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Active Distribution System Expansion Planning Using Lion Pride Optimization Algorithm

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Abstract- Distribution expansion planning (DEP) is conceived as one of the main challenges ahead of distribution companies. DEP problem deals with the optimal expansion of the distribution network and its constituent equipment. The incorporation of a vast number of parameters and decision-making variables, as well as the complexity of modelling, have made the solution of this problem very difficult and more complicated. The present study proposes a novel approach to solve a DEP problem, where distributed generation (DG) resources are also incorporated into a distribution system. The purpose of this paper is to meet economic and operational requirements using DGs as candidate equipment for expansion of distribution system in order to avoid uncertainties of substations and expansion of feeders. In order to have a more precise simulation, the type of DG should be specified. Thus, in this study, the solid oxide fuel cell (SOFC) technology is utilized as the DG source. In order to achieve the optimum solution, the lion pride optimization algorithm seeks the solution space considering the solution of backward-forward sweep load flow problem for two modes of with and without the integration of DGs in a 30-bus test system. The results of simulations imply that the voltage profiles of the system are improved and the total expansion cost is also mitigated.

Keywords- Distribution expansion planning (DEP), Distributed generation (DG), Solid oxide fuel cell (SOFC), Lion pride optimization algorithm (LPO), Backward-forward sweep.

1. Introduction

The tradition power systems can be classified into three layers of generation, transmission, and distribution. When a distribution operator or planner anticipates that the voltage will drop in a specific point of low voltage (LV) grid or the passing current will increase in a specific feeder or the number of substation transformers in a node will increase, the investment for enhancement of capacity is indispensable. The options for expansion are restricted to the expansion of substations or feeders [1]. Then the planners consider just a few practical replacement options to tackle these problems, and the selected option must satisfy the economic and reliability objectives. Regard to the recent technological developments, the distributed generation (DG) is promoted as a novel option to tackle the problems corresponded with distribution networks. The optimal DG placement is a fascinating optimization problem in the area of distribution system planning [2]. The impacts of DG on distribution networks can be positive or negative, which are relevant to the operation and planning of distribution systems, and the characteristics of DG sources. In a general manner, the primary goal of expansion of each system is to meet the demand rise in an economical, secure, and reliable way. The DEP problem for the satisfaction of demand growth entails optimization of the best location for installations (placement) as well as the best capacity of new components, substations, and feeders which are restrained by substation capacity limitations, the thermal capacity of feeders, voltage drop, the radial configuration of networks, and reliability constraints. Regard to this fact that a lot of variables and constraints must be incorporated in the model; the optimization problem turns out to be a sophisticated problem in large-scale investigations [3]. The DEP problem is usually described as a single-objective problem to portray the economic costs of planning, which is correlated with the placement of components and the optimal capacity of feeders and substations. The costs pertaining to equipment incur two types of expenses: the operation costs and the investment cost [4]. The investment cost consists of the cost of equipment, ground procurement, constructions, workforce for installation, and installation costs. The operation cost is composed of the workforce, operational equipment, protection devices, services, tax, rents, and the value of the lost power due to ohmic losses. The investment cost is treated as a one-time permanent cost while the operation cost is regarded as a continuous or periodic cost. It is evident that the purpose of planning is to retain these costs at their lowest level. With respect to the trend of deregulation in various countries as well as the proliferation of modern technological equipment, the necessity of improvement in traditional approaches of planning has arisen. The DEP approaches can be segregated into two models of single-step and multi-step methods in order to determine the optimal expansion plan for a specific region and a particular time horizon of study [5]. The single-step approaches are static methods, which contemplate that the demand rise will not change during the time horizon of study. The multi-step methods indicate that the rise in demand will be included in the model at some intervals. Each interval can be treated as a single-step method. Thus, the multi-step method is a dynamic approach, which procures more accurate anticipation of future grid's state and more appropriate expansion planning. In most previous studies, the single approach is investigated.

In [6], the DEP and DG placement problems by incorporation of uncertainties are solved concurrently. In this study, the uncertainties of load and costs are modeled by probability density functions, and the Monte Carlo approach is used to describe the intermittencies. Besides, the particle swarm optimization method is used to solve the optimization. In [7], a new benefit model is defined for the multi-step DEP problem. In this model, the utilization of some automation technologies for the distribution sector is incorporated in the model of smart distribution grids. In addition, this paper has introduced a method to assess the reliability of distribution networks in a DEP problem. The authors in this work have employed the genetic algorithm to optimize the model. The considered functions in automation part correspond with automatic voltage control, automatic fault management, fault location estimator, and automatic metering devices. The reference [8] has proposed a planning model, including DG utilization and technical and economic restrictions. This model meets two goals of cost reduction and satisfactory level pertaining to placement, sizing, timing, and the augmentation of distribution grids for a specific period. An evolutionary approach is also used to find the extravagant irrational solutions, and a fuzzy-based approach is employed for satisfactory analysis. In [9], a dynamic model is suggested to deal with DEP problem. This model optimizes the investment cost as well as the operation cost of distribution grids. This model determines the optimal size and location of DG units by a specific strategy to augment the feeders. In this model, the investment costs such as DG installation cost and primary distribution feeder augmentation along with operation cost such as power losses costs, the maintenance cost of equipment, and the costs pertaining to the bought power from the upstream grid are included. In order to solve the optimization problem, a modified evolutionary algorithm is used. Reference [10] introduces a DEP problem that deals with the determination of size, location, and the proper time of installation of new equipment for the targeted substation, the determination of feeder path, the voltage drops in the grid, and the forecast of rising demand during time horizon. The authors in this work initially have solved the problem using a simple static approach with a fixed time horizon. This method is commonly known as short-term planning model. In the next step, by the inclusion of uncertainties of load forecasting, it is attempted to estimate and to extend the time horizon of the study. In this respect, the problem is proposed as a multi-step and multi-layer approach.

