# Determinations of Annual Investments of DisCo and Private Sector in Expansion Planning of Distribution Network

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*Abstract*: Ever-increasing load-demand, threaten the continuity of power supply and diminishes power quality causing serious technical challenges in distribution networks. In this regards, commonly used cheaper practices like capacitor allocation and network configuration, can enhance operational parameters of the network. On the other hand, supplying the future load-demand, requires installing new substations or distributed generations (DGs). Because of DGs inherent technical and economic advantages, Distribution Company (DisCo), encourage private investment to install DGs, by signing long-term Power Purchase Agreement (PPA) with DG owners (DGO). In such a situation created, DG allocation and simultaneously capacitor allocation and network configuration can be economical for both DisCo and DGO and also can enhance the reliability and power quality. So, this paper is aimed to find the annual instants for network configuration; timing, sizing and sitting of capacitors and DGs, and PPA rates using Multi-Objective Particle Swarm Optimization (MOPSO). Also, the uncertainties of load-demand and electricity-price, voltage-sensitive loads and load priority in power supply are applied into the planning problem. Voltage deviation and voltage stability are considered as constraints which must be better in optimum solution. The effectiveness of the proposed scheme, is validated by computer simulation done on a 33-Bus IEEE distribution network and the outcomes are discussed.

*Keywords*: Dynamic Modeling's, Configuration; Distributed Generation; Capacitor, Distribution Network; Uncertainty, Multi-Objective;

| *Nomenclature* | | | |
|---|---|---|---|
| $n_l$ | Number of load buses | $\lvert I(f,s,t)\rvert$ | The current magnitude of f–th line in the state s and year t |
| $n_{ll}$ | Number of load levels | $I_{\max(f,t)}$ | The maximum allowed current of f–th line in year t. |
| $ns$ | Number of states | $I_{CAP(f)}$ | The current capacity of f–th line in the base year |
| $n_y$ | Planning horizon | $M_f$ | The factor by which the line is upgraded. |
| $n_f$ | Total number of feeders | $Y_{UP(f)}$ | The year when upgrade of f–th line is essential |
| f | f-th feeder | $KM(f)$ | The length of f–th line |
| $Y_{ij}$, $\theta_{ij}$ | Magnitude and Angle of Line admittance between buses i and j, respectively | $C_{KM}$ | Cost of line upgrade per km |
| $\alpha_l$ | Annual Load growth rate | $CF_{DT(dl,s,y)}$ | The capacity factor related to the DG unit m |

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| Nomenclature | | | |
|---|---|---|---|
| $\lambda_f$ | Failure rate of f-th feeder | $CP_n$ | The contract price between the DGO and the DisCo |
| $r_f$ | Repair time of f-th feeder | $V_{rated}$ | Magnitude of rated voltage |
| $T_{ll}$ | Duration of load level LL (h) | $v_{safe}^{min}, v_{safe}^{max}$ | Lower and upper limit of buses voltages for safe operating condition, respectively |
| $Q_i^c$ | Capacitor Capacity | $v_{crit}^{min}, v_{crit}^{max}$ | Lower and upper limit of buses voltages for critical operating condition, respectively |
| $EP_{peak}$ | Peak Price | $R_{ij}$, $X_{ij}$ | Resistance and Reactance of feeders between buses i and j, respectively |
| $S^l_{i,p}$ | Peak Load | $\delta_{i,ll,s}, V_{i,ll,s}$ | Voltage magnitude and angle of bus i, in load level LL and state s |
| $prob_s^c$ | The probability of each combined state | $MPL$ | Maximum penetration level |
| $p^l_{i,ll,s}$, $Q^l_{i,ll,s}$ | Active and Reactive load demand in bus i, load level LL and state s, respectively | $ICDG_i(s)$ | Installation cost of dispatchable DG with the capacity of s in bus i ($/kVA) |
| $PLC_{ll}$, $QLC_{ll}$ | Active and Reactive loss cost in load level LL and sate s ($/kWh) , respectively | $O\&MCDG_{ll,s}$ | Operation cost of DDG in load level LL and sate s ($/kWh) |
| $RC_{ll}$ | Reliability cost of unsupplied energy in load level LL and sate s ($/MWh) | $P^{DG}_{i,ll,s}$, $Q^{DG}_{i,ll,s}$ | Active and Reactive power generated by DG installed in bus i, in load level LL and state s, respectively |
| $C_{SW}$ | Cost per one switching operation | $P^{Trans}_{i,ll,s}, Q^{Trans}_{i,ll,s}$ | The active and reactive power purchased from power market by DisCo, respectively |
| | | $LNS_{f,ll,s}$ | The load not supplied in load level LL and state s due to the outage of f-th feeder |
| | | $N_{obj}$ | the number of objective functions |
| | | $obj_i^{max}$, $obj_i^{min}$ | Maximum and minimum value of the i-th objective function |

