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A Novel Economic Power Flow Solution in Practical Multi-terminal AC-DC Systems using Genetic Algorithm

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Abstract

This paper presents a novel approach for economic power flow in multi-terminal AC-DC systems. Unlike 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 real accurate results for practical AC-DC applications. Economic power flow solution for minimum generation cost is provided by Genetic Algorithm (GA). The proposed approach is tested on the modified IEEE 14-bus AC-DC test system. The 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.

Keywords: Economic power flow, AC-DC, multi-terminal, ULTC, genetic algorithm.

1. INTRODUCTION

Optimal operation of the electrical power system is very important because of the high generation costs. In power systems, most of the generators operates by fuel force. Fuel costs increase depending on the power requested by the customers. The relationship between the demanded active power and fuel costs are in proportion but not linear. On the other hand, the power systems are generally operated with many generators in a power system. Because of this situation, each generator's active power is very important to obtain total economic generation cost. Minimum generation cost is achieved by economic power flow in power systems [1].

Although the built-up costs of High Voltage Direct Current (HVDC) systems are high, they are more economic than AC transmission lines for longer distances. On the other hand, system consistency and reliability, 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 studying on integrated AC-DC systems for a long time. Many methods have been proposed for AC-DC power flow studies. These methods in the literature are divided into two main part: simultaneous method and sequential method. AC and DC power flows are implemented separately and convergence is provided by getting back and forward in sequential method [3]. In simultaneous method, all equations related to AC-DC system are one within other and the equations are solved together [4].

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

Heuristic methods like artificial bee colony 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 mentioned methods are more efficient with respect to accurate and faster

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convergence and not getting stuck to local minima than conventional numerical techniques mentioned above.
Genetic algorithm (GA) is one of the heuristic techniques mentioned above. It is successfully applied to economic power flow, optimal reactive power flow and optimal active-reactive power flow in AC power systems as well as in other fields [18-19].

In this study, a novel approach is presented for solution of economic power flow in multi-terminal AC-DC systems by using GA. Sequential technique is used for AC-DC power flow problem. The real equivalent circuits of the DC converters' ULTCs are considered in the AC-DC power flow algorithm to be valid in practical applications. GA is used for economic power flow solution. On the other hand, the system constraints of the control and state variables are also included into the economic power flow. 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 flow study. The 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 and 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 ULTC's model and the equivalent circuit are given in Fig. 1 [20].

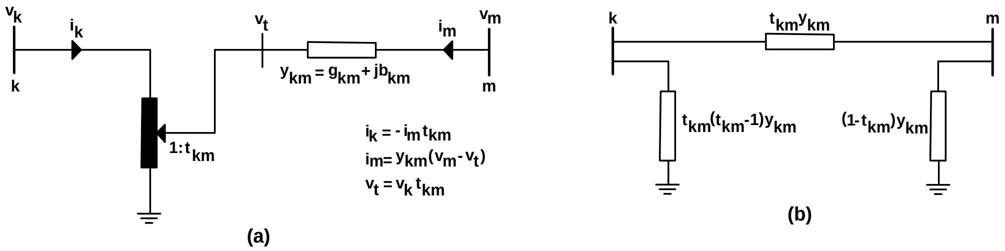


Fig. 1. ULTC model a) representation of ULTC b) equivalent circuit of ULTC

k , m , t_{km} and y_{km} show 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;

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

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

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

(4)

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

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,

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

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

The general bus representation for the AC-DC system used in this economic power flow 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.

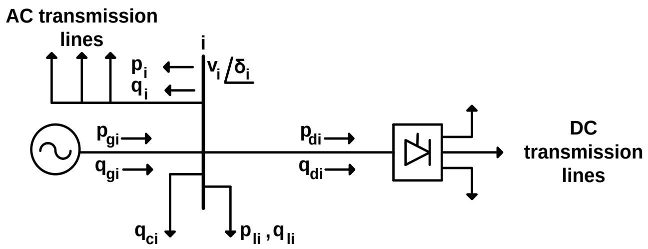


Fig. 2. General bus representation for the proposed AC-DC system

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,

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

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

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,

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

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

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.