In [11], a fuzzy-based DEP model is proposed which concurrently optimizes some parameters such as the economic cost of the expansion, reliability, and the risk of overloading of the system. The results derived from the execution of the optimization for a real distribution network confirm the practical effectiveness of the model in economic and technical affairs. Reference [12] has proposed a DEP model to evaluate the required number of MV/LV transformers as well as the optimum place and capacity for installation of them. The results of this study express that the serving region of loads is highly dependent on the capacity and installation location of transformers as well as the structure of the grid. In [13], a DEP problem for the expansion of high-voltage substations and the expansion of sub-transmission transmission lines for multiple intervals is conducted. In this work, by applying graph theory and a greedy algorithm, the radial structure is suggested. The employment of imperialist competitive algorithm (ICA) is the novelty and contribution of this study. Reference [14] investigates the expansion of a distribution network by assessment of the implications of microgrids connected to the medium-voltage distribution network on the structure of the grid, reliability, and the economy of expansion scheme. The results presented in this study obviously demonstrate the profound impacts of microgrids on the economy of the expansion of distribution grids. Ultimately, in [15], a multi-step dynamic DEP problem is presented. This work explores a comprehensive analysis on the investment for expansion within the targeted perspective of the study. The numerical results of this study express that some investments in the expansion of distribution networks should be ignored or can be postponed. This matter helps to alleviate the expansion cost of distribution network while some certain objectives must be met. The authors in [16] have introduced a MILP model to solve the DEP problem in the presence of renewable sources subject to optimize reliability. A similar study is also investigated in [17], in which a multi-objective approach is used to solve a multi-stage DEP problem. in this work the aim is to find the impact of penetration of renewable resources on DEP scheduling. A stochastic mixed-integer convex model is also presented in [18], to solve DEP problem while trying to mitigate the greenhouse gas emission. In [19], the DEP for an interconnected distribution system comprised of multiple active distribution networks with consideration of optimal load shedding is investigated. In some other references [20-26], various aspects of distribution expansion planning problem are investigated. In these papers, the roles of many types of renewable sources, as well as electric vehicles and storage facilities in active distribution systems have been studied.

As it is evident from the literature presented above, in the most types of conducted research in the area of distributed network expansion planning regard to their complexity and difficulty of this problem the expansion of power stations and the expansion of transmission lines are investigated separately. Even though separate expansion planning alleviates the complexity of the problem, it deviates the seeking process from the optimum solution. The present paper delves into a new model to deal with the DEP problem in the presence of renewable energy resources. In this study, some new concepts and a more elaborated objective function are taken into consideration, and more powerful methods are incorporated to investigate the various aspect of the DEP problem. The contemplated objective function includes economic and operational goals subject to satisfy prevailing constraints. For more accurate results, the DGs' types must be specified. Hence, the solid oxide fuel cell (SOFC) technology is deployed as DG sources, which is not well surveyed in the distribution systems in the previous studies and can be regarded as a distinctive feature for this work. This optimization problem intends to find the most optimum planning schedule for distribution grid with respect to the integration of renewable energy sources as an alternative source of energy and avoiding unnecessary expansion of existing substations as well as upgrade of feeders as much as possible. To obtain optimal decisions, the lion pride optimization algorithm (LPO) is employed. This algorithm is a meta-heuristic algorithm which has brilliant performance in the optimization of non-linear non-convex and non-smooth problems. A combination of these cutting-edge items is used to define several scenarios to compare the effectiveness of the proposed method for a DEP problem which definitely has not never been investigated yet. Finally, the proposed method is simulated by a 30-bus test system, and the impacts of various factors on the DEP are observed.

2. Problem outlines

In the following section, the details of the proposed method and their prevailing formulation are described.

2.1. Objective function

The objective function (J_{TEC}) of the problem portrays the total expansion cost (TEC) which consists of four sections; the cost of installation of new transformers in power stations (fixed cost and variable cost), DG cost (both fixed cost and variable cost), the upgrade cost of new feeders (fixed cost), and the cost of active power losses (variable cost).

Fixed costs translate into the amount of investment, which is made in the installation and startup stage. These expenditures include the costs of installations and constructions in the early stage stages. The variable costs encompass the operation and maintenance costs. A substation is treated as a source of electricity, which can serve the loads with a certain variable cost that is capped by a specific final (maximum) limit. The formulation of total expansion cost can be represented by the following equation. In this paper, the objective is to minimize the total expansion cost [27-28].

$$J_{TEC} = C_{IOES} + C_{IODG} + C_{FU} + C_{EL} \tag{1}$$

Where, C_{IOEC} denotes the investment and operation cost of expansion substation, C_{IODG} is the investment and operation cost of DG sources, C_{FU} stands for the investment cost for the upgrade of feeder, and C_{EL} represents the costs pertaining to the energy losses [29].

$$C_{IOES} = \sum_{i=1}^{T_{Bus}} \sum_{p=1}^{T_{PSi}} C_{i,PS} \times \sigma_{i,PS} + 8760 \sum_{t=1}^{T_N} \beta^t \left(\sum_{i=1}^{T_{Bus}} \sum_{j=1}^{T_{PSi}} C_E \times P_{i,PS} \right) \tag{2}$$

In the above equation, T_{Bus} stands for the total number of system's buses, T_{PS} represents the total number of substations' transformers, $C_{i,PS}$ is the cost of transformer of PS in the cost of prevailing substation (\$), $\sigma_{i,PS}$ is a binary decision-making variable pertaining to the transformer of PS in the i^{th} substation, β expressed the current value factor, t shows the incremental time, C_E indicates the selling price of electricity (\$/MWh), and $P_{i,PS}$ represents the nominal power of transformer of PS in the transmitted power from the i^{th} substation.

$$C_{DG} = \left(\begin{array}{l} \sum_{i=1}^{T_{BL}} C_{CUB_i} \times \left(S_{DG_i} + BDGC \right) \times \sigma_{DG_i} \\ +8760 \sum_{t=1}^{T_N} \beta^t \left(\sum_{i=1}^{T_{BL}} C_{ODG_i} \times PF \times S_{DG_i} \right) \end{array} \right) \tag{3}$$

In above, BL represents the total buses connected to loads, C_{CUB} is the investment cost for feeder upgrade, S_{DG} shows the generated power by a DG in MVA, $BDGC$ denotes the capacity of supplying of DG unit in MVA, σ_{DG} is the binary decision-making variable of DG, T stands for the time horizon of study in term of year, C_{ODG} indicates the operation cost of DG in \$/MWh, and PF shows the power factor of the system.

$$C_{FU} = \sum_{i=1}^{T_{Bus}} \sum_{j=1}^{T_{BL}} C_{i,j} \times \sigma_{i,j} \tag{4}$$

In Eq. (4), $C_{i,j}$ shows the total cost of the feeder from bus i to j (\$/km), and the binary decision-making variable of the feeder from i to j is designated by $\sigma_{i,j}$.

