The Economic Power Dispatch Solution in Practical Multi-terminal HVDC Systems based on Artificial Bee Colony Algorithm under System Constraints

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Abstract: *This paper presents a new approach for economic power dispatch in multi-terminal High Voltage Direct Current (HVDC) systems. Apart from the similar AC-DC power flow studies, real equivalent circuit for the under load tap changer transformers (ULTCs) of the DC converters are considered in the AC-DC power flow algorithm. So the study provides exact accurate results for practical AC-DC applications. Economic power dispatch for minimum generation cost is provided by Artificial Bee Colony (ABC) algorithm. The presented approach is tested on the modified IEEE 14-bus AC-DC test system. The obtained results show that the proposed approach is efficient to reach the global optimum point of minimum generation cost without getting stuck to local minima while satisfying system constraints.*

Key Words: *economic power dispatch, HVDC, multi-terminal, ULTC, artificial bee colony algorithm.*

1. INTRODUCTION:

Economic operation of the electrical power systems is very important due to high generation costs. Most of the generators in power systems operates with fuel force. Fuel costs increase depending on the demanding power by the customers. Relationship between the demanding active power and fuel costs are not linear. On the other hand, the power systems are not operated with only one generator, so there are many generators in a power system. So, the produced active power of each generator is very important to achieve total economic generation cost. This is achieved by economic power dispatch in power systems [1].

Although the establishment costs of High Voltage Direct Current (HVDC) systems are high, they are more economic than AC transmission lines for long distances. Additionally, system reliability and consistency, efficient implementation, efficient conductor intersection, flexible control, no reactive power problem and continuously increasing development in semiconductor technology are the advantages of the HVDC systems [2]. Because of these reasons, researchers are working on integrated AC-DC systems for a long time. Many methods have been proposed for AC-DC power flow. These methods in the literature are divided into two main part as simultaneous method and sequential method. In sequential method, AC and DC power flows are implemented separately and convergence is provided by getting back and forward [3]. In simultaneous method, all equations regarding to AC-DC system are one within other and the equations are solved together [4].

Even though there are many studies for AC-DC power flow, there are not enough studies on optimal power flow of two or multi-terminal HVDC systems. The existing optimal power flow studies in AC-DC systems are implemented successfully by using numerical optimization methods such as quadratic programming, linear programming, mixed-integer nonlinear programming, gradient-restoration algorithm and steepest descent algorithm [5-12]. But there are convergence and getting stuck to local minima problems in these methods [13].

Heuristic methods like genetic algorithm [14], differential evolution [15], particle swarm optimization [16] and artificial ant colony [17] are developed for the solution of global optimization problems and they are applied to those problems successfully. These methods are more efficient with respect to accurate and faster convergence and not getting stuck to local minima than conventional numerical techniques mentioned above.

Artificial bee colony (ABC) algorithm is one of the heuristic methods mentioned above. It is successfully applied to the solution of economic power dispatch, optimal reactive power flow and optimal active-reactive power flow in AC power systems as well as in other fields [18-19].

In this paper, a new approach is presented for solution of economic power dispatch in multi-terminal HVDC systems by using ABC algorithm. Sequential method is used for AC-DC power flow problem. Real equivalent circuits of the DC converters' ULTCs are considered in the AC-DC power flow algorithm to be used in practical applications. ABC algorithm is used for economic power dispatch solution. On the other hand, the system constraints of the control and state variables are also included into the economic power dispatch. The proposed approach's accuracy and consistency are tested on the modified IEEE 14-bus AC-DC test system.

2. THE PROPOSED SEQUENTIAL AC-DC POWER FLOW ALGORITHM:

This section presents the proposed sequential AC-DC power flow algorithm used in economic power dispatch study. Sequential AC-DC power flow is performed by getting backwards and forwards between the proposed sequential AC and DC power flow algorithms.

2.1. The illustration of the proposed sequential AC power flow algorithm

This section presents the proposed sequential AC power flow algorithm used in this optimal AC-DC power flow study. The AC power flow algorithm is based on Newton-Raphson method. The real equivalent circuit models are considered for DC converters' ULTCs as well as the other ULTCs used in AC system in this study. The model and the equivalent circuit of the ULTC are given in Fig. 1 [20].