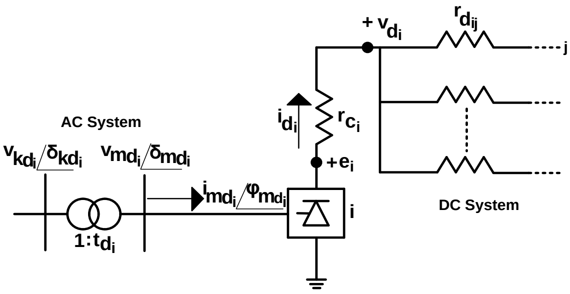


Fig. 3. The proposed multi-terminal DC power model

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,

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

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,

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

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,

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

and can also be obtained from,

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

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

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

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

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,

$$r_{d_{bus}} = y_{d_{bus}}^{-1} \quad (18)$$

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

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,

$$e_1 = v_{d_1} + r_{c_1} i_{d_1} \quad (19)$$

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

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 flow in the study to achieve most suitable converter active powers and converter types that improve the total generation cost minimization.

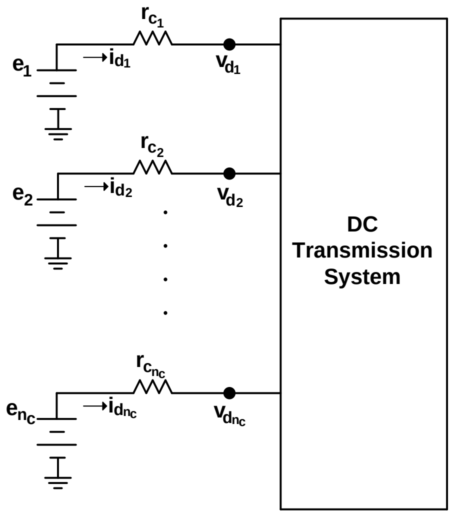
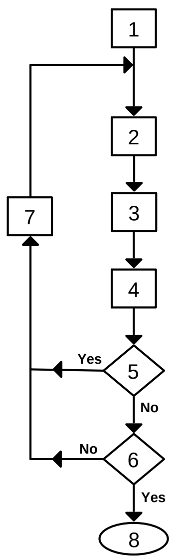


Fig. 4. The multi-terminal DC system model

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 FLOW PROBLEM

The general optimization formula can be shown below,

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

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:

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

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,

$$p_{gi} - p_{li} - p_{di} - p_i = 0 \quad (24)$$

$$q_{gi} + q_{sci} - q_{li} - q_{di} - q_i = 0 \quad (25)$$

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

The equality constraints for the DC system,

$$\sum_{i=1}^{n_c} i_{di} = 0 \quad (26)$$

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

The inequality constraints for the AC system are given as,

$$p_{gi}^{\min} \le p_{gi} \le p_{gi}^{\max} \quad (27)$$

$$q_{gi}^{\min} \le q_{gi} \le q_{gi}^{\max} \quad (28)$$

$$q_{sci}^{\min} \le q_{sci} \le q_{sci}^{\max} \quad (29)$$

$$v_i^{\min} \le v_i \le v_i^{\max} \quad (30)$$

$$t_i^{\min} \le t_i \le t_i^{\max} \quad (31)$$

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,

$$p_{di}^{\min} \le p_{di} \le p_{di}^{\max} \quad (32)$$

$$v_{di}^{\min} \le v_{di} \le v_{di}^{\max} \quad (33)$$

$$t_{di}^{\min} \le t_{di} \le t_{di}^{\max} \quad (34)$$

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

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

$$x = \left[x_{AC}, x_{DC}\right] \quad (35)$$

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

$$x_{AC} = \left[\delta_2, \ldots, \delta_{nb}, v_1, \ldots, v_{nl}\right] \quad (36)$$

$$x_{DC} = \left[i_{d1}, \ldots, i_{dnc}, v_{d1}, \ldots, v_{dnc}\right] \quad (37)$$