## 1. Introduction

High-quality services and permanency of the power supply to the end-user consumers are the key goals in distribution networks planning and operation [1], which are threaten by the ever-increasing load demand. To gain more profit, any DisCo needs to increase the adequacy of his/her network, i.e. constantly fulfilling the consumers load demand, and when considering the competitive environment, the power supply must be in higher quality. Due to the limited budget of DisCo, reinforcement of the distribution network by adding high-voltage substation capacity would not be possible especially in developing countries with hot climate where the electricity consumption growth is much higher. In this regards, DisCo operational measures like network configuration [1-5], cheaper practices like capacitor allocation [6-14] and encouraging private investment to install DGs [15-20] would be eco-technical solutions. Distribution network is designed as close loop configuration, while operated as tree-liked structure. This is possible because, distribution feeders are equipped with a number of switches, normally closed one namely tie-switch and the sectionalizing switches which are normally open. Distribution network configuration is done by varying the status of these switches purposing: meet the energy demand, voltage profile improvements, loss minimization, contingency management, reliability enhancement and *etc* from the DisCo viewpoints [1-5]. In [3] distribution network configuration is done in order to reach lower power using Improved Harmony Search Algorithm. In [4] single and multiobjective optimization framework is investigated for configuration of distribution network. Loss minimization is commonly defined as the objective of network configuration. In [5] a two-stage approach is defined which in the first stage loss minimization is aimed and the second stage is defined for load-ability limit enhancement. Moreover, installation of capacitor in distribution network is a common measure used for local compensation of loads reactive power resulting power losses and voltage deviation minimization and also corrected power factor and higher voltage stability. So, optimization of capacitors sites and sizes have absorbed great attention of researchers and so there is a vast body of scientific papers on allocation of capacitor studies in the radial distribution networks from eco-technical viewpoints of DisCo. In [6] shark smell optimization is used to site and size capacitors aims to minimize the cost of losses. In [7], capacitor allocation is done aiming minimization of losses and energy cost. This problem is solved using salp swarm algorithm combine by loss sensitivity analysis. Application of flower pollination algorithm is reported in [8]. The optimization tries to find the optimum site and size of capacitors by reducing the cost of capacitor installation plus losses costs. In [9] grey wolf and water cycle optimization algorithms, are used to optimally site and size of the capacitors in distribution network. Minimization of power losses and maximization of network savings are the implemented objective functions. In [10] optimal allocation of capacitor in a distribution network with high penetration of wind-distributed generation is done. The proposed approach is based on data clustering. In [11], a meta-heuristic optimization technique is developed to find an optimum solution of the capacitor allocation problem. The goal is to decrease the power losses and enhancing the voltage profile. In [12] a two-stage methodology is proposed to find the capacitors optimal sites and sizes aims to reduce losses and improves voltage profile. The candidate buses for capacitor installation if found in the first stage by performing loss sensitivity analysis and at the final stage, ant colony algorithm finds the optimal size and site of capacitors. Optimal allocation of capacitor considering different load levels is reported in [13]. In this paper, a modified artificial bee colony algorithm is used for the purpose. Compensation of the reactive power in distribution network by optimal allocation of capacitor is reported in [14]. The used optimization technique is a hybrid evolutionary scheme combining the particle swarm optimization and electromagnetic-like algorithm. As known, suppling ever-increasing load demand needs to installation of power generators. Limitation of financial resources and international agreements to reduce greenhouse gas emissions are to main drivers towards application of DGs. Moreover, DGs have inherent merits from the economic, technical and environmental viewpoints. Lowering the transmission and distribution costs and hence electricity price, fuel efficiency, reductions of sound and air pollution, peak shaving, improving power quality and loss minimization, are such the merits. In other words, DGs have positive effects on efficiency, integrity and reliability of the distribution network [15, 20], resulting a rapid developments of DG technologies in different forms and capacities [17]. These benefits are achievable if DGs will be properly sited and sized. In this regards, optimal DG allocation has become an interesting study for the researchers. DG allocation can be done from the DisCo and the DGO points of view. In [18] power loss minimization is done by proposing a method for optimizing DG allocation in the distribution system based on enhanced sunflower optimization. Ref [19] solves the optimal allocation of DG in distribution network considering power and energy loss minimization. Optimal siting and sizing of DGs is done using SPEA algorithm in [20]. The review shows that, a lot of efforts has been done towards solving distribution network configuration, DG allocation, capacitor sizing and siting; separately, and also there are numerous studies considering all the mentioned measures, simultaneously [21-35]. Optimal allocation of capacitors and simultaneously configuration of distribution network is reported in [21-24]. In [21] mixed-integer second-order cone programming is formulated and proposed. In [22] a novel perturbation particle swarm optimization considering nonlinear loads is proposed. In [23] the mentioned problem is solved using modified version of krill herd algorithm. In [24] a symbiotic organisms search accompanied with a particle swarm algorithm is proposed to find an optimum solution for the mentioned problem. Ref [25-27] solves the simultaneous optimal allocation of capacitors and DGs in distribution networks. In [25] a developed multiobjective algorithm based on decomposition is proposed for minimization of losses by optimally installing capacitors and DGs. Application of water cycle algorithm to optimally allocate the DGs and capacitors from the techno-economic viewpoints is reported in [26]. The authors of [27] has used non-dominated sorting genetic algorithm to find optimum solutions for capacitor and DG allocation problem with considering the load and generation uncertainties. In [28-31] simultaneous optimal configuration of distribution network and siting and sizing of DGs are reported. In [28], an optimization scheme namely three-dimensional group search is suggested to solve such a problem. Power loss minimization and enhancing the load restoration capability of distribution network by DG allocation and network configuration is studied in [29]. In another article [30], power loss minimization is aimed. In this paper, a heuristic scheme involving the uniform voltage distribution based constructive configuration algorithm, is employed. In another report, simultaneous optimizing of power loss and voltage stability are aimed in Ref [31]. The objectives of [32] are pollutant reduction besides ones considered in [31]. The authors of [33-35] have solved simultaneous distribution network configuration, DG and capacitor allocation. In [33] an ant colony and harmony search algorithms are used with considering the generation uncertainty. In [34] multi-objective approach from the DisCo viewpoint is defined for the purpose. The authors of [35] have proposed a hybrid heuristic search algorithm combining Harmony search and artificial bee colony algorithms. Thus, the survey depicts that significant work has been done towards the solving, distribution network configuration, DG allocation and capacitor sizing and siting; separately and simultaneously, however, almost all of the reported works, have focused on DisCo preferences while the investments on DG allocation is mostly taken by the private sector. Nevertheless, it might be a few papers, which considers both the DisCo and DGO viewpoints especially when optimizing distribution network configuration, DG and capacitor allocation. Recently, optimal DG allocation from the DGO viewpoints is solved in [36] and the role of DisCo is ignored. In this paper, the uncertainties of generation sources are incorporated into the problem and is solved by means of genetic algorithm. In [37] DG allocation problem with multiple objectives including cost minimization of DisCo and simultaneously profit maximization of DGO, is solved. In this paper, MOPSO is used for optimization purposes and the operational factors e.g. power losses, reliability, voltage stability and voltage deviation are measured as the hard-limit limits. In [37], the load and market price uncertainties are added to what Ref [38] has been done and the problem is solved using NSGA II. In both mentioned papers, network configuration and capacitor allocation are not considered and despite that the reliability is modeled in both papers, but consumption type and load priority in power supply are not applied into the modeling's. Recently, optimal distribution network configuration and simultaneously wind-based distribution generation siting and sizing problem is solved from DisCo and DGO viewpoints using ε-constraint method [39]. In this paper, capacitor allocation is not considered and improving operational factors e.g. power losses, reliability, voltage stability and voltage deviation versus the base network are ignored. Note that, an appropriate strategy for reliable power supply, requires to prioritize the customers especially from the viewpoints of residential, industrial and commercial. Moreover, in the practical situation, load representation is vital feature on approaching the realistically in power system. As reviewed, in none of the [37-39], load models and load priority in power supply are not considered. Also, the mentioned papers, are based on static modeling's of the problem focusing on a horizon year and do not have any plan for the middle years, why so, the limited budget of DisCo and private sector, does not permit to put all the investments in a year and the investments must be applied in different years till horizon year using dynamic modeling's of the planning problem.