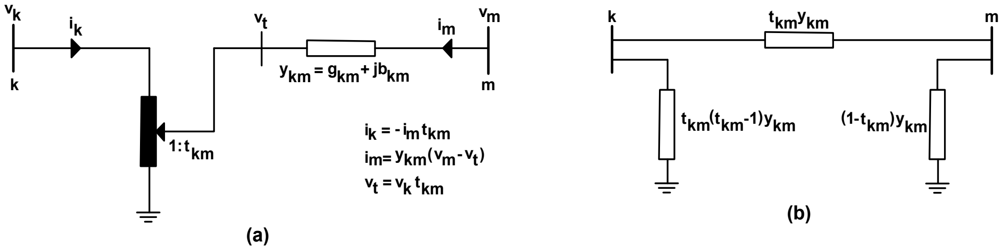


Fig. 1. ULTC model a) representation of ULTC b) equivalent circuit of ULTC

k, m, t_{km} and y_{km} represent the bus that ULTC's primary side is connected to, the bus that ULTC's secondary side is connected to, the tap value of ULTC and the admittance of ULTC's windings, respectively in Fig. 1.

$$y_{km} = g_{km} + jb_{km} \tag{1}$$

The series and shunt admittance values of ULTCs depending on the tap values are changed as the tap values of DC converters' ULTCs are changed in each sequential DC power flow iteration to achieve DC power balance in the study as shown in Fig. 1. Thus, bus admittance matrix of the AC system must be rebuilt for each new sequential AC power flow algorithm. Only the ULTC's serial winding admittance y_{km} is considered in the AC bus admittance matrix y_{bus} and shunt admittances for bus k and m are considered as zero to avoid rebuilding of the AC bus admittance matrix for new ULTCs' tap values. Depending on these conditions, p_k, q_k, p_m and q_m which are active power flowing from bus k to other buses in AC network, reactive power flowing from bus k to other buses in AC network, active power flowing from bus m to other buses in AC network and reactive power flowing from bus m to other buses in AC network respectively can be defined as follow;

$$p_k = v_k \sum_{\substack{j=1 \\ j\neq k,m}}^{nb} v_j \left(g_{bus_{kj}} \cos\delta_{kj} + b_{bus_{kj}} \sin\delta_{kj} \right) + v_k v_m t_{km} \left(g_{bus_{km}} \cos\delta_{km} + b_{bus_{km}} \sin\delta_{km} \right) + v_k^{\,2} \left[g_{bus_{kk}} - \left(t_{km}^{\,2} - 1 \right) g_{bus_{km}} \right] \tag{2}$$

$$q_k = v_k \sum_{\substack{j=1 \\ j\neq k,m}}^{nb} v_j \left(g_{bus_{kj}} \sin\delta_{kj} - b_{bus_{kj}} \cos\delta_{kj} \right) + v_k v_m t_{km} \left(g_{bus_{km}} \sin\delta_{km} - b_{bus_{km}} \cos\delta_{km} \right) + v_k^{\,2} \left[-b_{bus_{kk}} + \left(t_{km}^{\,2} - 1 \right) b_{bus_{km}} \right] \tag{3}$$

$$p_m = v_m \sum_{\substack{j=1 \\ j\neq m,k}}^{nb} v_j \left(g_{bus_{mj}} \cos\delta_{mj} + b_{bus_{mj}} \sin\delta_{mj} \right) + v_m v_k t_{km} \left(g_{bus_{mk}} \cos\delta_{mk} + b_{bus_{mk}} \sin\delta_{mk} \right) + v_m^{\,2} g_{bus_{mm}} \tag{4}$$

$$q_m = v_m \sum_{\substack{j=1 \\ j\neq m,k}}^{nb} v_j \left(g_{bus_{mj}} \sin\delta_{mj} - b_{bus_{mj}} \cos\delta_{mj} \right) + v_m v_k t_{km} \left(g_{bus_{mk}} \sin\delta_{mk} - b_{bus_{mk}} \cos\delta_{mk} \right) - v_m^{\,2} b_{bus_{mm}} \tag{5}$$

where n_b, v_i, $g_{bus_{ij}}$, $b_{bus_{ij}}$ and δ_{ij} represent the total bus number of the AC system, ith bus voltage, conductance value of y_{bus}'s ith and jth component, the susceptance value of y_{bus}'s ith and jth component and the phase angle difference between ith and jth bus voltages, respectively.

