variables for the control variables. Improper choice of the initials of the variables may lead to divergence of the power flow algorithm at the beginning. On the other hand, updated variables in the next optimization steps may also cause divergence in the power flow algorithm. Sometimes the divergence problem may not occur in the power flow algorithm with the proper choice of the state variables for both the initial and updated control variables during the optimization process, but optimization cannot be improved with the updated control variables because of getting stuck in local minima due to derivative calculations. Today, some of these optimal power flow studies are applied in the real-life AC-DC power systems in the Indian 2-terminal 96-bus and AC-bus systems [16] and the Chinese Southern 3-HVDC link and 2572 AC-bus systems [17].

Recently, heuristic methods like the genetic algorithm (GA) [18], differential evolution [19], particle swarm optimization [20], and artificial ant colony [21] have been developed for the solution of global optimization problems, and they have been implemented to those problems successfully. These methods are more efficient with respect to accurate and faster convergence and not getting stuck in local minima than are the conventional calculation techniques mentioned above.

The artificial bee colony (ABC) algorithm is also one of the heuristic methods. It has been successfully applied to the solution of optimal active, reactive, and active-reactive power flow in AC power systems as well as in other fields [22–25]. The ABC algorithm is based on the intelligent foraging behavior of honey bee swarms and it tries to find the optimum solution around the solution area defined by the variable constraints of the problem that is optimized. The heuristic-based searching structure of the ABC prevents divergence, as more than one control and state variable set is used, and prevents getting stuck in local minima, as it does not use derivative calculations like the conventional methods mentioned above.

In this study, the newest approach is presented for the solution of the ORPF problem in multiterminal AC-DC systems using the ABC algorithm. The ABC algorithm is used for the ORPF problem. The searching-based and heuristic structure of the ABC prevents divergence during the power flow algorithm and getting stuck in local minima during optimization. Unlike similar studies, to obtain a better global optimum point that provides the minimum active power loss, the active powers of all of the converters, except for at least one, are selected as control variables for the ORPF to achieve the most suitable converter active powers and converter types that improve the active power loss minimization. For this, a sequential AC-DC power flow algorithm is proposed that is used in the optimization algorithm by the ABC. Furthermore, the constraints of the control and state variable vectors are also included in the solution. Finally, the accuracy and consistency of

the proposed approach are tested on the modified IEEE 14-bus AC-DC test system. The obtained results are compared with the GA, which is a similar heuristic method, and the steepest descent algorithm (SDA), which is a derivative-based conventional method, to show the efficiency and reliability of the proposed approach.

Power flow algorithms are the main backbone of optimal power flow studies in power systems because of the requirement of system stability. Furthermore, optimization algorithms need power flow algorithm results. Thus, first, the proposed sequential AC-DC power flow algorithm is described in Section 2. In Section 3, the ORPF problem is given in detail. In Section 4, the ABC algorithm is expressed and the ORPF solution by the ABC is described. Section 5 shows the results and Section 6 draws the conclusions of the study.

2. The illustration of the proposed sequential AC-DC power flow

The power flow problem in a multiterminal AC-DC system is solved using the sequential method as mentioned above. DC power flow is performed using the Gauss iteration method and AC power flow is performed using the Newton method throughout the ORPF solution. Because the variables belonging to the DC system are not taken into account when calculating the Jacobian matrix, a smaller dimension is required and a fast convergence rate is achieved. The active and reactive powers of the converters are taken into account as the constant load for the AC power flow in terms of the sequential method.

2.1. Basic equations for the multiterminal DC system

The converter model for the DC system is shown in Figure 1. In this model, the main harmonic components for the AC system and average values without ripples for the DC system are taken as base values. This study is based on the per-unit system and per-unit values of the AC and DC systems, and their relations are given in the Appendix.

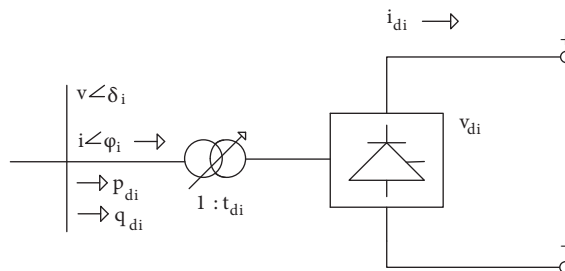


Figure 1. Equivalent representation of a monopolar converter station.

The DC terminal voltage of the i th converter is:

$$v_{di} = t_{di} \cdot v_i \cdot \cos \varphi_i - r_{ci} \cdot i_{di}, \tag{1}$$

where t_{di} , v_i , φ_i , r_{ci} , and i_{di} represent the tap value of the tap changer connected to the i th converter, AC line voltage of the bus connected to the i th converter, α firing angle for the rectifier mode or γ extinction angle for inverter mode, commutation resistance, and DC current value, respectively.

The DC terminal voltage can also be defined as follows:

$$v_{di} = t_{di} \cdot v_i \cdot \cos \theta_i \quad (\theta_i = \delta_i - \phi_i), \tag{2}$$

where angle θ_i represents the difference between the AC voltage angle of the bus connected to the i th converter (δ_i) and current angle of the i th converter's tap changer (ϕ_i).

The active power for the i th converter, either in or out, is:

$$p_{di} = v_{di} \cdot i_{di}. \quad (3)$$

Reactive power for the i th converter is:

$$q_{di} = |p_{di} \cdot \tan \theta_i|. \quad (4)$$

If the DC terminal connected to the first converter in the DC system is chosen as a reference node, the open circuit voltages of the i th converter are determined as follows:

$$e_i = e_1 - r_{c1} \cdot i_{d1} + r_{ci} \cdot i_{di} + \sum_{j=2}^{n_c} r_{ij} \cdot i_{dj} \quad (i = 2 \dots n_c), \quad (5)$$

where e_1, r_{ij} , and n_c represent the referenced DC terminal open circuit voltage, bus resistance matrix components obtained from the first DC terminal, and converter number of the DC system, respectively.