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,

$$u = \left[u_{AC}, u_{DC}\right] \quad (38)$$

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

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

$$u_{DC} = \left[p_{d2}, \ldots, p_{dnc}\right] \quad (40)$$

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 flow in the multi-terminal AC-DC system tries to minimize the total generation cost defined in (23) while providing system constraints in (27-33) defined as $h\left(x,u\right)$. So, the objective function that is optimized can be given as,

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

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

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

4. GA AND ITS APPLICATION FOR ECONOMIC POWER FLOW PROBLEM

GA is a kind of heuristic method for searching and optimizing based on evolutionary process. GA is firstly proposed and used for solving optimization problems by Holland in 1975 [21]. GA is based on natural selection. The main stages of natural selection are separated into three parts: human is born, human grows and human dies. The parameters which produce objective function that will be optimized by GA are defined as gens in GA. For the economic power flow solution, these parameters are the control variables defined in (38). The set of the gens is defined as individual in GA. According to the natural selection, the individual represents human. All of the individuals create population. The flow chart of the economic power flow solution in multi-terminal AC-DC system by GA is given in Fig. 6. Main stages of GA can be determined as follows; initial population, fitness scaling, selection, crossover, mutation and optimization criterion [22].

Initial population of the algorithm is defined as,

$$w_{ij} = w_{\min,j} + rand(0,1) \times \left(w_{\max,j} - w_{\min,j}\right) \qquad \left(i = 1 \ldots n_{ind}\right) \qquad \left(j = 1 \ldots n_p\right) \quad (43)$$

where n_{ind}, n_p, $w_{\min,j}$ and $w_{\max,j}$ represent the number of the individuals within the population, the number of the parameters of the individuals, the minimum and maximum values of the parameters, respectively.

In the fitness scaling stage, the individuals that will be used in selection stage are defined as,

$$fit_{ave} = \frac{\sum_{i=1}^{n_{ind}} fit_i}{n_{ind}} \quad (44)$$

where fit_{ave} and fit_i represent the average fitness value of the population and fitness value of the ith individual that equals to objective function defined in (41), respectively. The individuals whose fitness values are better (smaller) than the average fitness value are used in the selection stage.

In the selection stage, the parents to be crossed for producing children are selected within the defined individuals. For the selection of the parents within these defined individuals, tournament method is used and can be formulated as,

$$g_i = \frac{fit_i}{\sum_{j=1}^{n_{ind}} fit_j} \quad (45)$$

where g_i is the weight of the ith individual. The weight of an individual determines the elective probability in this stage and the sum of the weights within population is 1.

$$\sum_{i=1}^{n_{ind}} g_i = 1 \quad (46)$$

The number of the individuals for selection of the parents within the population is twice of the children number defined in the beginning of the algorithm. The parents in the same number of the children are selected within these selected individuals.

In the crossover stage, the children are produced as new individuals by parents defined in selection stage. These new individuals in the same number of the children are produced through the crossing method. 0 and 1 values in the same number of individual's gen number for crossing are produced randomly.

If the value is 0, then gen is taken from father, if the value is 1, then gen is taken from mother and thus the child is produced. Crossing process can be presented as follows:
Cross: 0 1 1 0 1
Mother: a b c d e
Father: u w x y z
Child: u b c y e

In the mutation stage, new individuals are produced to be changed all or some gens of the selected individuals that undergo mutation in the population. The number of the selected individuals is defined in the beginning of the algorithm. These individuals are reproduced to be formed all the gens of the selected individuals within algorithm. So, new individuals in the same number of the selected individuals that undergo mutation are randomly produced by (43). Mutation process increases variety of the population and prevents losing the individuals that provide good solutions.