$$C_{EL} = 8760 \sum_{t=1}^{T_N} \beta^t \left(\sum_{j=1}^{T_{BL}} \frac{\Delta V_{i,j}^2}{\left| Z_{i,j} \right|} \times PF \times C_E \right) \tag{5}$$

Where ΔV stands for the maximum permissible voltage drop in per unit, and $Z_{i,j}$ is the impedance of feeder from bus i to j. The equation below represents the current value factor, in which d signifies interest rate [30].

$$\beta^t = \frac{1}{\left(1+d\right)^t} \tag{6}$$

2.2. The structure and model of the incorporated type of DG

In this study, a fuel cell is selected to be integrated into the distribution network. A fuel cell is a new technology for high-efficient energy production that has no environmental and noise pollution. A fuel cell converts the chemical energy into electrical energy through a pair of redox reactions between hydrogen (as fuel) and oxygen (as an oxidizing agent). In the solid oxide fuel cell (SOFC), the solid oxide has particular importance. This fuel cell operates at a temperature between 100 °C to 1000 °C and shows the efficiency of 60% to generate 100 MW of active power. In this technology, a ceramic electrolyte is utilized, which is covered by specific porous-material coated electrodes. In higher temperatures of fuel cell operation, oxygen ions with negative charge pass through a crystal network. When a gas fuel containing hydrogen passes through the anode a negatively-charged current pass through the electrolyte which contains oxygen ions in order to oxidize the fuel. The stored oxygen in cathode usually are absorbed from the air, and the created electrons in anode pass through an external load while transmitting to the cathode. Hence, an electrical loop for an electrical circuit is completed, and electric power is generated. Fig. 1 depicts the paradigm of a fuel cell [31-32].

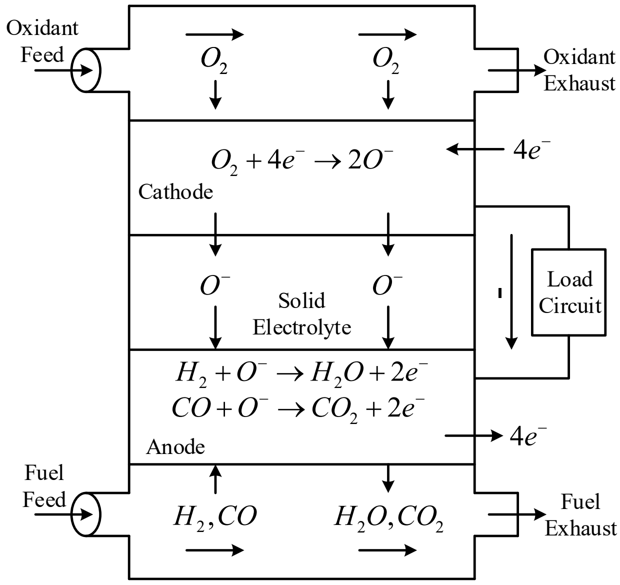

Fig. 1. the schematic of solid oxide fuel cell

The chemical reaction in anode and cathode can be described as follows:

$$H_2 + O^- \rightarrow H_2O + 2e^- \tag{7}$$

$$\frac{O_2}{2} + 2e^- \rightarrow O^- \tag{8}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{9}$$

The advantages of this fuel cell can be mentioned as follows:

- Insensitivity to carbon monoxide
- The ability to consume diverse fuels
- Lack of obligation to use pure hydrogen
- High efficiency of the system
- Lack of need to separate exclusive fuels
- The possibility of use of natural gas as fuel
- Applicable in dual-purpose generators
- Lack of utilization of liquid electrolyte
- Lack of use of precious and scarce metals for manufacturing
- In the case of usage of water electrolyze for production of consuming hydrogen, the emission of air pollution will be reduced to zero [33-34].

With respect to the aforementioned advantages, the deployment of this large-scale technology will be mounted in distribution systems in the future. This matter necessitates the elaborate assessment of the integration of fuel cells into the DEP problem [35]. In order to examine the impact of the fuel cell in the DEP problem, in this study, the following assumptions are made:

- The gases are supposed to be ideal
- A fuel cell works with hydrogen and air
- The pressure ratio between the internal part and extrinsic parts of electrode channels is enough to take the choking phenomenon into consideration.
- The electrode channels are adequately narrow to ignore the pressure drop across them.
- The fuel cell temperature is stable
- The voltage drops due to losses are classified as follows: 1- ohmic 2- activation 3- Mass transfer

The modelling starts with the flow of inlet as presented below:

$$\frac{\dot{m}_{fc}}{p_u} = K\sqrt{M} \tag{10}$$

Where m_{fc} is the mass flow rate, K denotes the inlet constant, P_u shows the upstream pressure (in the electrode channels), and M stands for the molar flow rate. The usage factor (U_f) is defined as the ratio of the amount of hydrogen reacted with oxygen ($H_{2,reacted}$) to the amount of entering hydrogen ($H_{2,in}$).

$$U_f = \frac{\dot{m}_{fc}, H_2, reacted}{\dot{m}_{fc}, H_2, in} \tag{11}$$

Regard to this point that the molar flow of each gas at the inlet is proportional to its partial pressure, the following equations can be obtained:

$$\frac{q_{H_2}}{P_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{12}$$

$$\frac{q_{H_2O}}{P_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O} \tag{13}$$

In above, q is the mass flow rate, P represents the partial pressure, K_{an} shows the inlet constant for the anode, and K stands for the molar constant of the inlet. By replacement and combination previous equations, Eq. (10) can be redefined as follows:

$$\frac{\dot{m}_{fc}}{P_{an}} = K_{an}\left[\left(1-U_f\right)\sqrt{M_{H_2}} + U_f\sqrt{M_{H_2O}}\right] \tag{14}$$

Where P_{an} is the pressure in the electrode channel. To obtain the partial pressure of the flowing gases through electrodes, the ideal gas law is employed. In this study, this equation is written just for hydrogen. For water and steam, it will be similar. The ideal gas equation for hydrogen can be expressed as follows:

$$P_{H_2}V_{an} = n_{H_2}RT \tag{15}$$

In above, V_{an} shows the anode channel volume, R is the ideal gas constant, T denotes the temperature, and n_{H2} indicates the amount of mole of hydrogen in the channel. By separation of pressure and derivation, the following formula is obtained:

$$\frac{dP_{H_2}}{dt} = \frac{RTq_{H_2}}{V_{an}} \tag{16}$$

The hydrogen flow can be segregated into three types of input, output, and reacting. Hence, Eq. (16) can be shown as below:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right) \tag{17}$$