The algebraic sum of the DC currents flowing to the DC system must be zero:

$$\sum_{i=1}^{n_c} i_{di} = 0. \quad (6)$$

The least square method and current-balancing mode are used in order to balance the DC currents of the converters regarding the multiterminal DC system in Eq. (6) [26]. The active powers of all of the converters, except for at least one, are selected as control variables for the ORPF in this study to achieve the most suitable converter active powers and converter types that improve active power loss minimization. Thus, the active powers selected as control variables must be constant during the DC power flow algorithm. The DC currents of the converters being operated in constant active power mode are:

$$i_{di} = p_{di}^{set} / v_{di} \quad (i = 1 \dots n_c^{set}), \quad (7)$$

where p_{di}^{set} represents the active powers of the converters operating in a constant active power mode and n_c^{set} represents the converter quantity that operates in constant active power mode.

DC currents for converters that do not operate in constant active power mode can be determined as follows:

$$i_{di} = \left(i_{di}^* - \frac{\eta}{\sigma_i} \right) + \left| \frac{p_{di}}{\sum_{j=1}^{n_c^{set}} p_{dj}^{set}} \right| \cdot \left(\sum_{k=1}^{n_c^{set}} i_{dk}^* - \frac{\eta}{\sigma_k} - i_{dk} \right) \quad (i = 1 \dots (n_c - n_c^{set})), \quad (8)$$

where i_{di}^* is the estimated DC current of the i th converter, η is the Lagrangian multiplier, and σ_i is the weight coefficient. σ_i is selected by considering the system operation procedures and converter power rating. Its value is directly proportional to the inverse of the converter active power.

The estimated DC currents can be calculated as:

$$i_{di}^* = p_{di} / v_{di} \quad (i = 1 \dots n_c). \quad (9)$$

η , the Lagrangian multiplier, can be calculated as:

$$\eta = \left(\sum_{i=1}^{n_c} \frac{1}{\sigma_i} \right)^{-1} \cdot \sum_{j=1}^{n_c} i_{dj}^*. \quad (10)$$

2.2. Sequential AC-DC power flow algorithm for ORPF solution

Details of the sequential AC-DC power flow algorithm used for the ORPF solution are shown in Figure 2. Having the linear structure of the Gauss iteration method used in the proposed DC power flow and not including the DC variables into the Jacobian matrix prevents the increment of its dimension from accelerating the solution of the AC-DC power flow. The algorithm has a flexible structure and any method instead of the AC and DC power flow methods might be used conveniently and efficiently without changing the optimization algorithm.

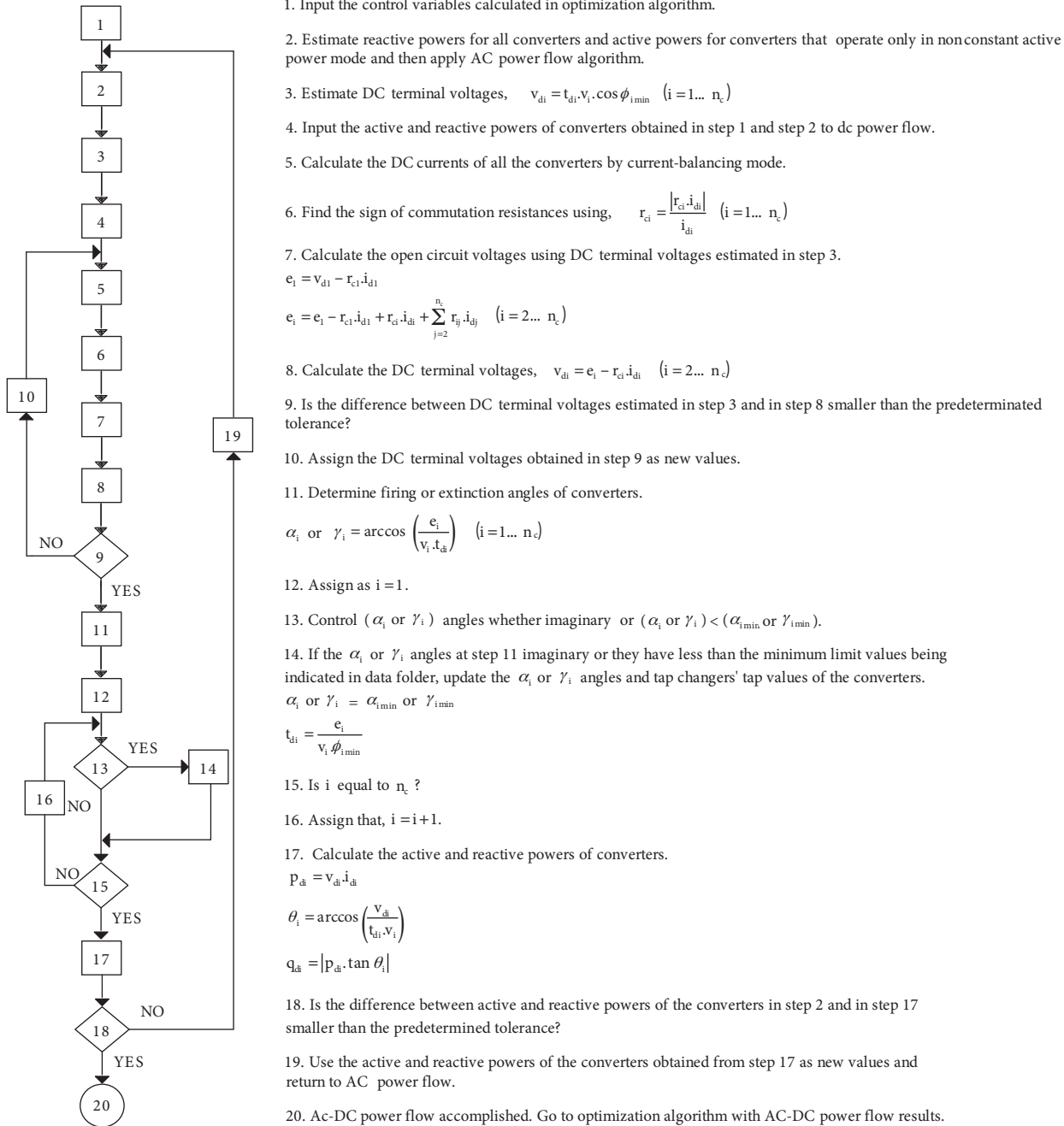


Figure 2. The proposed sequential AC-DC power flow algorithm for the ORPF solution.