As a result of recently published papers survey, there is a need for a strategic solution and a more efficient way, where, annual network configuration; timing, sizing and sitting of capacitors and DGs from the DisCo and the DGO points of view, simultaneously, seems to be an eco-technical solution and is the main contribution of this paper.

Meanwhile, power losses, voltage deviation, voltage stability and reliability are considered as hard-limit constraints which must be in better condition in optimum solution compared to the base case network.

So, this paper is structured to provide an inclusive study on determinations of annual investments of disco and private sector in expansion planning of distribution network which the main contributions can be listed as follows:

- ✓ Distributed Generation timing, siting and sizing
- ✓ Determining Power Purchase Agreement value
- ✓ Capacitor timing, siting and sizing
- ✓ Annual Reconfiguration instants
- ✓ Considering both the DisCo and DGO points of view
- ✓ Considering Operational Factors as hard-limit Constraints e.g. Reliability, Voltage deviation, Voltage Stability and Power Losses
- ✓ Voltage-sensitive loads and load priority in power supply are considered
- ✓ load demand and energy price uncertainties are applied
- ✓ MOPSO is used as extensively used multiobjective dilemmas to cope with the optimization problem
- ✓ Fuzzy set theory is used to find the best compromised solution.

## 2. Problem Formulation

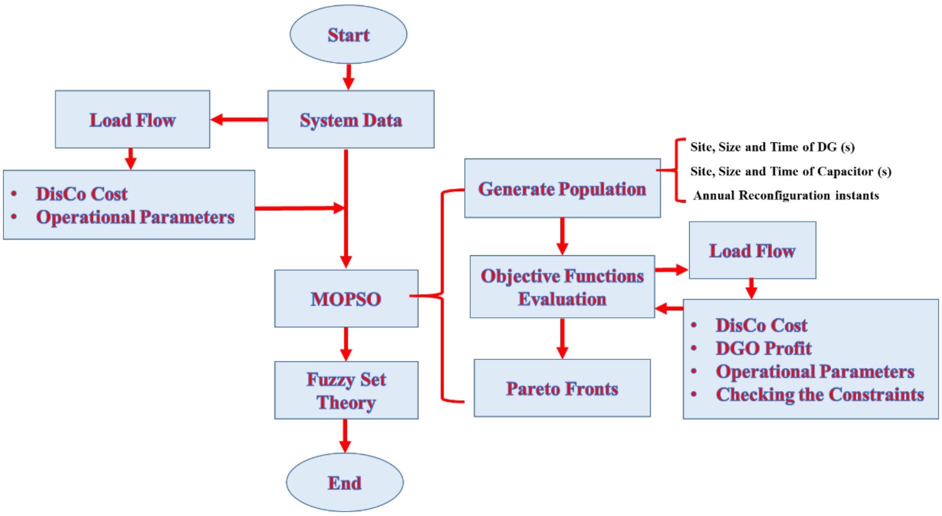


Figure 1. Proposed flowchart of Determinations of Annual Private Investment in Expansion Planning of Distribution Network