Where q^{in}_{H2} is the input molar flow rate of hydrogen, q^{out}_{H2} represents the output molar flow rate of hydrogen, and q^{r}_{H2} shows the amount of molar flow rate of hydrogen that is reacting. With respect to the electrochemical relation, q^{r}_{H2} can be calculated as the following equation:

$$q^{r}_{H_2} = \frac{N_0 I}{2F} = 2K_r I \tag{18}$$

In above, N_0 represents the number of fuel cells, F is the Faraday constant, the electrical current is shown by I, and K_r shows the modulation constant. By replacing Eqs. (11) and (18) in Eq. (17), and using Laplace transform, Eq. (19) can be obtained.

$$P_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2} s}\left(q^{in}_{H_2} - 2K_r I\right) \tag{19}$$

Where, τ_{H2} indicates the time, during which anode pole is in tough with hydrogen flow. The output voltage can be obtained with respect to the Nerst equation. The term rI indicates the ohmic loss, which is due to electrode resistance and electrolyte resistance against the flow of O^{2-} ions.

$$V = N_0\left[E_0 + \frac{RT}{2F}\left(Ln\frac{P_{H_2} P_{O_2}^{\ 0.5}}{P_{H_2O}}\right)\right] - rI \tag{20}$$

According to Eq. (20), V displays the output voltage of fuel cell, E_0 is the initial voltage of fuel cell (according to the Gibbs free energy law), and r stands for ohmic resistance. The activation loss is originated from the slowness of reactions on the surface of electrodes. A share of voltage magnitude is also deducted due to the ease of chemical reaction in order to transfer electrons toward electrodes. In order to calculate this type of loss, the Tafel equation, which is a well-known method, can be used. This equation can be achieved by conducting physical experiments on different chemical reactions, and can be pointed out using the following equation:

$$\Delta V_{act} = -ALn(i) \tag{21}$$

In this equation, ΔV_{act} is the voltage activation loss, A shows the slope of the Tafel line (a specific constant for the solid oxide fuel cell), and i represents the current density. The mass transfer loss is occurred due to a change in the fuel concentration while flowing around electrodes. When air and fuel enter the electrodes, they have high concentration and density, but after passing through electrodes, they will be used in the chemical reaction. This density affects the partial pressure of reagents as well as the voltage created by that electrode. This type of loss cannot be calculatable analytically. Hence, the experimental results can be used to estimate this value, which can be exhibited by the following equation that is regarded as an appropriate and accurate approximation for the mass transfer loss [36].

$$\Delta V_{trans} = me^{(ni)} \tag{22}$$

In above, ΔV_{trans} is the mass transfer loss, and m and n are coefficients that are obtained by experiment. The deduction of losses from Eq. (20) results in a general equation for the voltage of fuel cell. In a real fuel cell-based plant, some fuel cells are joint to each other to generate the required voltage and current. Thus, the final voltage can be expressed as:

$$V = N_0\left[E_0 + \frac{RT}{2F}\left(Ln\frac{P_{H_2} P_{O_2}^{\ 0.5}}{P_{H_2O}}\right)\right] - rI - ALn(i) + me^{(ni)} \tag{23}$$

Finally, the total output generated power of fuel cell can be yielded by the following equation:

$$P_{FC} = N_0 VI \tag{24}$$

2.3. The constraints of the problem

The targeted constraints to deal with this problem can be expressed as follows:

2.3.1. The total power equality

The summation of power injected or absorbed to or from a feeder must be equal with the total demand of loads on that feeder with regard to the number of feeder losses and the amount of power provided by DG sources if it exists [37].

$$\sum_{i=1}^{T_{Bus}}\left(S_{i,j} - \frac{\Delta V_{i,j}^2}{\left|Z_{i,j}\right|}\right) - \sum_{j=1}^{T_{BL}} S_{i,j} + S_{DG_i} = D \tag{25}$$

So that S represents the input and output power of feeder in MVA, S_{DG} demonstrates the generated power by DG unit in MVA, and D stands for demand in MVA.

2.3.2. The thermal capacity of distribution feeder

The load flow in feeders must be observed to be within their capacity range [38].

$$S_{i,j} \le S_{i,j}^{Max} \times \sigma_{i,j} \tag{26}$$

Where, Si,jmax shows the thermal capacity cap of feeder in MVA.

2.3.3. The capacity of distribution substation

The total power delivered to the grid through substation's transformers must be congruent with the total capacity of substation so that the amount of delivery is not allowed to exceed the maximum tolerable capacity of transformers [39].

$$\sum_{j=1}^{T_{BL}} S_{PS_{i,j}} \le S_{PS_i}^{Max} \tag{27}$$

In the above-mentioned equation, S_{PSi}^{max} represents the capacity of a substation in MVA.

2.3.4. The distributed generation restriction

The amount of power generated by DG must be met the criteria of DG generation permissible range that is restrained by technical and operational limitations [40].

$$S_{DG_i} \le S_{DG_i}^{Max} \times \sigma_{DG_i} \tag{28}$$

In above, S_{DGi}^{max} stands for the capacity range of DG unit in MVA.

2.3.5. Voltage drop limitations

The voltage magnitude in all buses is not allowed to violate a prespecified range.

$$\left|V_i - V_j\right| \le \Delta V \quad ; \quad \forall i \in T_{Bus} \ ; \ \forall j \in T_{BL} \tag{29}$$

$$V_i \le V_n \tag{30}$$

In the above equations, ΔV represents the maximum allowed voltage drop in per unit, V is the voltage magnitude of the bus in p.u., T_{bus} represents the total number of system's buses, T_{BL} shows the total number of load buses, and V_n stands for the nominal voltage of the grid [41-42].