3. ORPF problem

The general optimization formula is shown below:

$$\begin{aligned} & \text{Minimize} && f(x, u) \\ & \text{Subjected to} && g(x, u) \\ & && h(x, u), \end{aligned} \tag{11}$$

where $f(x, u)$, $g(x, u)$, $h(x, u)$, x , and u represent the objective function, equality constraints, inequality constraints, state variables, and control variables, respectively.

The total active power loss in the AC-DC system can be calculated as follows:

$$p_{loss} = \sum_{i=1}^{n_g} p_{gi} - \sum_{i=1}^{n_b} p_{loadi} - \sum_{i=1}^{n_c} p_{di}, \tag{12}$$

where n_g , n_b , p_{gi} , and p_{loadi} represent the generator number, AC bus number, generator active power output, and active powers for AC loads, respectively.

The equality constraints for the AC system are:

$$p_{gi} - p_{loadi} - p_{di} - p_{linei} = 0, \tag{13}$$

$$q_{gi} + q_{sci} - q_{loadi} - q_{di} - q_{linei} = 0, \tag{14}$$

where q_{gi} , q_{sci} , q_{loadi} , p_{linei} , and q_{linei} represent the generator reactive power output, synchronous condenser reactive power, reactive powers of the AC loads, active power flowing from the i th AC bus to the other AC buses, and reactive power flowing from the i th AC bus to the other AC buses, respectively.

Equality constraints for the DC system are:

$$\sum_{i=1}^{n_c} i_{di} = 0. \tag{15}$$

Equality constraints in Eqs. (13)–(15), defined as $g(x, u)$, are solved in the AC-DC power flow mentioned in Section 2.

Inequality constraints for the AC system are:

$$p_{gi}^{\min} \leq p_{gi} \leq p_{gi}^{\max}, \tag{16}$$

$$q_{gi}^{\min} \leq q_{gi} \leq q_{gi}^{\max}, \tag{17}$$

$$q_{sci}^{\min} \leq q_{sci} \leq q_{sci}^{\max}, \tag{18}$$

$$v_i^{\min} \leq v_i \leq v_i^{\max}, \tag{19}$$

$$t_i^{\min} \leq t_i \leq t_i^{\max}, \tag{20}$$

where t_i represents the tap values of the tap changers between the AC buses.

Inequality constraints for the DC system are:

$$p_{di}^{\min} \leq p_{di} \leq p_{di}^{\max}, \tag{21}$$

$$v_{di}^{\min} \leq v_{di} \leq v_{di}^{\max}, \quad (22)$$

$$t_{di}^{\min} \leq t_{di} \leq t_{di}^{\max}, \quad (23)$$

where the min and max superscripts represent the lower and upper limits of the associated variables, respectively.

State variables of the AC-DC system are:

$$x = [x_{ac}, x_{dc}], \quad (24)$$

where x_{ac} and x_{dc} represent the state variables of the AC and DC systems, respectively.

$$x_{ac} = [\delta_2, \dots, \delta_{nb}, v_1, \dots, v_{nl}] \quad (25)$$

$$x_{dc} = [i_{d1}, \dots, i_{dnc}, v_{d1}, \dots, v_{dnc}, t_{d1}, \dots, t_{dnc}, \varphi_1, \dots, \varphi_{nc}] \quad (26)$$

Here, δ and n_l represent the AC bus voltage angle and AC load bus number without a synchronous condenser, respectively.

Control variables of AC-DC system are:

$$u = [u_{ac}, u_{dc}], \quad (27)$$

where u_{ac} and u_{dc} represent the control variables of the AC and DC systems, respectively.

$$u_{ac} = [p_{g2}, \dots, p_{gng}, v_1, \dots, v_{ng}, v_1, \dots, v_{nsc}, t_1, \dots, t_{nt}] \quad (28)$$

$$u_{dc} = [p_{d1}, \dots, p_{dnc^{set}}] \quad (29)$$

Here, n_t and n_{sc} represent the number of tap changers between the AC buses and the number of synchronous condensers in the AC system, respectively.

The ORPF in the multiterminal AC-DC system tries to minimize the active power loss defined in Eq. (12) while providing the system constraints in Eqs. (16)–(23), defined as $h(x, u)$. Thus, the objective function that is optimized can be defined as:

$$\begin{aligned} f(x, u) = & c_1 \cdot p_{loss} + c_2 \cdot \sum_{i=1}^{n_g} |p_{gi} - p_{gi}^{\lim}| + c_3 \cdot \sum_{i=1}^{n_g} |q_{gi} - q_{gi}^{\lim}| + c_4 \cdot \sum_{i=1}^{n_{sc}} |q_{sci} - q_{sci}^{\lim}| + c_5 \cdot \sum_{i=1}^{n_b} |v_i - v_i^{\lim}| \\ & + c_6 \cdot \sum_{i=1}^{n_t} |t_i - t_i^{\lim}| + c_7 \cdot \sum_{i=1}^{n_c} |p_{di} - p_{di}^{\lim}| + c_8 \cdot \sum_{i=1}^{n_c} |v_{di} - v_{di}^{\lim}| + c_9 \cdot \sum_{i=1}^{n_c} |t_{di} - t_{di}^{\lim}| \end{aligned}, \quad (30)$$

where c represents the penalty coefficients of the objective function. Variables having the lim superscript can be defined as:

$$(x, u)^{\lim} = \begin{cases} (x, u), (x, u)_{\min} \leq (x, u) \leq (x, u)_{\max} \\ (x, u)_{\min}, (x, u) < (x, u)_{\min} \\ (x, u)_{\max}, (x, u) > (x, u)_{\max} \end{cases}. \quad (31)$$