There are many stopping criterions for optimization that is performed by GA and similar heuristic methods in the literature. In this study, iteration number is selected for stopping the optimization by GA. The stopping iteration number is selected as 100 for the study. GA stops when it reaches the defined maximum iteration number, 100. On the other hand, in this study, system constraints defined (27-33) are included in the optimization stopping criterion so that all of the system constraints are provided at the end of GA.

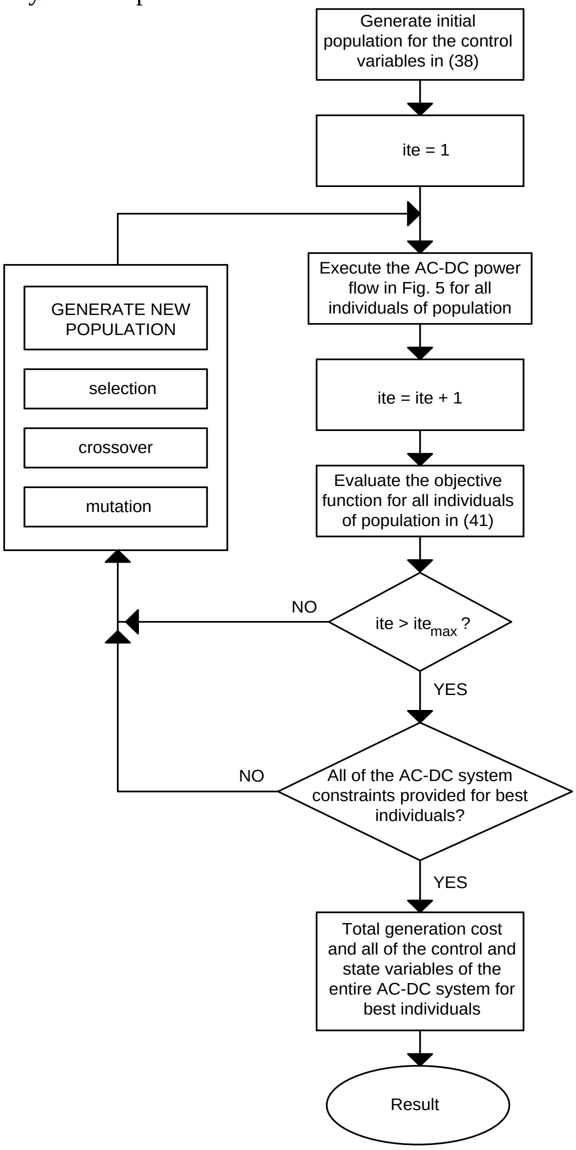


Fig. 6. The proposed flow chart for economic power flow in multi-terminal AC-DC system by GA

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.

Total generation cost throughout the proposed GA based optimization algorithm is shown graphically in Fig. 8. Total generation cost obtained with proposed GA based 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 GA for the optimization.

The proposed optimization algorithm is performed for 50 optimization trials with different AC-DC system initials. GA approximately has reached to global optimum at about 65th iteration for the best trial. For GA: 20 population sizes, 0.5 crossover rate and 0.1 mutation rate are used. These values used for GA are found at trials. The upper values of the used ones do not change the global optimum for GA.

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 GA are 1181.9 \$/hour and 1166.2 \$/hour, respectively. Error deviation for GA is 1.32%. It is observed that all control and state variables are in their limit values at the end of the optimization.