DisCo aims to reduce the operation costs and simultaneously increase the network performance by commonly used cheaper practices like capacitor allocation and network configuration. Also, in order to meet future load demand, two options can be chosen from: installing new substation or encouraging private investment to install DGs, by signing long-term PPA with DGO. Although, based on DGs inherent technical and economic advantages, DisCo prefers to benefit from DGs and, simultaneously network configuration and capacitor allocation can improve the performance of the network. Also, DG installation must be profitable for DGO. It is worth to note that, the presented methodology leads to desirable increased value of voltage stability and acceptable decreased values of voltage deviation and energy-not-supplied. To achieve the most realistic solution, necessary uncertainties of load demand and electricity price are considered in the planning problem. Finally, the suggested solution leads to the best practical scheme form the economical viewpoints subjected to proper operational constraints. Considering Figure 1, the network information including line and load bus data, economic and technical data required for optimization, accompanied by load flow results, operation costs and operational parameters of the base network are entered into the MOPSO as system data. MOPSO, initially generates populations randomly. Forward/Backward load flow analysis is applied on all the populations to check the constraints and calculate optimum networks operational parameters and hence each networks objective functions. Finally MOPSO coverage to the non-dominated solutions (pareto-fronts). These solutions are all optimal and can be used as the final strategy. To find the best compromised solution, fuzzy set theory is applied on the pareto-fronts.

PSO shares many similarities with other evolutionary computation techniques. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. PSO is easy to implement and there are few parameters to adjust. In PSO algorithm, a population of potential solutions to an optimization problem is evolved toward better solutions. MOPSO is the multi-objective version of the PSO, which can optimize several objective functions, separately and independently resulting pareto-fronts. It should be noted that, exploring the principle of MOPSO is out of the scope of this paper and several literatures e.g. [40] covers the details. However, the overall view of Multi-Objective PSO algorithm is represented in Figure 2.