4. ABC algorithm and its application for the ORPF problem

The ABC algorithm is a kind of heuristic optimization method that was inspired by the intelligent foraging behavior of honey bee swarms. The ABC was first proposed by Karaboga in 2005 [27]. Worker, onlooker, and scout bees are the backbone of the algorithm's structure. Each bee (workers, onlookers, and scouts) is sent to a food source. Worker bees search for nearby food sources, while onlooker bees, created by nearby worker bees, search for new food sources. If onlooker bees find better-quality food sources, their role will change to that of a worker bee; if not, the base value will be incremented by 1. If the base value exceeds its limit, that food source will be abandoned and the worker bees at those sources will be recreated as scout bees. Bees with sufficient eligibility rates in all of the created sources will be represented for the next iteration. This loop will continue until the stopping criteria of the algorithm are achieved. The parameters regarding each food source are the control variables defined in Eq. (27), which produce the objective function that will be optimized with the ABC. The food quality is represented as the fitness value in the ABC algorithm. The fitness value is equal to the objective function calculated in Eq. (30). If the fitness value of a food source is minimum, this means that the food source is the best of all of the food sources. A general flow chart of the ABC is given in Figure 3 and the flow chart of the ORPF solution in the multiterminal AC-DC system by the ABC is given in Figure 4. The main stages of the ABC algorithm can be defined as follows [28].

4.1. Initial population

The initial population of the algorithm can be produced as:

$$y_{ij} = y_{\min j} + rand(0.1) x (y_{\max j} - y_{\min j}) \quad (i = 1 \dots n_f) \quad (j = 1 \dots n_p), \quad (32)$$

where n_f , n_p , y_{ij} , $y_{\min j}$, and $y_{\max j}$ represent the food source number, parameter number, parameters of the initial population, and minimum and maximum values of the parameters, respectively. Each food source in the initial population includes the parameter set of the algorithm. Parameters of the initial population produced through Eq. (32) indicate the control variables defined in Eq. (27) for the ORPF solution.

4.2. Worker bees

Worker bees are produced by the knowledge of the initial population as:

$$w_{ij} = y_{ij} + \beta_{ij} \cdot (y_{ij} - y_{kj}) \quad (k = 1 \dots n_f) \quad (i = 1 \dots n_f \neq k) \quad (j = 1 \dots n_p), \quad (33)$$

where β_{ij} is a randomly produced number in $[-1,1]$.

4.3. Onlooker bees

Onlooker bees are produced near the selected worker bees through the roulette selection method for searching for new food sources. If onlooker bees find better quality food sources, their role will change to that of worker bees; if not, the base value will be incremented by 1. In the roulette selection method, if a bee has high efficiency, its probability to be selected is high. The selection probability of a bee in the population can be determined as:

$$sp_i = \frac{mfit_i}{\sum_{j=1}^{n_f} mfit_j}, \quad (34)$$

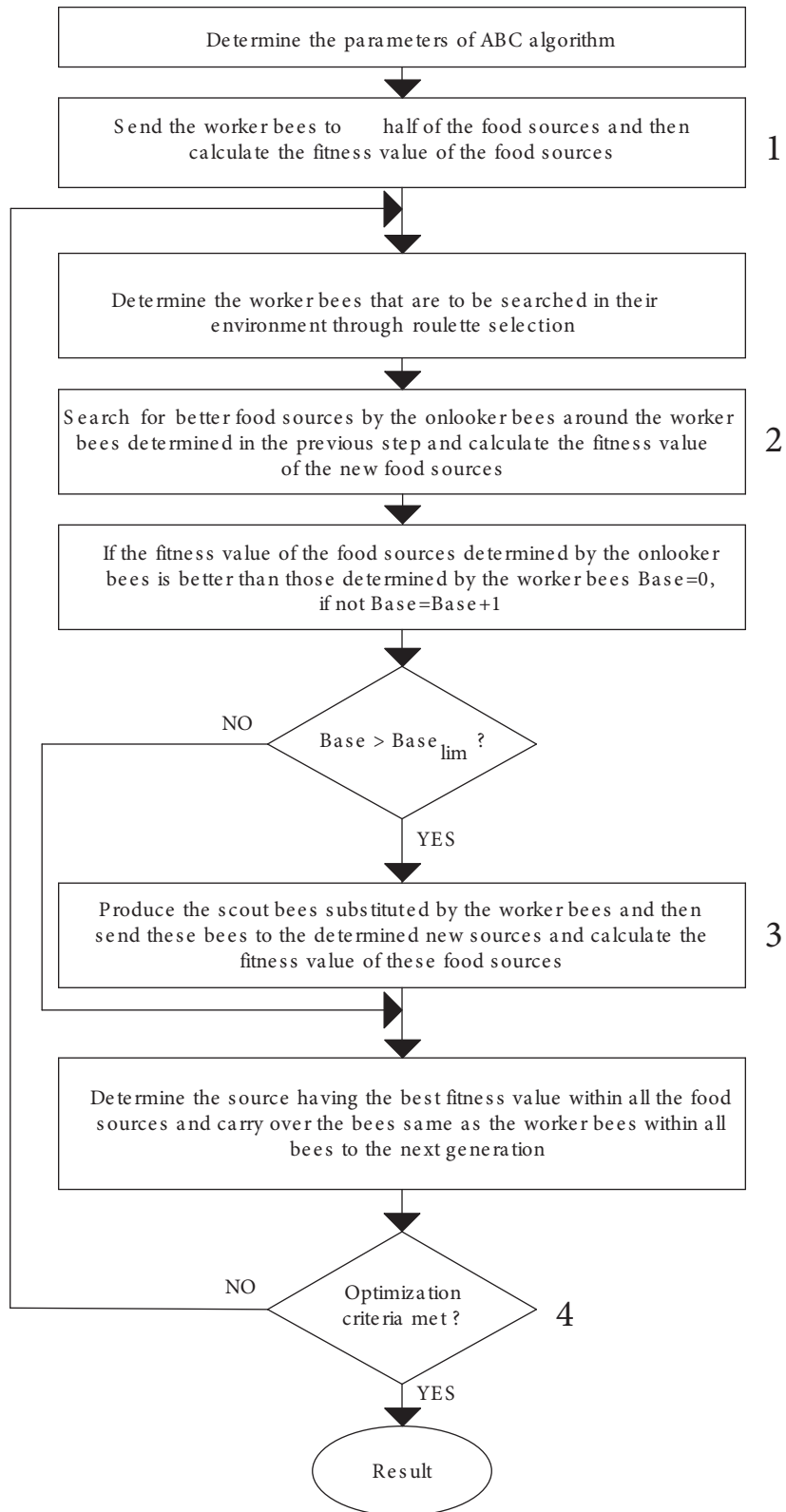


Figure 3. General flow chart of the ABC.