The active and reactive powers flowing from the buses different than the buses k and m that are connected to ULTC to the other buses in AC system are defined as,

$$p_i = v_i \sum_{j=1}^{nb} v_j \left(g_{bus_{ij}} \cos \delta_{ij} + b_{bus_{ij}} \sin \delta_{ij} \right) \tag{6}$$

$$q_i = v_i \sum_{j=1}^{nb} v_j \left(g_{bus_{ij}} \sin \delta_{ij} - b_{bus_{ij}} \cos \delta_{ij} \right) \tag{7}$$

The general bus representation for the AC-DC system used in this economic power dispatch study is given in Fig. 2. In Fig. 2, p_{gi}, q_{gi}, p_{di}, q_{di}, p_{li}, q_{li}, q_{ci}, p_i and q_i represent the active power of the ith bus' generator, the reactive power of the ith bus' generator, the active power of the DC converter connected to ith bus, the reactive power of the DC converter connected to ith bus, the active power of the ith bus' load, the reactive power of the ith bus' load, the reactive power of shunt reactive power supply of the ith bus, the active power flowing from ith bus to other buses in AC system given by (2), (4), (6) and the reactive power flowing from ith bus to other buses in AC system given by (3), (5), (7), respectively.

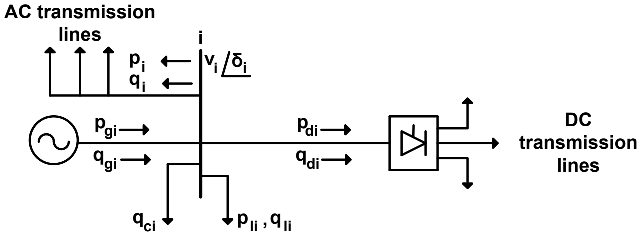


Fig. 2. General bus representation for the proposed AC-DC system

The active and reactive powers of the DC converters are considered as constant loads in the proposed sequential AC power flow algorithm for the buses where the DC converters are connected. Updated active and reactive powers of the DC converters at the end of the sequential DC power flow algorithm are transferred to the sequential AC power flow algorithm. Thus, the power equations to be provided in the Newton-Raphson based sequential AC power flow algorithm for general bus representation given in Fig. 2 are given as,

$$g_{pi} = p_i + p_{d_i} + p_{l_i} - p_{g_i} = 0 \quad \left(i = 2, \ldots n_b \right) \tag{8}$$

$$g_{qi} = q_i + q_{d_i} + q_{l_i} - q_{c_i} = 0 \quad \left(i = n_g + 1, \ldots n_b \right) \tag{9}$$

where n_g represents the total generator bus number in the system.

The tap values of DC converters' ULTCs which are changed in the sequential DC power flow algorithm are considered as control variables during the sequential AC power flow algorithm. So, the state and control variables for the proposed AC power flow algorithm are given as,

$$x_{AC} = \left[\delta_2, \ldots, \delta_{nb}, v_{ng+1}, \ldots, v_{nb} \right] \tag{10}$$

$$u_{AC} = \left[p_{g2}, \ldots, p_{gng}, v_1, \ldots, v_{ng}, t_1 \ldots t_{nt}, t_{d_1} \ldots t_{d_{nd}} \right] \tag{11}$$

where t, n_t, t_d and n_{td} represent the tap value of the ULTC which is not connected to a DC converter, the total number of the ULTCs which are not connected to the DC converters, the tap value of the DC converter's ULTC and the total number of the DC converters' ULTCs, respectively.

2.2. The illustration of the proposed sequential DC power flow algorithm

This section demonstrates the proposed sequential DC power flow algorithm based on the proposed DC power model shown in Fig. 3.

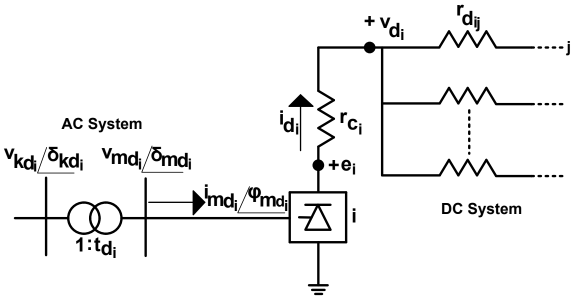


Fig. 3. The proposed multi-terminal DC power model

e_i, v_{d_i}, i_{d_i}, r_{c_i}, $r_{d_{ij}}$, t_{d_i}, v_{kd_i}, v_{md_i}, i_{md_i}, δ_{kd_i}, δ_{md_i} and φ_{md_i} represent the ith DC converter's open circuit direct voltage, the ith DC converter's terminal direct voltage, the ith DC converter's direct current, the ith DC converter's commutation resistance, DC line resistance between the ith and the jth DC converters, the ith DC converter's ULTC tap value, the ith DC converter's ULTC primary alternative voltage, the ith DC converter's ULTC secondary alternative voltage, alternative current flowing from the DC converter's ULTC secondary to DC converter, phase angle of the ith DC converter's ULTC primary alternative voltage, phase angle of the ith DC converter's ULTC secondary alternative voltage and phase angle of alternative current flowing from the ith DC converter's ULTC secondary to DC converter, respectively.