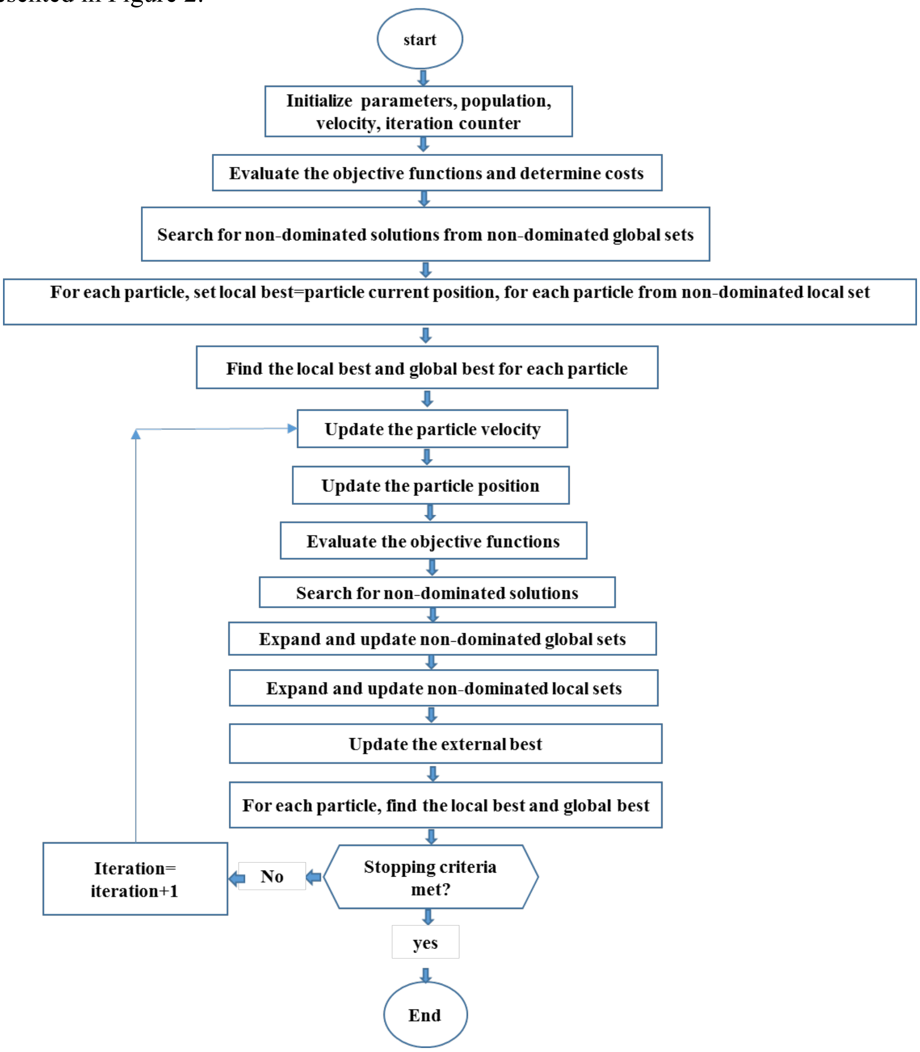


Figure 2. Flowchart of MOPSO algorithm

*A. The Formulation of Uncertainty Modeling (Load Demand and Market Price)*

The modeling scheme of uncertainties related to electricity price and electric load is adapted from [16, 34]. Regarding the price and load duration curve in Figure. 3, $N_{ll}$ and $t_{ll}$ indicate the number of divided levels in each year and duration of each level, respectively. Also, Figure. 3, shows the five states of normal distribution curve of load/price level factor (LLF, PLF). It should be noted that, each state has definite probability of occurrence.

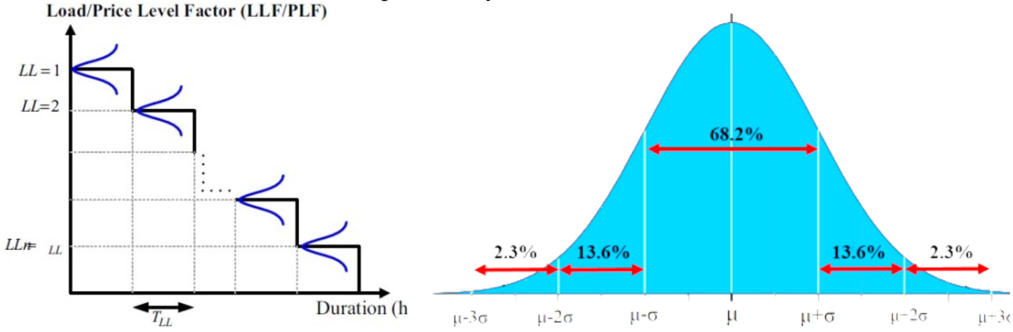


Figure. 3. Load and price level factor in uncertainty modeling

Uncertainty modeling's of electricity price and load are formulated as the followings.

*A.1. Electricity Price*

The following equation is to represent the uncertainty modelling of electricity price considering load level $LL$ and state $s$:

$$EP_{LL,S} = EP_{peak} PLF_{LL,S} \tag{1}$$

*A.2. Electric Load*

The demand in bus $i$, in year $t$, load level $LL$ and state $s$ can be obtained from:

$$S^{l}{}_{i,t,ll,s} = S^{l}{}_{i,peak} LLF_{LL,S} \left(1+\alpha_l\right)^t \tag{2}$$

*A.3. Combined states*

Finally, the whole set of states are generated using (3) and (4):

$$states_s^{comb} = \left[load(s) \quad price(s)\right] \tag{3}$$

$$prob_s^{comb}(\pi_s^c) = prob_s^l \times prob_s^p = \pi_s^l \pi_s^p \tag{4}$$

As suggested in [16, 34], in order to prevent heavy computational burden imposed due to high number of states, a scenario reduction method should be used.

*B. Objective Functions*

The suggested objective functions are optimized using MOPSO through optimizing various objective functions dependently and simultaneously subjected to the operating constraints. The implemented objective functions are as follow:

- Cost Minimization of DISCO
- Profit Maximization of DGO's

The defined objective functions are optimized considering economic points of view of DisCo and DGO's, where each objective function is a combination of several criteria.

The mathematical formulations of the suggested objective functions and the constraints related to the planning problem are explained in the following sections.

*B.1. Cost Minimization of DISCO*

The suggested cost function must include several subsets covering the main goal of DisCo is to deliver cost effective service to end-user consumers within standard sorts. So, the offered cost function consists of: installation cost of capacitor, cost of configuration, cost of reliability, cost of power losses, cost of purchased active power from power market and DGO's and line upgrade cost. Considering the dynamic modeling's of the problem, net present worth (NPW) of costs must be evaluated.

$$DiscoCOST = NPW_{ICC} + NPW_{DSR} + NPW_{PLC} + NPW_{PPPC} + NPW_{CENS} + NPW_{Upgradelines} \quad (5)$$

Considering DisCo's economic points of view, the defined cost function must be minimized. In other words, any solution is satisfactory which is able to diminish the DisCo's costs in comparison to the base case network.

*B.2. Profit Maximization of DGO*

The goal of profit-based objective function for the generation owners is to make them able to recoup all or most of their procurement and installation costs through selling the generated power during normal conditions. The following fitness function identify potential cost recovery during normal operation.

$$DGO's\ \mathbf{Pr}ofit = NPW_{P_{DGO}} - (NPW_{ICDG} + NPW_{O\&M\,CDG}) \quad (6)$$

Considering economic viewpoints of DGO's, the beyond fitness function must be maximized. In other words, any solution is satisfactory which be profitable for DGO's.