3. Lions pride optimization algorithm

The lion pride optimizer is inspired by the social and individual behaviour of lions is a group, called pride. The concept of LPO algorithm is simple and comprehensible, and the implementation of LPO is easy. LPO algorithm is regarded as one of the most powerful methods in evolutionary optimization. Due to its modified feature, it has evident superiority over previously introduced algorithms such as GA and PSO and ICA algorithms. The performance of LPO conveys that it has faster convergence ability and it can reach to a more accurate global optimum solution. One of the prominent features of LPO is that it is not sensitive to its parameters, which implies the features of robustness and not being problem-dependent. Two major factors that affect the performance of LPO (Elitism) are the pride update strategy and the individual's brutal competition. Due to the magnificent performance of LPO, it is particularly useful and attractive for large-scale applications in the real-world optimization problems. LPO is classified as a population-based optimizer. In LPO, a population consists of a group of lions that live together. Each lion or lioness (female lion) in pride is also referred to as a member or an individual. All male lions compete against each other to obtain the king position. Each pride has its individual king. The kings are allowed to mate with nearly all lionesses in the group to reproduce offspring. The offspring will grow up in the pride and will get stronger year by year. They can take over the king position when they become a young lion and are able to defeat the king of their own pride. In addition, the pride's territory may be jeopardized by other lion prides nearby. This means the group must defend their own territory against the invasion of other lions. The king must be adequately strong to defend the territory as well as his own life when it is threatened by any internal or external menace whether it is alone or is accompanied by its pride. Otherwise, the king will lose the king position. The king of pride will be replaced by a stronger male lion. If the new king has been an offspring, it can mate now with all the lioness in the group and has the possession of the territory. When a new cohort of male lions takes over a pride, they surprisingly kill all young cubs, which are sired by their predecessors. In the following, first, the fundamental concept of LPO and the process of seeking better solutions are explained. Then, the crossover strategy and the procedure of solution space scaling are defined. Finally, some equations are presented to find the global optimum solution [43].

3.1. Fundamental concepts

In Fig. 2, the details and the flowchart of the LPO algorithm are illustrated. Similar to all of the evolutionary algorithms, the LPO begins its process with an initial population. In this study, the initial population of lions is supposed to be M=50. In the problems with n dimension, the member of pride is designated by x_i^k, which represents the i^{th} member (lion) in the k^{th} pride.

3.2. Obtaining two best solutions

In LPO, it is supposed that two lions can better lead the group rather than a lion. Hence, the two best solutions are stored in each iteration. This matter is shown by Eq. (31) as below:

$$\begin{aligned} & x_{b_1}^k \in \left\{ x_i^k, i=1,2,...,M \right\}, \\ & st: f(x_{b_1}^k) = \max\left\{ f(x_i^k) \right\}, i=1,2,...,M \end{aligned} \tag{31}$$

3.3. Crossover strategy

Each female can reproduce four children with the two best members, but just one in four of them can survive at last. Thus, the birth strategy can be sketched by the following formula.

$$x_{4i-3}^{k+1} = x_{b_1}^k + mc_i^k (x_{b_1}^k - x_i^k), i=1,2,...,M \tag{32}$$

$$x_{4i-2}^{k+1} = x_{b_1}^k + mc_i^k (x_{b_1}^k - x_i^k), i=1,2,...,M \tag{33}$$

$$x_{4i-1}^{k+1} = x_{b2}^k + mc_i^k (x_{b_1}^k - x_i^k), i=1,2,...,M \tag{34}$$

$$x_{4i}^{k+1} = x_{b_2}^k + mc_i^k (x_{b_1}^k - x_i^k), i=1,2,...,M \tag{35}$$

The algorithm automatically and randomly generates the initial factor of mc_0. The multiplier of mc_i^k will be obtained through Eq. (36).

$$mc_i^k = mc_0 (rand(1,1) - 0.5), i=1,2,...,M \tag{36}$$

In above, $rand(1,1)$ generates random numbers within 0 and 1. In this regard, different mc_i^k will be produced for various x_i^k. Only one in four children can be survived that can be specified using Eq. (37).

$$\begin{aligned} & x_1^{k+1} = x_\alpha^k, \alpha \in \left\{1,2,...,4M\right\}, \\ & s.t: f(x_\alpha^{k+1}) = \max\left\{ f(x_i^{k+1}), i=1,2,...,4M \right\} \end{aligned} \tag{37}$$

In the above equation, x_1^{k+1} denotes the first member in the iteration of $k+1$. Similarly, x_j^{k+1} show the j^{th} member in the new iteration (j=2, 3, …, M).

3.4. The scaling process for searching space

In order to prevent premature convergence, which is not desired by all optimization algorithms due to causing poor performance, in order to tackle this problem, the scaling strategy can be imported. Hence, to calculate the scaling of searching space, Eq. (38) can be employed.

$$I^k = \begin{cases} I^0, \mathrm{mod}(t_s, k_2) = 0 \\ \sum \dfrac{I^0}{k_1 \ln(t_s + 2) - k_1 + 1}, \mathrm{mod}(t_s, k_2) \neq 0 \end{cases} \tag{38}$$

If the algorithm is unable to find for a more optimal result, it will be terminated. In such a condition, the optimum direction can be updated with respect to the two best solutions at each iteration using Eqs. (39) and (40).

$$D_{b_1}^{k+1} = \frac{x_\alpha^{k+1} - x_{b_1}^k}{\left\| x_\alpha^{k+1} - x_{b_1}^k \right\|_2}, s.t: \frac{f(x_\alpha^{k+1}) - f(x_{b_1}^k)}{\left\| x_\alpha^k - x_{b_1}^k \right\|_2} = \max \left\{ \begin{aligned} & \frac{f(x_i^{k+1}) - f(x_{b_1}^k)}{\left\| x_i^k - x_{b_1}^k \right\|_2}, \\ & i=1,2,...,2M \end{aligned} \right\} \tag{39}$$

$$D_{b2}^{k+1} = \frac{x_\beta^{k+1} - x_{b_2}^k}{\left\| x_\beta^{k+1} - x_{b_2}^k \right\|_2}, s.t: \frac{f(x_\beta^{k+1}) - f(x_{b_2}^k)}{\left\| x_\beta^k - x_{b_2}^k \right\|_2} = \max \left\{ \begin{aligned} & \frac{f(x_i^{k+1}) - f(x_{b_2}^k)}{\left\| x_i^k - x_{b_2}^k \right\|_2}, \\ & i=1,2,...,2M \end{aligned} \right\} \tag{40}$$

According to the two best dimensions, the two best members must be optimized using Eqs. (41) to (43):

$$x_{b_1}^{k+1} \in \left\{ x_{b_1}^{k+1} + \varepsilon D_{b_1}^{k+1} \right\}, s.t: f(x_{b_1}^{k+1}) = \max\left\{ f(x_{b_1}^{k+1} + \varepsilon D_{b_1}^{k+1}) \right\} \tag{41}$$

$$x_{b_2}^{k+1} \in \left\{ x_{b_2}^{k+1} + \varepsilon D_{b_2}^{k+1} \right\}, s.t: f(x_{b_2}^{k+1}) = \max\left\{ f(x_{b_2}^{k+1} + \varepsilon D_{b_2}^{k+1}) \right\} \tag{42}$$

$$\varepsilon = \frac{(1001-j)\left\|l^{\circ}\right\|_2}{2000\ln(k+2)} \tag{43}$$

In above, ε represents the summation of searching steps (a set of answers) while j=1,2, …, 2000 in this study. $\|x\|_2$ represents the Euclidian distance of variable of x.