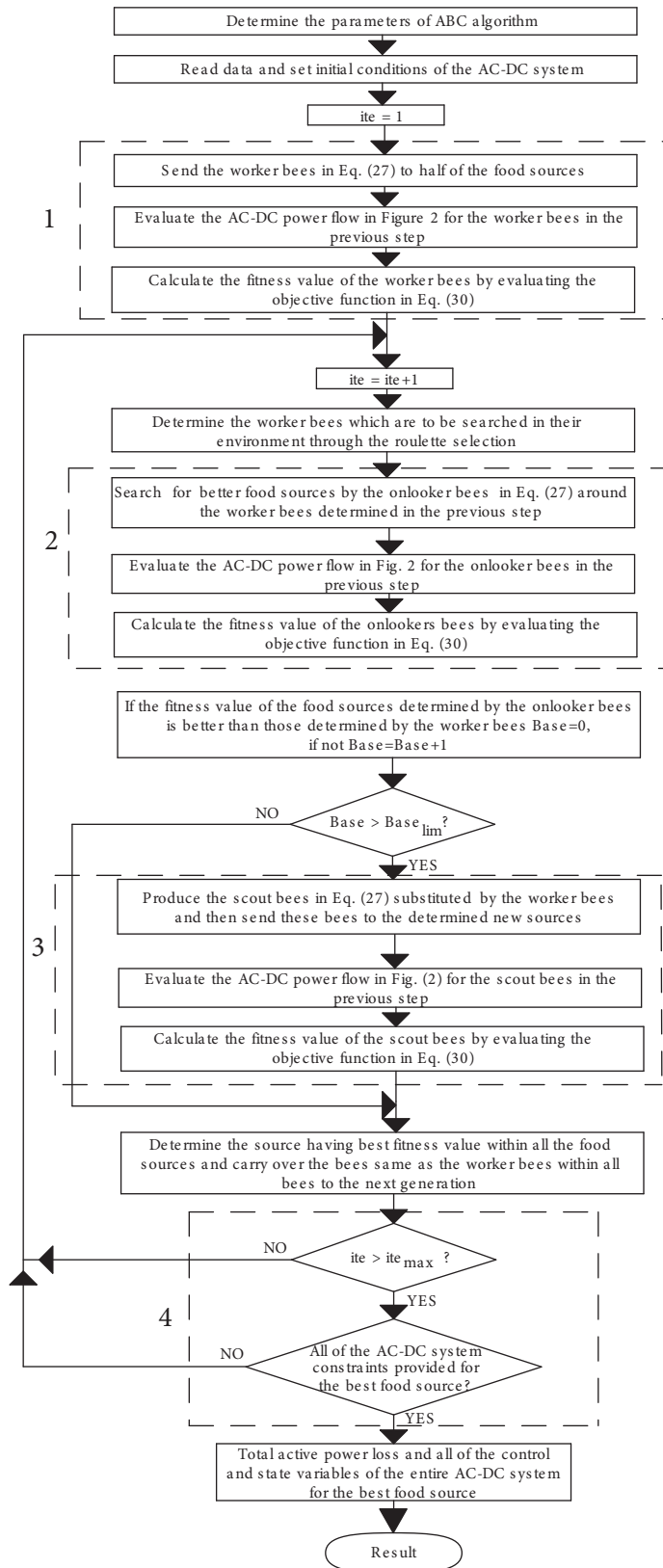


Figure 4. The proposed flow chart for ORPF in the multiterminal AC-DC system by ABC.

where mf_{it_i} represents the modified fitness value of the i th solution and can be defined as:

$$mf_{it_i} = \frac{1}{fit_i}, \tag{35}$$

where fit_i represents the fitness value of the i th solution and equals the objective function defined in Eq. (30).

4.4. Scout bees

If the base value of the onlooker bees searching for new food sources around the worker bee exceeds the predetermined limit value, the food sources are abandoned by the worker bees. The worker bees are then reproduced as scout bees for searching for new food sources through Eq. (30).

5. Results

The accuracy and efficiency of the proposed approach are tested on the modified IEEE 14-bus AC-DC test system as shown in Figure 5.

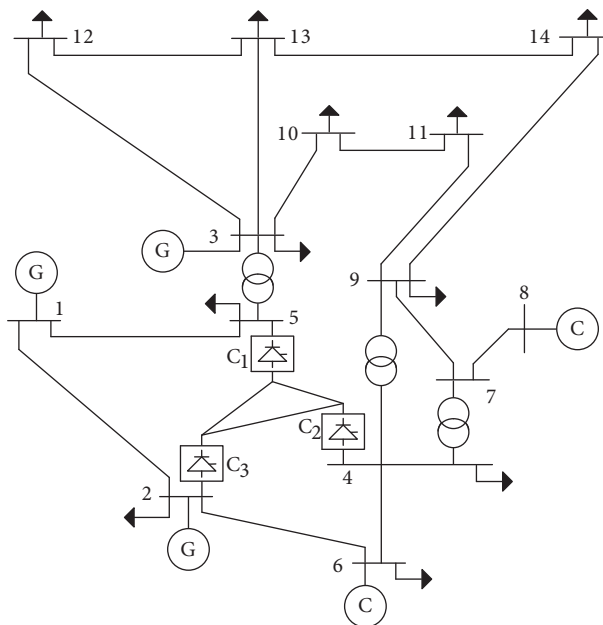


Figure 5. The modified IEEE 14-bus AC-DC test system.

The data regarding the test systems are given in Tables 1–4.

Table 1. Test system line resistance data.

Line resistance		r (in p.u.)
From bus	To bus	
5	4	0.0134
5	2	0.0570
4	2	0.0581

Table 2. Test system impedance-line charging data.