*B.3. Mathematical Formulations of different terms of the defined Objective Functions*

In the following, the mathematical formulation of different part of objective function is described in details. The net present worth is calculated using the following formulation:

$$PW^t = \left(\frac{1 + Inf\ Rate}{1 + Int\ Rate}\right)^t \quad (7)$$

*- Installation Cost of Capacitor*

The capacitors with fixed sizes, inject constant amount of reactive power. In the real world, capacitor sizes are discrete as considered in this paper. The mathematical formulation of capacitor cost is as follows:

$$NPW_{ICC} = \sum_{t=1}^{n_y} PW^t \sum_{i,j=1, i \neq j}^{n_l} K_{cf} + K_i^c Q_i^c \quad (8)$$

Where; is the fixed cost of the capacitor installation is defined as $K_{cf}$ and the constant $K_i^c$ is the annual capacitor installation cost for each compensated bus. The required technical and economic information about the used capacitors are borrowed from [27].

*- Cost of Reconfiguration*

Distribution system reconfiguration (DSR) is a intricate optimization process done by opening and closing of tie and sectionalizing switches. The network configuration is performed in case of fault to enhance reliability of power supply and in normal condition, mainly to minimize the voltage deviation and hence power losses.

Actually, network reconfiguration is based on following three principles [34]:

- ✓ The configuration of the network must be maintained radial
- ✓ All the end-user consumers must be supplied
- ✓ The network constraints, e.g. bus voltages and thermal limits of feeders, must be maintained

In this work, the DSR cost is obtained as follows:

$$NPW_{DSR} = \sum_{t=1}^{n_y} PW^t \times C_{SW} (x'_{(k)} - x_{(k)}) \tag{9}$$

- *NPW of Power Loss Cost*

Losses in the distribution of electricity cannot be eliminated and are directly depend on the network characteristics. The considerable share of power losses in a power system is in distribution network due to energy wasting in the conductors and equipment. As an effective solution, proper allocation of capacitors and/or DG and network configuration can reduce power losses.

As a result, reducing the power losses lead to considerable decrease of total electricity cost. Finally, the economic growth of DisCo's will be accelerated and the efficiency and flexibility of DisCo's will be improved. To evaluate the cost of power losses, the following equations are used:

$$P_{i,ll,s}^{loss} + jQ_{i,ll,s}^{loss} = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} I_{i,ll,s}^2 \times (R_{ij} + jX_{ij}) \tag{10}$$

$$NPW_{PLC} = \sum_{t=1}^{n_y} PW^t \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} \left( T_{ll} \times Q_{i,ll,s}^{loss} \times \pi_s^c \times QLC_{ll,s} + T_{ll} \times P_{i,ll,s}^{loss} \times \pi_s^c \times PLC_{ll,s} \right) \tag{11}$$

- *NPW of Cost of Purchased Active Power from Power Market by DisCo*

A deregulated environment is a system that enables DisCo to purchase electricity from the power market as the final process in the delivery of electricity to end-user customers. Some percentage of purchased power wasted as power losses and the rest supply the consumers. The different states of purchased active power during delivery process can be described by:

$$P_{i,ll,s}^{Trans} = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} (p_{i,ll,s}^{l} + P_{i,ll,s}^{loss} - P_{i,ll,s}^{DG}) \tag{12}$$

Regarding power balanced equation, cost of purchasing active power from power market is computed using (13):

$$NPW_{PPPC} = \sum_{t=1}^{n_y} PW^t \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} P_{i,ll,s}^{Trans} \times T_{ll} \times EP_{ll,s} \times \pi_s^c \tag{13}$$

- *NPW of Line Upgrades Cost*

Line upgrade due to power structural weaknesses is an essential task to meet load growth and voltage security. Enhancement of service quality and networks reliability, reduction of losses, limitation of power cut duration and frequency, enlargement of distribution capacity are the most vital impacts of line upgrades. Based on equations (14) and (15), the cost of line upgrades process are estimated as (16):

$$\left| I(f, \mathrm{s}, t) \right| \le I_{\max(f,t)} \qquad \forall \mathrm{f,s,t} \tag{14}$$

$$I_{\max(f,t)} = \begin{cases} I_{CAP(f)} & \forall t < Y_{UP(f)} \\ M_f I_{CAP(f)} & \forall t \ge Y_{UP(f)} \end{cases} \qquad \forall f, \mathrm{t} \tag{15}$$

$$NPW_{Upgradelines} = \sum_{t=1}^{n_y} PW^t \sum_{f} \frac{KM(f).\mathrm{C}_{KM}}{(1+t)^{Y_{UP(f)}}} \qquad \forall f \tag{16}$$

*- NPW of Reliability Cost*

Regarding power distribution networks as a most risky part facing more failure events make the reliability and performance of distribution networks as an important topic. In this case, incorporating new technologies, automation and increased penetration of distributed generations improve the standard levels of distribution networks' reliability. Note that, DisCo's have responsibility to gratify their consumptions even in case of failures. The most practical reliability index known as load not supplied ( $LNS$ ) is calculated due to interruptions. $C_{RC}$ is calculated considering the branch's failure rate and the amount of the interrupted loads in failure occurrences. Lower $C_{RC}$, represents more stable operation level of distribution network is guaranteed.

$$NPW_{CENS} = \sum_{t=1}^{n_y} PW^t \sum_{f=1}^{n_f} \lambda_k \times r_k \sum_{ll=1}^{n_{ll}} RC_{ll} \times T_{ll} \sum_{s=1}^{ns} LNS_{f,ll,s} \tag{17}$$