3.5. Creation of better members

The proposed strategy of LPO is mainly designed based on the behaviour of male lions. However, some parameters such as female density, adult female mortality, cub productivity, and the adult females' average age can affect the long-term persistence of a pride. The weaker lions that are not evolved through the time will gradually disappear, and their territory and resources will be occupied by stronger coalitions. This phenomenon, which implies that if a lion has not been evolved for a specific period of time, is called long stagnation and can be calculated by defining a threshold. The strongest member can be found by searching in each dimension using Eqs. (44) and (45).

$$x_{b_1}^{k+1} \in \left\{x_{b_1}^{k+1} + \varepsilon e(n,i)\right\}, f(x_{b_1}^{k+1}) = \max\begin{Bmatrix} f(x_{b_1}^{k+1}) + \varepsilon e(n,i), \\ i = 1,2,...,n \end{Bmatrix} \tag{44}$$

$$\varepsilon = \frac{l^{\circ}(1)(201-j)}{2000\times 10^{2tls-1}}, j = 1,2,...,400 \tag{45}$$

In above, ε shows a set of search steps and tls denotes the time pertaining to the long stagnation. Besides, $e(n, i)$ represents a unit vector with n dimensions. The flowchart of LPO is demonstrated in Fig. 2 to describe the procedure of this algorithm.

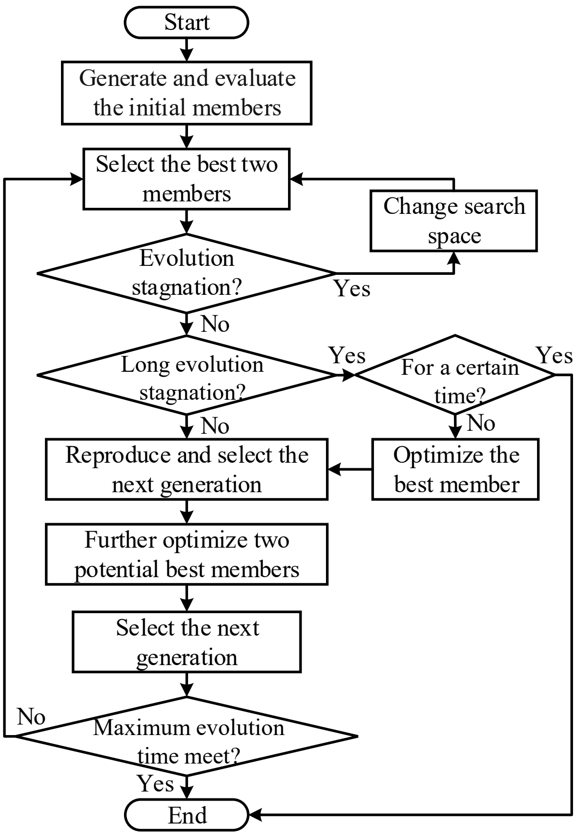

Fig. 2. The flowchart of the LPO algorithm [43]

4. Simulation and results

The configuration of the targeted distribution network is depicted in Fig. 3 [44]. This distribution system consists of 30 buses, including slack bus. This grid has a primary feeder which is branched into three secondary feeders. The main feeder of the grid is fed through a 132/11 kV 12 MVA substation located at bus 1, and the loads are connected to the distribution grid in the buses 2 to 30 [45]. The system capacity is determined as 10.224 MVA, and the thermal capacity of feeders is supposed to be 12 MVA [46].

In the present work, it is assumed that the demand will increase by 40% in comparison with the benchmark year during the next 5 years. This matter conveys the demand of 14.314 MVA at the end of the time horizon of study. This amount of demand necessitates the installation of new DG sources (a fuel cell, in this study) with respect to the unavailability of generation sources due to routine maintenances. The power factor for DG sources is assigned to be equal to 85%. The integrated type of DG in this study is supposed to be SOFC, and its capacity is defined as multiples of 0.2 MVA. The maximum dedicated installation capacity of DG at each bus is limited to 0.6 MVA that can be accompanied by back-up DG-based supply sources. The substation expansion planning entails the installation of two 10 MVA transformers. The feeder upgrade to a greater capacity is needed to procure the capacity of 20 MVA with the impedance of Z20MVA=0.1469+0.2719j Ω/km. The calculations show the highest level of losses of 10%. The characteristics pertaining to the feeders and the system's loads are presented in Tables 1 and 2. In the calculations, the electricity purchasing price from the upstream grid is assigned to be equal with 0.035 \$/kWh. The costs of each DG unit are equal with 500 \$/kVA, and the variable operation cost of these units is 0.07 \$/kWh. The fixed cost of the requirement for a new 10 MVA transformer is estimated to be about 0.1 million dollars. The costs of feeder upgrade to a higher capacity (20 MVA) is calculated by 75000 \$/km. Besides, the profit rate is estimated to be around 6%. In addition, the total demand of the grid in the benchmark year and at the end of the time horizon of study is demonstrated in Table 2.