The DC converters' open circuit direct voltages are given as,

$$e_i = v_{md_i} \cos\theta_i \quad \left(i = 1, \ldots, n_c\right) \tag{12}$$

where n_c represents the total number of DC converters in the system. θ_i defines α_{d_i} and γ_{d_i} where the firing angle of the ith DC converter that operates in the rectifier mode and the extinction/recovery angle of the ith DC converter that operates in the inverter mode, respectively.

DC converters' terminal direct voltages are given as,

$$v_{d_i} = e_i - r_{c_i} i_{d_i} \quad \left(i = 1, \ldots, n_c\right) \tag{13}$$

The commutation resistance r_{c_i} is positive for the DC converter that operates in the rectifier mode and negative for the DC converter that operates in the inverter mode in (13).

The phase angle between the DC converter's ULTC secondary alternative voltage angle and angle of the alternative current flowing from the DC converter's ULTC secondary to DC converter is given as,

$$\phi_{md_i} = \delta_{md_i} - \varphi_{md_i} \quad \left(i = 1, \ldots, n_c\right) \tag{14}$$

and can also be obtained from,

$$\phi_{md_i} = \arccos\left(\frac{v_{d_i}}{v_{md_i}}\right) \quad \left(i = 1, \ldots, n_c\right) \tag{15}$$

The active and reactive powers of the DC converters can be defined as,

$$p_{d_i} = v_{d_i} i_{d_i} \quad \left(i = 1, \ldots, n_c\right) \tag{16}$$

$$q_{d_i} = \left| p_{d_i} \tan\phi_{md_i} \right| \quad \left(i = 1, \ldots, n_c\right) \tag{17}$$

The multi-terminal DC system model is shown in Fig. 4. The commutation resistances are not included into the DC bus resistance matrix to avoid rebuilding of the DC bus resistance matrix in each DC algorithm iteration in this model, as the commutation resistance values change their sign in each iteration when the converters are updated from the rectifier mode to the inverter mode or vice versa. If the DC terminal direct voltages are considered as source voltages, the commutation resistances can be ignored in the DC bus resistance matrix and the DC bus resistance matrix is given as,

$$r_{d_{bus}} = y_{d_{bus}}^{-1} \tag{18}$$

where $y_{d_{bus}}$ represents the DC bus admittance matrix which includes only the admittances of the DC lines.

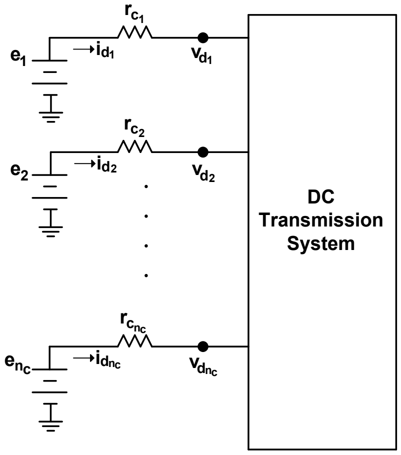


Fig. 4. The multi-terminal DC system model

If the 1st DC converter's terminal direct voltage is considered as reference voltage, the DC converters' open circuit direct voltages can be given as,

$$e_1 = v_{d_1} + r_{c_1} i_{d_1} \tag{19}$$

$$e_i = e_1 - r_{c_1} i_{d_1} + r_{c_i} i_{d_i} + \sum_{j=2}^{n_c} r_{dbus_{ij}} i_{d_j} \quad \left(i = 2,\ldots,n_c\right) \tag{20}$$

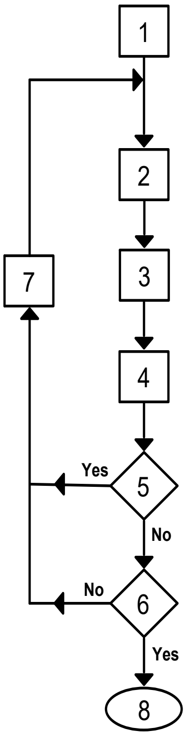
According to the DC model shown in Fig. 4, the algebraic sum of the DC converters direct currents must be zero,

$$\sum_{i=1}^{n_c} i_{d_i} = 0 \tag{21}$$

The active powers of all converters except at least one are selected as control variables for economic power dispatch in the study to achieve most suitable converter active powers and converter types that improve the total generation cost minimization.