- NPW of Installation, Operation and Maintenance Cost of DGs

It's assumed that, the output ratings of incorporated DGs in this method set as a discrete multiple of 100kW and 0.9 power factor. In this regards, installation, operation and maintenance costs of DGs are computed using (18) and (19):

$$NPW_{ICDG} = \sum_{t=1}^{n_y} PW^t \sum_{i,j=1,i\neq j}^{n_l} ICDG_i(S) \tag{18}$$

$$NPW_{O\&M\,CDG} = \sum_{t=1}^{n_y} PW^t \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} O\&MCDG_{ll,s} \times T_{ll} \times \pi_s^c \times P_{i,ll,s}^{DG} \tag{19}$$

- Financial Transactions between DGO's and DISCO

The existence of bilateral contract between the DisCo and the DGO's, the power generated by DG units is purchased by DisCo. So, the financial transaction between them based on the contract price and the amount of purchased power is formulated as the followings:

$$NPW_{P_{DGO}} = \sum_{t=1}^{n_y} PW^t \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} T_{ll} \times \pi_s^c \times P_{i,ll,s}^{DG} \times CF_{DT(dl,s,y)} \times CP_n \tag{20}$$

*C. Operational Indices*

It's clear that, DGO's aim to maximize profit, so, they care about operation and maintenance of their own equipment and have no responsibility for about the technical issues of distribution network.

Besides, it is DisCo's major task to provide a service with high standard ranges of power quality to make customers satisfied. In this case, essential operational parameters should be assessed when making decisions. Hence, in order to achieve high enhancement of network performance, major operational aspects of distribution networks are applied for this optimization problem.

So, proper considered operational indices known as minimizing voltage deviation and maximizing voltage stability are described as below:

*C.1. Minimizing the Voltage Deviation*

A sum of voltage deviations at all buses in the distribution network from the desired value, is an essential index in distribution network operation that is represented as follows [38]:

$$VD = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} \pi_s^c \times (V_{i,ll,s} - V_{rated})^2 / n_l \tag{21}$$

*C.2. Maximizing Voltage Stability*

Voltage stability as given in (23) is the ability of distribution network to withstand fixed tolerable voltage at every single bus of the network under standard operating conditions [38].

$$VSF_{total} = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} \left(2V_{i+1,ll,s} - V_{i,ll,s}\right) / n_l \tag{22}$$

More voltage stable condition is The higher value of $VSF_{total}$ ensures.

*D. Constraints*

Two classes of constraints, hard and soft are applied in optimization problem. Each class is described in detail as below:

*D.1. Hard constraints*

*- Network radially constraint*

To guarantee the radial configuration of distribution networks, its topology is compared with a tree based on graph theory. A tree is a connected graph without any cycles, which in tree, the number of arcs is equal to the number of nodes minus one.

*- Power Flow equation*

$$P_{i,ll,s}^{Trans} = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} (p_{i,ll,s}^{l} + P_{i,ll,s}^{loss} - P_{i,ll,s}^{DG}) \tag{23}$$

$$Q_{i,ll,s}^{Trans} = \sum_{i=1}^{n_l} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} (Q_{i,ll,s}^{l} + Q_{i,ll,s}^{loss} - Q_{i,ll,s}^{DG} - Q_{i,ll,s}^{c}) \tag{24}$$

$$P_{i,ll,s}^{Trans} = V_{i,LL,S} \sum_{J=1}^{n_n} V_{j,ll,s} Y_{ij} \cos(\delta_{i,ll,s} - \delta_{j,ll,s} - \theta_{ij}) \tag{25}$$

$$Q_{i,ll,s}^{Trans} = V_{i,LL,S} \sum_{J=1}^{n_n} V_{j,ll,s} Y_{ij} \sin(\delta_{i,ll,s} - \delta_{j,ll,s} - \theta_{ij}) \tag{26}$$

*- Operating constraint of DG units*

The output power of DG units must be less or equal than their maximum allowable capacity.

$$S_{i,ll,s}^{DG} \le S_{i,\max}^{DG} \tag{27}$$

*- Maximum penetration of DG units*

Due to possibility of maximum allowable voltage increase, maximum penetration level of DGs must be considered as [30]:

$$\sum_{i=1}^{n_l} P_i^{DG} \le MPL \times \sum_{i=1}^{n_l} P_{i,peak}^{L} \tag{28}$$

*D.2. Soft constraints*

The vital technical constraints, bus voltages and thermal limits of feeders should be taken into account which in the proposed method, satisfaction of the mentioned constraints are evaluated by fuzzy modeling,

*- Voltage limitation*

The voltage should operate in safe mode in order not to violate. So, voltage satisfaction which is attained by a penalization function [16], is represented as below:

$$\mu_{i,ll,s}^{V} = \begin{cases} \dfrac{V_{i,ll,s} - V_{crit}^{\min}}{V_{safe}^{\min} - V_{crit}^{\min}} & V_{crit}^{\min} \le V_{i,ll,s} \le V_{safe}^{\min} \\ 1 & V_{safe}^{\min} \le V_{i,ll,s} \le V_{safe}^{\max} \\ \dfrac{V_{i,ll,s} - V_{crit}^{\max}}{V_{safe}^{\max} - V_{crit}^{\max}} & V_{safe}^{\max} \le V_{i,ll,s} \le V_{crit}^{\max} \\ 0 & else \end{cases} \tag{29}$$