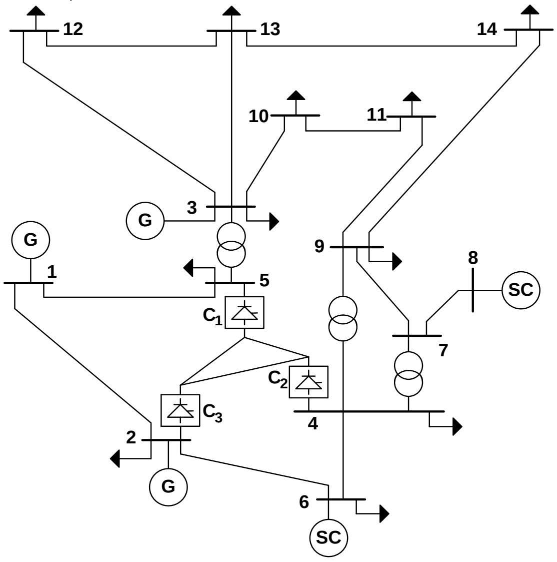


Fig. 7. The modified IEEE 14-bus AC-DC test system

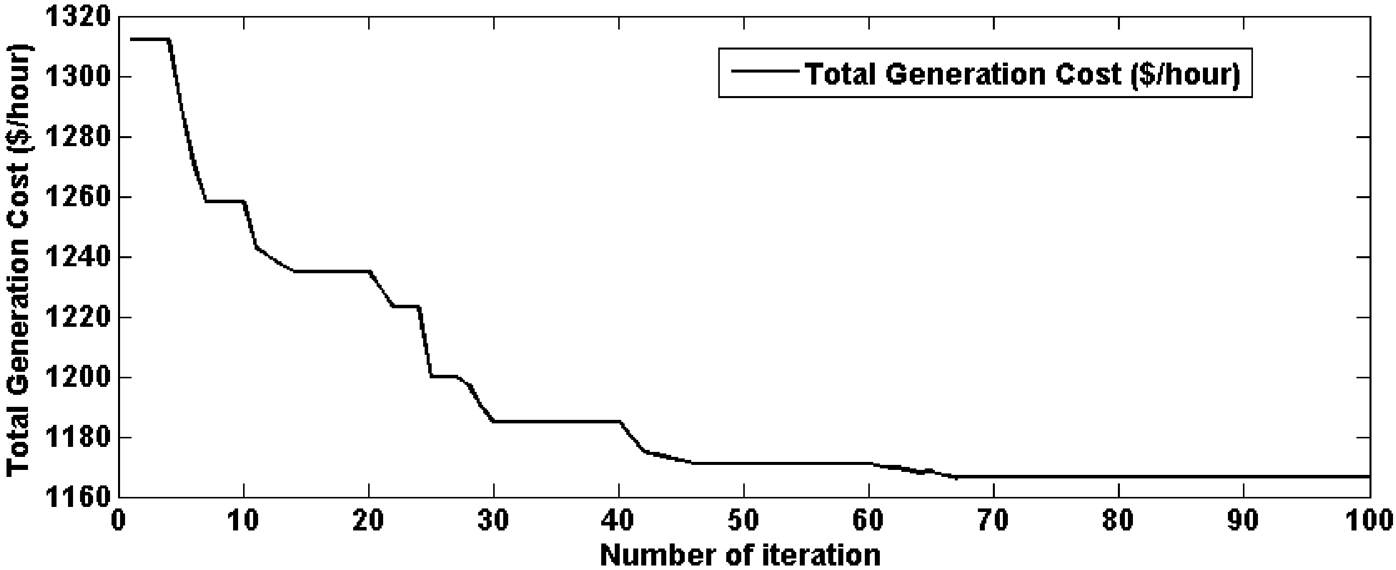


Fig. 8. Variation of total generation cost against iteration for the proposed approach

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

	GA	SDA [23]
Total Generation Cost	1166.2 \$/hour	2007.8 \$/hour

6. CONCLUSION

In this paper, a novel approach is proposed for economic power flow in multi-terminal AC-DC systems. GA is used for the first time in multi-terminal AC-DC system for economic power flow solution in this study. Any AC and DC power flow method can be used without any change in optimization algorithm as the sequential method in AC-DC power flow is used. Unlike the similar studies in the literature, converter active powers are used as control variables for optimization in the entire dc system in this study. Thus, both the most suitable converter active powers $\left(p_{di}^{\min} \leq p_{di} \leq p_{di}^{\max}\right)$ and converter types (rectifier or inverter) are achieved at determined system conditions. Thus, efficiency of the achieving economic generation cost is enhanced. The obtained results have presented 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 have also provided the system constraints for security and healthy system operation.

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