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

The proposed sequential AC-DC power flow algorithm is given through the sequential AC and DC power flow algorithms given in section 2.1 and 2.2 in this section. The proposed AC-DC power flow algorithm is shown in detailed in Fig. 5.



1. Estimate the active and reactive powers for DC converters. Consider the minimum values for the tap values of the DC converters' ULTCs.
2. Execute the proposed sequential AC power flow algorithm given in section 2.1.
3. Send the active and reactive powers of the DC converters used in the proposed sequential AC power flow algorithm to the proposed sequential DC power flow algorithm.
4. Execute the proposed sequential DC power flow algorithm given in section 2.2.
5. Is any tap value of the DC converters' ULTCs updated to a new value in the DC power flow algorithm?
6. Are the differences between all of the active and reactive powers of the DC converters used in the AC power flow algorithm and calculated at the end of the DC power flow algorithm smaller than determined error tolerance?
7. Return to the AC power flow algorithm with the updated tap values of the DC converters' ULTCs and the calculated active and reactive powers of the DC converters at the end of the DC power flow algorithm.
8. The sequential AC-DC power flow algorithm is accomplished.

Fig. 5. The proposed AC-DC power flow algorithm

3. THE ECONOMIC POWER DISPATCH PROBLEM:

The general optimization formula can be shown below,

$$\begin{aligned} &\textit{Minimize} && f\left(x,u\right) \\ &\textit{Subjected to} && g\left(x,u\right) \;\&\; h\left(x,u\right) \end{aligned} \tag{22}$$

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

The total generators generation cost in AC-DC system can be calculated as follows:

$$f_{cost}\left(x,u\right) = \sum_{i=1}^{n_g} a_{g_i} p_{g_i}^2 + b_{g_i} p_{g_i} + c_{g_i} \tag{23}$$

where a_{g_i}, b_{g_i} and c_{g_i} represent the generation cost coefficients of the generators.

The equality constraints for the AC system,

$$p_{gi} - p_{li} - p_{di} - p_i = 0 \tag{24}$$

$$q_{gi} + q_{sci} - q_{li} - q_{di} - q_i = 0 \tag{25}$$

where q_{sci} represents the reactive power of the synchronous condensers.

The equality constraints for the DC system,

$$\sum_{i=1}^{n_c} i_{di} = 0 \tag{26}$$

The equality constraints in (24-26) defined as $g(x,u)$ are solved in the proposed AC-DC power flow algorithm mentioned before.

The inequality constraints for the AC system are given as,

$$p_{gi}^{\min} \le p_{gi} \le p_{gi}^{\max} \tag{27}$$

$$q_{gi}^{\min} \le q_{gi} \le q_{gi}^{\max} \tag{28}$$

$$q_{sci}^{\min} \le q_{sci} \le q_{sci}^{\max} \tag{29}$$

$$v_i^{\min} \le v_i \le v_i^{\max} \tag{30}$$

$$t_i^{\min} \le t_i \le t_i^{\max} \tag{31}$$

where t_i represents the tap values of the tap changers between the AC buses, $\min$ and $\max$ superscripts represent the lower and upper limits of the associated variables, respectively.

The inequality constraints for the DC system,

$$p_{di}^{\min} \le p_{di} \le p_{di}^{\max} \tag{32}$$

$$v_{di}^{\min} \le v_{di} \le v_{di}^{\max} \tag{33}$$

$$t_{di}^{\min} \le t_{di} \le t_{di}^{\max} \tag{34}$$

The proposed DC power flow algorithm automatically provides the inequality given in (34).

The state variables of the AC-DC system are given as,

$$x = [x_{AC}, x_{DC}] \tag{35}$$

where x_{AC} and x_{DC} represent the state variables of the AC and the DC system, respectively.

$$x_{AC} = [\delta_2, \ldots, \delta_{nb}, v_1, \ldots, v_{nl}] \tag{36}$$

$$x_{DC} = [i_{d1}, \ldots, i_{dnc}, v_{d1}, \ldots, v_{dnc}] \tag{37}$$

where δ_i and n_l represent the AC bus voltage angle and the AC load bus number without synchronous condenser, respectively.