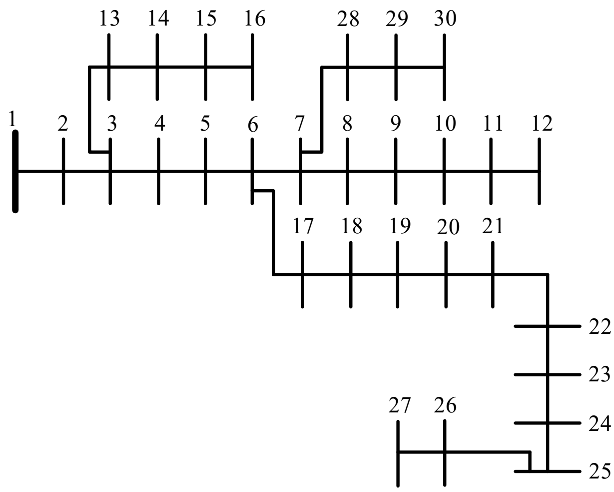

Fig. 3. The targeted standard 30-bus distribution system

Table 1. The characteristics of feeders in the 30-bus distribution system

Bus	$Node_s$	$Node_r$	Resistance (pu)	Reactance (pu)	Line length (km)
1	1	2	0.0967	0.0397	0.6
2	2	3	0.0886	0.0364	0.55
3	3	4	0.1359	0.0377	0.55
4	4	5	0.1236	0.0343	0.5
5	5	6	0.1236	0.0343	0.5
6	6	7	0.2598	0.0446	0.6
7	7	8	0.1732	0.0298	0.4
8	8	9	0.2598	0.0446	0.6
9	9	10	0.1732	0.0298	0.4
10	10	11	0.1083	0.0186	0.25
11	11	12	0.0866	0.0149	0.2
12	12	13	0.1299	0.0223	0.3
13	13	14	0.1732	0.0298	0.4
14	14	15	0.0866	0.0149	0.2
15	15	16	0.0433	0.0074	0.1
16	16	17	0.1483	0.0412	0.6
17	17	18	0.1359	0.0377	0.55
18	18	19	0.1718	0.0391	0.55
19	19	20	0.1562	0.0355	0.5
20	20	21	0.1562	0.0355	0.5
21	21	22	0.2156	0.0372	0.5
22	22	23	0.2165	0.0372	0.5
23	23	24	0.2598	0.0446	0.6
24	24	25	0.1732	0.0298	0.4
25	25	26	0.1083	0.0186	0.25
26	26	27	0.0866	0.0149	0.2
27	27	28	0.1299	0.0223	0.3
28	28	29	0.1299	0.0223	0.3
29	29	30	0.1299	0.0223	0.3

4.1. Problem-solving scenarios

The DEP optimization problem intends to find a trade-off between the expansion of existing substations and the installation of new DG sources on the load buses subject to satisfy the forecasted incremental demand of the distribution network. The expansion of current feeders implies the installation of new transformers as well as upgrade of existing feeders. If the feeder's temperature has violated its thermal capacity boundary, the feeder must be replaced with a new feeder with higher capacity. In this case, two scenarios can be supposed:

- Scenario 1: The expansion of existing substations (traditional solution) along with feeder upgrade (DG penetration rate= 0%)
- Scenario 2: The expansion of existing substations or installation of DGs on load buses along with feeder upgrade (DG penetration rate= 40%)

4.2. The numerical results of the simulation

The results of the LPO algorithm to obtain the total expansion cost of two above-mentioned scenarios are demonstrated in Table 3. This Table shows that the first option is to perform the expansion of substation without installation of any DG sources. In this scenario, a transformer is installed to cope with the new condition of increasing loads, and five feeders are upgraded because the future load flow condition entails a higher thermal capacity. In this case, the old feeders (12 MVA) must be replaced with new feeders (20 MVA). Fig. 4 portrays the position of upgraded feeders in the distribution network.

Table 2. The demand condition for the 30-bus distribution system

Bus number	Benchmark year's		At the end of time horizon	
	Active power (MW)	Reactive power (MVAR)	Active power (MW)	Reactive power (MVAR)
2	0.42	0.26	0.588	0.364
3	0	0	0	0
4	0.42	0.26	0.588	0.364
5	0.42	0.26	0.588	0.364
6	0	0	0	0
7	0	0	0	0
8	0.42	0.26	0.588	0.364
9	0.42	0.26	0.588	0.364
10	0.41	0.25	0.574	0.35
11	0.42	0.26	0.588	0.364
12	0.25	0.15	0.35	0.21
13	0.11	0.07	0.154	0.098
14	0.11	0.07	0.154	0.098
15	0.11	0.07	0.154	0.098
16	0.02	0.01	0.028	0.014
17	0.44	0.27	0.616	0.378
18	0.44	0.27	0.616	0.378
19	0.44	0.27	0.616	0.378
20	0.44	0.27	0.616	0.378
21	0.44	0.27	0.616	0.378
22	0.44	0.27	0.616	0.378
23	0.44	0.27	0.616	0.378
24	0.44	0.27	0.616	0.378
25	0.44	0.27	0.616	0.378
26	0.44	0.27	0.616	0.378
27	0.26	0.16	0.364	0.224
28	0.17	0.11	0.238	0.154
29	0.17	0.11	0.238	0.154
30	0.17	0.11	0.238	0.154

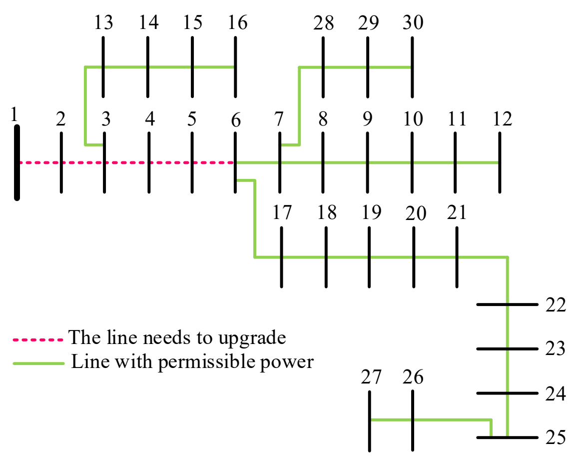

Fig. 4. The location of upgraded feeders in the targeted network

With respect to the results of Table 3, in the second scenario, if the option of DG installation along with substation expansion is adopted, the results of the problem will be more optimal. In the second scenario, no feeder is upgraded because the installation of DGs underlie all feeders to operate under their thermal capacity limits. Therefore, according to Table 3, by drawing a comparison between the two scenarios, it can be perceived that the second scenario has reduced the expansion cost by 7.061%.

In Fig. 5, the voltage profiles of the grid's buses for two defined scenarios are illustrated. As can obviously be seen, the voltage profile in the second scenario is better than the first one. In the first scenario, the lowest voltage magnitude corresponds with bus 27 by 0.83298 p.u. In the second scenario, the lowest voltage level belongs to bus 27, while the voltage magnitude is equal to 0.9084, which conveys the priority of the second scenario. The voltage profile improvement is one of the main advantages of the integration of DG sources in the distribution networks.