Line no.	From bus	To bus	Line impedance		Line charging
			r (in p.u.)	x (in p.u.)	b (in p.u.)
1	1	2	0.01938	0.05917	0.0528
2	1	5	0.05403	0.22304	0.0492
3	2	6	0.04699	0.19797	0.0438
4	3	11	0.09498	0.19890	0
5	3	12	0.12291	0.25581	0
6	3	13	0.06615	0.13027	0
7	4	7	0	0.20912	0
8	4	9	0	0.55261	0
9	5	3	0	0.25202	0
10	6	4	0.06701	0.17103	0.0346
11	7	8	0	0.17615	0
12	7	9	0	0.11001	0
13	9	10	0.03181	0.08450	0
14	9	14	0.12711	0.27038	0
15	10	11	0.08205	0.19207	0
16	12	13	0.22092	0.19988	0
17	13	14	0.17093	0.34802	0

Table 3. Test system load data.

Bus no.	Load data	
	p (in p.u.)	q (in p.u.)
1	0	0
2	0.217	0.127
3	0.112	0.075
4	0.478	0.040
5	0.076	0.016
6	0.942	0.190
7	0	0
8	0	0
9	0.295	0.166
10	0.090	0.058
11	0.035	0.018
12	0.061	0.016
13	0.135	0.058
14	0.149	0.050

Table 4. Test system commutation resistance data.

Terminal	r_c (in p.u.)
Converter 1 (C_1)	0.025680
Converter 2 (C_2)	0.028246
Converter 3 (C_3)	0.015329

The optimization results are shown in Table 5, where the values in the ‘Initial’ column indicate the first optimization iteration values regarding the ORPF being implemented with the ABC algorithm, and the values in the ‘Result’ column indicate the last optimization iteration values.

Table 5. Initial and result values for the test system.

Variable	Limits (in p.u.)		Initial (in p.u.)	Result (in p.u.)
	Min.	Max.		
v_1^*	1.00	1.10	1.0583	1.0550
v_2^*	1.00	1.10	1.0431	1.0431
v_3^*	1.00	1.10	1.0153	1.0189
v_4	0.90	1.10	1.0145	1.0321
v_5	0.90	1.10	1.0197	1.0557
v_6^*	1.00	1.10	1.0557	1.0221
v_7	0.90	1.10	1.0417	1.0043
v_8^*	1.00	1.10	1.0884	1.0884
v_9	0.90	1.10	1.0036	0.9786
v_{10}	0.90	1.10	0.9977	0.9766
v_{11}	0.90	1.10	1.0026	0.9924
v_{12}	0.90	1.10	1.0000	1.0018
v_{13}	0.90	1.10	0.9949	0.9934
v_{14}	0.90	1.10	0.9807	0.9651
P_{gen1}	0.30	2.00	1.9771	0.8253
P_{gen2}^*	0.30	1.20	0.4048	1.1398
P_{gen3}^*	0.30	1.20	0.3327	0.6963
q_{gen1}	-0.60	0.60	-0.5453	-0.5858
q_{gen2}	-0.60	0.60	-0.5010	-0.2979
q_{gen3}	-0.60	0.60	0.2824	0.0776
q_{sc6}	-0.60	0.60	0.3945	-0.0679
q_{sc8}	-0.60	0.60	0.2884	0.5199
δ_1	-	-	0°	0°
δ_2	-	-	-2.9580°	-1.5552°
δ_3	-	-	-14.0449°	-3.4309°
δ_4	-	-	-10.9513°	-5.6031°
δ_5	-	-	-12.0438°	-3.6835°
δ_6	-	-	-12.7321°	-8.6263°
δ_7	-	-	-13.8947°	-7.3124°
δ_8	-	-	-13.8947°	-7.3124°
δ_9	-	-	-15.5313°	-8.1887°
δ_{10}	-	-	-15.5886°	-7.6535°
δ_{11}	-	-	-14.9695°	-5.6811°
δ_{12}	-	-	-15.0410°	-4.6636°
δ_{13}	-	-	-15.1835°	-5.0078°
δ_{14}	-	-	-16.4948°	-7.9367°
i_{35}^*	0.90	1.10	0.9726	0.9959
i_{47}^*	0.90	1.10	1.0459	0.9241
i_{49}^*	0.90	1.10	0.9517	0.9716

Table 5. Continued.

Variable	Limits (in p.u.)		Initial (in p.u.)	Result (in p.u.)
	Min.	Max.		
p_{d1}^*	-1.00	1.00	0.7541	0.2427
p_{d2}^*	-1.00	1.00	-0.9761	-1.0000
p_{d3}	-1.00	1.00	0.2320	0.7771
q_{d1}	-	-	0.1654	0.0365
q_{d2}	-	-	0.3692	0.3780
q_{d3}	-	-	0.0309	0.1402
v_{d1}	0.90	1.10	1.0325	1.0439
v_{d2}	0.90	1.10	1.0224	1.0367
v_{d3}	0.90	1.10	1.0339	1.0614
i_{d1}	-	-	0.7304	0.2325
i_{d2}	-	-	-0.9548	-0.9646
i_{d3}	-	-	0.2244	0.7321
ϕ_1	rect. : 6.0000°	-	6.0000°	6.0000°
	inv. : 16.2600°			
ϕ_2	rect. : 6.0000°	-	16.2600°	16.2600°
	inv. : 16.2600°			
ϕ_3	rect. : 6.0000°	-	6.0000°	6.0000°
	inv. : 16.2600°			
t_{d1}	0.90	1.10	1.0367	1.0000
t_{d2}	0.90	1.10	1.0774	1.0739
t_{d3}	0.90	1.10	1.0000	1.0340
p_{loss}	-	-	0.1146	0.0517

*indicates the control variables

As seen in Table 5, the total active power loss is decreased from 0.1146 p.u. to 0.0517 p.u. This means that if the control variables of the system given in the initial column are changed by the control variables in the result column, the total active power loss of the system will be decreased under the same load conditions. In the practical application of such a study, an online monitoring control system is established in the power system. The online control system always reads the load and instant state variable data from the power system by measurement equipment and other system data (system constraints, impedance-line charging data, DC line resistance data, etc.) from the computer. Next, it executes the optimization algorithm and obtains the new control variable values for the optimal solution. These control variable data are sent to the related units by the online system and the related units are set by the control units immediately.