The control variables of the AC-DC system,

$$u = [u_{AC}, u_{DC}] \tag{38}$$

where u_{AC} and u_{DC} represent the control variables of the AC and the DC system, respectively.

$$u_{AC} = \left[p_{g2}, \ldots, p_{gng}, v_1, \ldots, v_{ng}, v_1, \ldots, v_{nsc}, t_1, \ldots, t_{nt} \right] \tag{39}$$

$$u_{DC} = [p_{d2}, \ldots, p_{dnc}] \tag{40}$$

where n_t and n_{sc} represent the number of the ULTCs between the AC buses and the number of the synchronous condensers in AC system, respectively. It must be noted that there is a difference between (11) and (39), the existing of t_{di} values in (11). As mentioned in section 2.1, in fact, t_{di} values are not part of the AC systems, but they are presented in (11) to show that they are considered in the sequential AC power flow algorithm as control values.

The economic power dispatch in the multi-terminal HVDC system tries to minimize the total generation cost defined in (23) while providing system constraints in (27-33) defined as $h(x,u)$. So, the objective function that is optimized can be given as,

$$\begin{aligned} f(x,u) &= c_1.f_{cost} + c_2.\sum_{i=1}^{n_g}\left|p_{gi} - p_{gi}^{\lim}\right| + c_3.\sum_{i=1}^{n_g}\left|q_{gi} - q_{gi}^{\lim}\right| \\ &+ c_4.\sum_{i=1}^{n_{sc}}\left|q_{sci} - q_{sci}^{\lim}\right| + c_5.\sum_{i=1}^{n_b}\left|v_i - v_i^{\lim}\right| + c_6.\sum_{i=1}^{n_t}\left|t_i - t_i^{\lim}\right| \\ &+ c_7.\sum_{i=1}^{n_c}\left|p_{di} - p_{di}^{\lim}\right| + c_8.\sum_{i=1}^{n_c}\left|v_{di} - v_{di}^{\lim}\right| \end{aligned} \tag{41}$$

where c_i represents the penalty coefficients of the objective function. The variables having $\lim$ superscript can be given as,

$$(x,u)^{\lim} = \begin{cases} (x,u), (x,u)_{\min} \le (x,u) \le (x,u)_{\max} \\ (x,u)_{\min}, (x,u) < (x,u)_{\min} \\ (x,u)_{\max}, (x,u) > (x,u)_{\max} \end{cases} \tag{42}$$

4. ABC ALGORITHM AND ITS APPLICATION FOR ECONOMIC POWER DISPATCH PROBLEM:

Artificial bee colony (ABC) algorithm is one of the heuristic optimization methods which is derived from the intelligent foraging behavior of the honey bee swarms. ABC was proposed by Karaboga in 2005 for the first time [21]. The worker, onlooker and scout bees are the main components of the algorithm's structure. Worker, onlooker and scout bees are sent to a food source. Onlooker bees created nearby worker bees search for new food sources whereas worker bees search for food nearby food sources. If the onlooker bees find better quality food sources, their role change as worker bee. If not, base value is incremented by 1. If base value exceeds the limit, that food source is abandoned and the worker bees at those sources are recreated as the scout bees. The bees with sufficient eligibility rates in all created ones are represented for the next iteration. This loop continue till stopping criteria of the algorithm is achieved. The parameters regarding to each food source are the control variables defined in (38) that produce the objective function that will be optimized with ABC algorithm. The food quality is represented as fitness value in ABC algorithm. The fitness value is equal to the objective function calculated in (41). If the fitness value of a food source is minimum, it means that food source is the best of all food sources. The flow chart of the economic power dispatch solution in multi-terminal HVDC system by ABC algorithm is given in Figure 6. The main stages of the ABC algorithm can be given as follows [22].

4.1. Initial population

The initial population of the ABC algorithm is produced as,

$$y_{ij} = y_{\min j} + rand(0.1)x\left(y_{\max j} - y_{\min j}\right) \qquad \left(i = 1\ldots n_f\right) \qquad \left(j = 1\ldots n_p\right) \tag{43}$$

where n_f, n_p, y_{ij}, $y_{\min j}$ and $y_{\max j}$ represent the food source number, the parameter number, the parameters of the initial population, the minimum and maximum values of the parameters, respectively. Each food source in the initial population includes the parameters set of the algorithm. The parameters of the initial population produced through (43) indicate the control variables defined in (38) for the economic power dispatch solution.

4.2. Worker bees

The worker bees are produced by the knowledge of the initial population as,

$$w_{ij} = y_{ij} + \beta_{ij}\left(y_{ij} - y_{kj}\right) \qquad \left(k = 1\ldots n_f\right) \qquad \left(i = 1\ldots n_f \neq k\right) \qquad \left(j = 1\ldots n_p\right) \tag{44}$$

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

4.3. Onlooker bees

The onlooker bees are produced nearby the selected worker bees through the roulette selection method for searching for new food sources. If the onlooker bees find better quality food sources, their role will change as the 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 defined as,

$$sp_i = \frac{mfit_i}{\sum_{j=1}^{n_f} mfit_j} \tag{45}$$

where $mfit_i$ represents the modified fitness value of the ith solution and can be given as,

$$mfit_i = \frac{1}{fit_i} \tag{46}$$

where fit_i represents the fitness value of the i^{th} solution and it equals to the objective function given in (41).