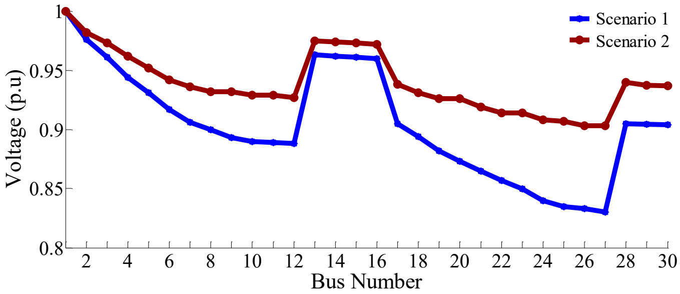

Fig. 5. The voltage magnitudes of different buses for two proposed scenarios

Fig. 6 depicts the load flow condition in the feeders. It is evident that the feeders in the second scenario are loaded less than the first scenario. The reason is that the feeders encompassing DG units can restrain the load flow of feeders by meeting part of loads locally and alleviate the thermal condition of feeders. This matter is counted as one of the prominent advantages of DGs, which leads to loss reduction and providing the opportunity of being used in DEP problem without the need to upgrade the feeders.

Table 3. Comparison of two scenarios defined in the proposed DEP problem incorporating LPO algorithm

	Scenario 1	Scenario 2
The maximum penetration rate of DG	0	40%
New transformer required	1	0
Fixed expansion cost (M$)	0.1	0
Total power of the system (MVA)	16.11576	14.99679
The acquired power of substation (MW)	13.54289	8.915688
The variable cost of substation expansion (M$)	25.22369	16.60579
Total substation expansion cost (M$)	25.32369	16.60579
Number of DGs	0	21
Number of back-up SOFC DGs	0	7
The bus number corresponded with the installed DGs	-	9, 11, 20, 23, 25, 27, 28
Fixed cost of DG (M$)	0	2.1
The variable cost of DG (M$)	0	6.297
Total DG cost (M$)	0	8.397
Number of feeder upgrade required	5	0
The bus number corresponded with the upgraded feeder	1,2,3,4,5	-
Fixed cost of feeders (M$)	0.2025	0
Total active power losses (MW)	0.6343	0.2692
Cost of losses (M$)	2.5373	1.0791
Total expansion cost (M$)	28.06349	26.08189
Iteration	200	200
Computation time (sec.)	11.4941	242.3261
Convergence condition time (sec.)	3.9355	106.0889

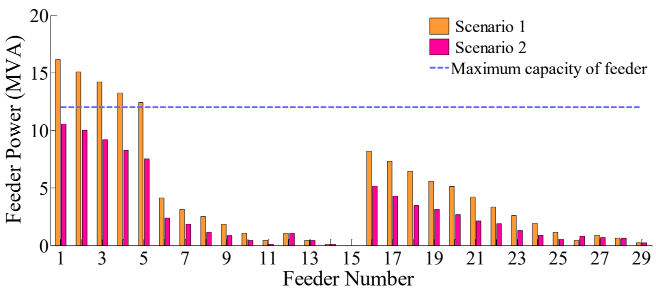

Fig. 6. The load flow condition for two proposed scenarios

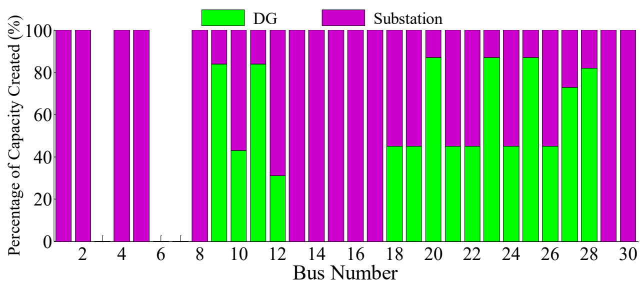

Fig. 7. The created capacity by substation and DG for two proposed scenarios

Fig. 7 demonstrates the percentage of created capacity from substation and DG in the second scenario. As can be seen, on the buses, which include DG sources, a considerable capacity is created by these generation sources. Therefore, as can be perceived from the results, the outcomes of the proposed method for DEP problem using LPO can be concluded as follows:

A. The results of optimization indicate that in contrast to the traditional methods, the integration of DG sources procures economic and technical benefits for the electric systems. The traditional approach entails the installation of new transformers in substations and replacement of some feeders (upgrade) on high-load buses.

B. The voltage profile in the scenario of deployment of DG sources is remarkably better improved compared to the traditional method. Regard to this fact that DG sources are installed on demand side, part of the loads are served locally, and the voltage profile is boosted in all nodes of the grid.

C. The integration of DGs into the ending nodes of the feeder results in better loss mitigation compared to the case of being installed at the upstream nodes. The results indicate that if DGs are installed at the nodes where severely suffer from voltage drop, it can provide better reactive power supply and voltage regulation for the downstream nodes.

D. The scenario of deployment of DG sources has inspired performance compared to the traditional methods (substation expansion) provided the comprehensive configuration and placement of DGs are determined and designed precisely and elaborately.

5. Conclusions

Distribution expansion planning (DEP) problem is one of the salient parts of power system expansion planning. Distribution grids are treated as a vital part of each power system because they play the role of a connector between the sub-transmission network and consumers. The present study has delved into a DEP problem in the presence of distributed generation (DG) sources. The solid oxide fuel cell (SOFC) has integrated into the model of the distribution network as the DG source. The main objective of this study was to meet the economic and operational needs by incorporation of DGs, which are regarded as a superior candidate over traditional solutions. The results have implied that the installation of DGs has reduced the need for expansion of existing substations, has prevented the installation of new substations, and has avoided the need for feeder upgrading to some extent. These positive points underlie a remarkable cut in expansion costs and considerable loss reduction. In general, it can be alleged that the integration of DG sources in DEP problem can result in better-optimized solutions economically and technically. However, to what extent this scheme is successful highly correlates to the proper design of the proposed scenario, which should be comprehensively carried out. For future works and further studies, the role of power quality indices, reliability indices, and also environmental limitations can also be added to the current work. In addition, a wide diversity of resources such as parking lots of electric vehicles, demand response resources, and various storage technologies can be integrated into the model.

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