The total active power losses gained with the proposed approach and other methods, the GA and SDA, are compared in the same test system. The total active power loss variation throughout the algorithm is shown to compare graphically with the GA in Figure 6. In the literature, generally, 100 iterations are performed for the comparison of the proposed ABC algorithm and GA approaches. Where the ABC approximately reaches the global optimum at the 65th iteration, the GA reaches it at the 55th iteration. For the ABC, 10 worker and 10 onlooker bees are used. On the other hand, for the GA, 20 population sizes, a 0.5 crossover rate, and 0.1 mutation rate are used. These values used for the ABC and GA are found in trials. The values used beyond the current values do not change the global optimum for either the ABC or GA. This situation, using more

sizes than the above values, decreases the number of iterations but increases the optimization time in order to reach the global optimum. The penalty coefficient values c used in Eq. (30) are found after several trials and 100 different optimization trials are done for the ABC and GA methods. The worst and the best total active power loss values for ABC are 0.0525 p.u. and 0.0517 p.u., respectively. Error deviation for ABC is 1.54%. For GA, the worst and the best total active power loss values are 0.0713 p.u. and 0.0683 p.u., respectively. Error deviation for GA is 4.39%. At the end of the optimization, it is observed that all of the control and state variables are at their limit values, as seen in Table 5.

The proposed approach's efficiency and reliability in convergence and its ability to not get stuck in local minima are compared in Table 6. As mentioned before, 100 different optimization trials are performed for the ABC and GA, and 50 different optimization trials were performed for the SDA in [29]. It is shown that the proposed approach (ABC) and the GA, which are heuristic-based methods, are more efficient and reliable than the SDA, which is a derivative calculation-based method, for convergence and for not getting stuck in local minima.

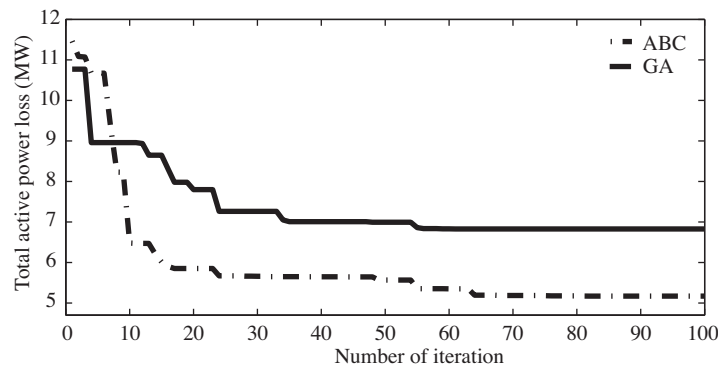


Figure 6. Variation of the total active power loss against the iterations for the proposed approach and GA ($P_{base} = 100$ MW).

Table 6. Comparison of the convergence and situations of getting stuck in local minima for the test system.

	Total number of optimization trials	Number of optimization trials in divergence	Number of optimization trials in getting stuck in local minima
ABC	100	0	0
GA	100	0	0
SDA [29]	50	18	7

The best active power loss values for the ABC in 100 different optimization trials, for the GA in 100 different optimization trials, and for the SDA in 50 different optimization trials are given in Table 7. It is seen that the proposed approach (ABC) is better and more reliable than the other methods (GA and SDA) for reaching the global optimum in obtaining the minimum active power loss.

Table 7. Comparison of the results for the test system.

	ABC	GA	SDA [29]
$p_{loss}(MW)$	5.170	6.830	8.532

6. Conclusion

In this article, a new approach, having the specifications and techniques given below, was proposed for the ORPF in multiterminal AC-DC systems.

This approach is one of the rare studies on ORPF in multiterminal AC-DC systems. Thus, it helps fill the gap in the literature and guides future studies in this area. The ABC algorithm, which is also a heuristic approach, is used here for the first time in a multiterminal AC-DC system for the ORPF solution. Because of the structure of the ABC algorithm, convergence and getting stuck in local minima problems are prevented. Any AC and DC power flow method can be used without any change in the optimization algorithm because of using the sequential method in the AC-DC power flow. Unlike other methods in the literature, converter active powers are used as control variables for optimization in the entire DC system, so that both the most suitable converter active powers ($p_{di}^{\min} \leq p_{di} \leq p_{di}^{\max}$) and the most suitable converter type (rectifier or inverter) are obtained at given load conditions by the proposed algorithm. Therefore, more efficient results are obtained for ORPF. The obtained results show that the proposed approach is better and more reliable for reaching the global optimum than similar approaches, without divergence or getting stuck in local minima. The proposed method can be used successfully in real-life online electrical power systems.

Appendix

Base active powers for the AC and DC systems are taken as equal.

$$P_{base} = P_{acbase} = P_{dcbase}$$

Choose P_{base} and V_{acbase} . Thus, for the AC system:

$$I_{acbase} = \frac{P_{base}}{\sqrt{3}V_{acbase}},$$

$$Z_{acbase} = \frac{V_{base}}{\sqrt{3}I_{acbase}}.$$

For the DC system:

$$V_{dcbase} = KV_{acbase},$$

$$I_{dcbase} = \frac{\sqrt{3}}{K}I_{acbase},$$

$$Z_{dcbase} = K^2Z_{acbase},$$

$$K = \frac{3\sqrt{2}}{\pi}n_s,$$

where n_s is the series-connected converter number. It is assumed that each converter has 6 pulses.

References

- [1] V.A. de Souza, E.C. Baptista, G.R.M. da Costa, "Optimal reactive power flow via the modified barrier Lagrangian function approach", *Electric Power System Research*, Vol. 84, pp. 159–164, 2012.
- [2] H. Fudeh, C.M. Ong, "A simple and efficient AC-DC load flow method for multi-terminal DC systems", *IEEE Transactions on Power Apparatus and Systems*, Vol. 100, pp. 4389–4396, 1981.