4.4. Scout bees

The food sources are abandoned by the worker bees if the base value of the onlooker bees searching for new food sources around the worker bee exceeds the predetermined limit value. Then, the worker bees are reproduced as the scout bees for searching for new food sources through (43).

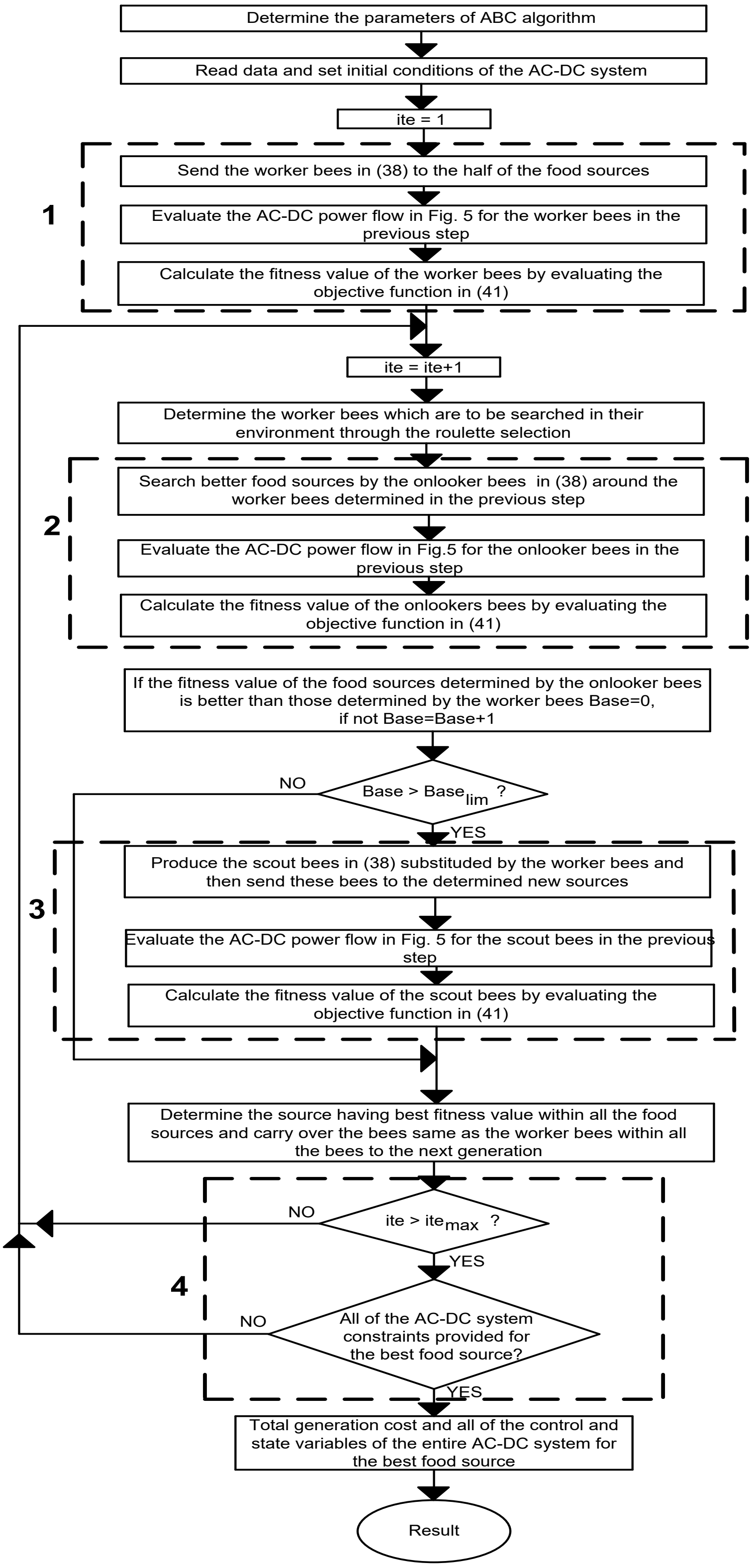


Fig. 6. The proposed flow chart for economic power dispatch in multi-terminal HVDC system by ABC algorithm

5. RESULTS:

The proposed approach's accuracy and efficiency are tested on the modified IEEE 14-bus AC-DC test system shown in Fig. 7.

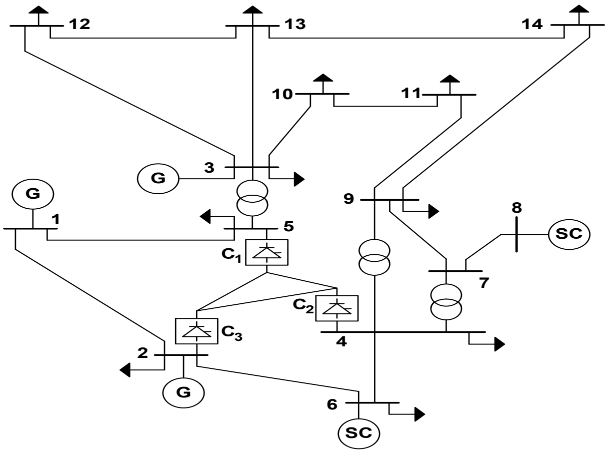


Fig. 7. The modified IEEE 14-bus AC-DC test system

Total generation cost throughout the proposed optimization algorithm is shown graphically in Fig. 8. Total generation cost obtained with proposed approach and another traditional numerical method, steepest descent algorithm (SDA), are compared in the same test system. In the literature, generally, 100 iterations are performed for heuristic methods. So, 100 iterations application is chosen for the proposed ABC algorithm for the optimization. The proposed optimization algorithm is performed for 50 optimization trials with different AC-DC system initials. ABC algorithm approximately has reached to global optimum at about 55th iteration for the best trial. For ABC algorithm, 10 worker and 10 onlooker bees are used. These values used for ABC algorithm are found at trials. The upper values of the used ones does not change the global optimum for ABC algorithm. The situation, using more sizes than the above values, decreased the number of iteration but increased optimization time in order to reach the global optimum. Penalty coefficient values c_i used in (41) are found after several trials. For the 50 optimization trials, the worst and the best total generation cost values for ABC algorithm are 1175.3 $/hour and 1162.5 $/hour, respectively. Error deviation for ABC algorithm is 1.09%. It is observed that all control and state variables are in their limit values at the end of the optimization.

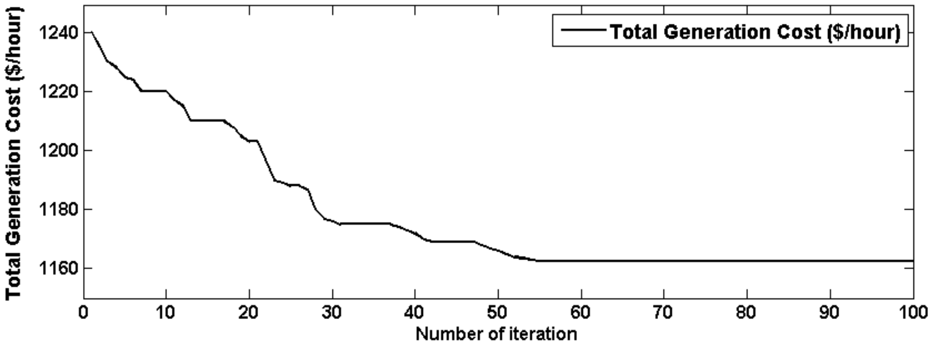


Fig. 8. Variation of total generation cost against iteration for the proposed approach

The proposed approach is better and more reliable than SDA [23] shown in Table 1 for reaching global optimum.

Table 1. Comparison of the results for the test system

	ABC	SDA [23]
Total Generation Cost	1162.5 $/hour	2007.8 $/hour

6. CONCLUSION

In this paper, a new approach is proposed for economic power dispatch in multi-terminal HVDC systems. ABC algorithm is used for the first time in multi-terminal HVDC system for economic power dispatch solution in this study. As the sequential method in AC-DC power flow is used, any AC and DC power flow method can be used without any change in optimization algorithm. Apart from the similar studies in the literature, converter active powers are used as control variables for optimization in the entire dc system in this study. So, both the most suitable converter active powers $\left(p_{di}^{\min} \le p_{di} \le p_{di}^{\max}\right)$ and converter types (rectifier or inverter) are achieved at determined system conditions. So, efficiency of the achieving economic generation cost is enhanced. The obtained results have shown that the proposed approach is better and more reliable for reaching global optimum than traditional numerical optimization methods not getting stuck to local minima. The proposed approach also provides the system constraints for security and healthy system operation.

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