- [3] C. Liu, B. Zhang, Y. Hou, F.F. Wu, Y. Liu, “An improved approach for AC-DC power flow calculation with multi-infeed DC systems”, *IEEE Transactions on Power Systems*, Vol. 26, pp. 862–869, 2011.
- [4] J.R. de Silva, C.P. Arnold, “A simple improvement to sequential AC/DC power flow algorithms”, *International Journal of Electrical Power & Energy Systems*, Vol. 12, pp. 219–221, 1990.
- [5] U. Arifoglu, “Load flow based on Newton’s method using Norton equivalent circuit for AC-DC multiterminal systems”, *European Transactions on Electrical Power*, Vol. 9, pp. 167–174, 1999.
- [6] T. Smed, G. Andersson, G.B. Sheble, L.L. Grigsby, “A new approach to AC/DC power flow”, *IEEE Transactions on Power Systems*, Vol. 6, pp. 1238–1244, 1991.
- [7] M.V. Mustafa, A.F.A. Kadir, “A modified approach for load flow analysis of integrated AC-DC power systems”, *Proceedings of the IEEE TENCON*, pp. 108–113, 2000.
- [8] J. Beerten, S. Cole, R. Belmans, “A sequential AC-DC power flow algorithm for networks containing multiterminal VSC HVDC systems”, *Proceedings of the IEEE Power and Energy Society General Meeting*, pp. 1–7, 2010.
- [9] D. Thukaram, G. Yesuratnam, C. Vyjayanthi, “Optimal reactive power dispatch based on voltage stability criteria in a large power system with AC/DC and FACTS devices”, *IEEE International Conference on Power Electronic, Drives and Energy Systems*, New Delhi, India, pp. 953–958, 2006.
- [10] J. Yu, W. Yan, W. Li, L. Wen, “Quadratic models of AC-DC power flow and optimal reactive power flow with HVDC and UPFC controls”, *Electric Power System Research*, Vol. 78, pp. 302–310, 2008.
- [11] U. De Martinis, F. Gagliardi, A. Losi, V. Mangoni, F. Rossi, “Optimal load flow for electrical power systems with multiterminal HVDC links”, *IEE Proceedings – C, Generation, Transmission & Distribution*, Vol. 137, pp. 139–145, 1990.
- [12] C.N. Lu, S.S. Chen, C.M. Ong, “The incorporation of HVDC equations in optimal power flow methods using sequential quadratic programming techniques”, *Transactions on Power Systems*, Vol. 3, pp. 1005–1011, 1988.
- [13] H. Ambriz-Perez, E. Acha, C.R. Fuerte-Esquivel, “High voltage direct current modelling in optimal power flows”, *International Journal of Electrical Power & Energy Systems*, Vol. 30, pp. 157–168, 2008.
- [14] U. Arifoglu, N. Tarkan, “New sequential AC-DC load flow approach utilizing optimization techniques”, *European Transactions on Electrical Power*, Vol. 9, pp. 93–100, 1999.
- [15] K. Ayan, U. Kiliç, “Artificial bee colony algorithm solution for optimal reactive power flow”, *Applied Soft Computing*, Vol. 12, pp. 1477–1482, 2012.
- [16] D. Thukaram, G. Yesuratnam, “Optimal reactive power dispatch in a large power system with AC-DC and FACTS controllers”, *IET Generation, Transmission & Distribution*, Vol. 2, pp. 71–81, 2008.
- [17] J. Yu, W. Yan, W. Li, C.Y. Chung, K.P. Wong, “An unfixed piecewise-optimal reactive power-flow model and its algorithm for AC-DC systems”, *IEEE Transactions on Power Systems*, Vol. 23, pp. 170–176, 2008.
- [18] J.R. Cho, J.H. Lee, K.M. Jeong, K.W. Kim, “Optimum design of run-flat tire insert rubber by genetic algorithm”, *Finite Elements in Analysis and Design*, Vol. 52, pp. 60–70, 2012.
- [19] L. Wang, L. Li, “A coevolutionary differential evolution with harmony search for reliability-redundancy optimization”, *Expert Systems with Applications*, Vol. 39, pp. 5271–5278, 2012.
- [20] M. Mohammadi, F. Dini, R. Amrollahi, “Optimization of Damavand tokamak poloidal field coils positions and currents with PSO algorithm”, *Journal of Fusion Energy*, Vol. 31, pp. 170–174, 2012.
- [21] O.P. Verma, P. Kumar, M. Hanmandlu, S. Chhabra, “High dynamic range optimal fuzzy color image enhancement using artificial ant colony system”, *Applied Soft Computing*, Vol. 12, pp. 394–404, 2012.
- [22] L. Slimani, T. Bouktir, “Optimal power flow using artificial bee colony with incorporation of FACTS devices: a case study”, *International Review of Electrical Engineering*, Vol. 6, pp. 3091–3101, 2011.
- [23] U. Kwannetr, U. Leeton, T. Kulworawanichpong, “Optimal power flow solution using artificial bees colony algorithms”, *International Review of Electrical Engineering*, Vol. 6, pp. 1870–1882, 2011.

- [24] A. Ozturk, S. Cobanli, P. Erdosmus, S. Tosun, “Reactive power optimization with artificial bee colony algorithm”, *Scientific Research and Essays*, Vol. 5, pp. 2848–2857, 2010.
- [25] S. Cobanli, A. Ozturk, U. Guvenc, S. Tosun, “Active power loss minimization in electric power systems through artificial bee colony algorithm”, *International Review of Electrical Engineering*, Vol. 5, pp. 2217–2223, 2010.
- [26] U. Arifoglu, “The power flow algorithm for balanced and unbalanced bipolar multiterminal AC-DC systems”, *Electric Power System Research*, Vol. 64, pp. 239–246, 2003.
- [27] D. Karaboga, “An idea based on honey bee swarm for numerical optimization”, Technical Report-TR06, Kayseri, Turkey, Erciyes University Engineering Faculty, Computer Engineering Department, 2005.
- [28] D. Karaboga, B. Basturk, “A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm”, *Journal of Global Optimization*, Vol. 39, pp. 459–471, 2007.
- [29] U. Arifoglu, “Optimal power flow using sequential power flow approach for an AC-DC power system”, PhD, İstanbul Technical University, İstanbul, Turkey, 1993.