Equation (29) shows the voltage constraint satisfaction for bus i in state s. Due to the number of states in genuine network, the weighted average of voltage satisfaction is calculated to achieve an index presenting the voltage situation of ith bus:

$$\mu_i^V = \frac{1}{8760} \sum_{ll=1}^{n_{ll}} \sum_{s=1}^{ns} \pi_s^c T_{ll} \mu_{i,ll,s}^{V} \tag{30}$$

Finally, for whole network's voltage condition is defined calculating the average value of $\mu_i^V$ for all buses as:

$$\mu^V = \frac{\sum_{i=1}^{n_l} \mu_i^V}{n_l} \tag{31}$$

*- Feeders' thermal limits*

The same process has been done for evaluating the satisfaction value of feeders' currents ($\mu^I$). The difference is that for the feeders' currents, only upper limit is considered.

Case study, simulation, results and discussion:

The proposed method is examined on the 20 kV IEEE 33-bus distribution test system, shown in Figure. 4. The proposed planning scheme is optimized using MOPSO algorithm based on MATLAB software. All necessary characteristics of test system branches are provided in Table 1. These data are borrowed from [34].

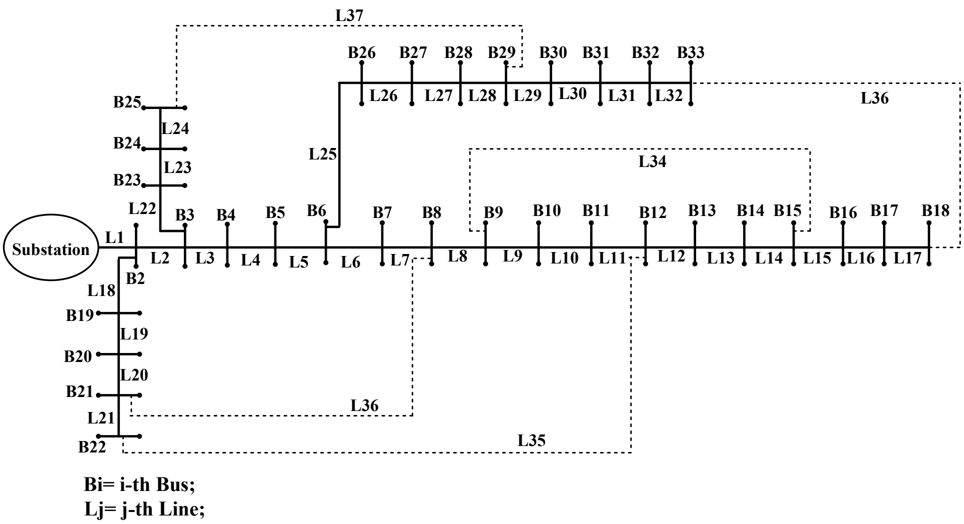


Figure 4. The 33-bus radial distribution network

Table 1. The Characteristics of 33-bus radial distribution network

| Line No. | Send Bus | Receive Bus. | R (ohm) | X(ohm) | Thermal limit (A) | length (m) | P (kW) | Q (kVaR) | No. of Customers | Load Type |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 2 | 0.0922 | 0.047 | 400 | 0.012 | 100 | 60 | 210 | Res |
| **2** | 2 | 3 | 0.493 | 0.2512 | 400 | 0.06 | 90 | 40 | 210 | Ind |
| **3** | 3 | 4 | 0.3661 | 0.1864 | 400 | 0.042 | 120 | 80 | 210 | Com |
| **4** | 4 | 5 | 0.3811 | 0.1941 | 400 | 0.042 | 60 | 30 | 1 | Res |
| **5** | 5 | 6 | 0.819 | 0.707 | 400 | 0.096 | 60 | 20 | 1 | Ind |
| **6** | 6 | 7 | 0.1872 | 0.6188 | 300 | 0.024 | 200 | 100 | 10 | Res |
| **7** | 7 | 8 | 0.7115 | 0.2351 | 300 | 0.084 | 200 | 100 | 10 | Res |
| **8** | 8 | 9 | 1.0299 | 0.74 | 200 | 0.12 | 60 | 20 | 1 | Ind |
| **9** | 9 | 10 | 1.044 | 0.74 | 200 | 0.12 | 60 | 20 | 1 | Res |
| **10** | 10 | 11 | 0.1967 | 0.0651 | 200 | 0.024 | 45 | 30 | 210 | Com |
| **11** | 11 | 12 | 0.3744 | 0.1298 | 200 | 0.042 | 60 | 35 | 210 | Res |
| **12** | 12 | 13 | 1.468 | 1.1549 | 200 | 0.18 | 60 | 35 | 200 | Ind |
| **13** | 13 | 14 | 0.5416 | 0.7129 | 200 | 0.066 | 120 | 80 | 1 | Com |
| **14** | 14 | 15 | 0.5909 | 0.526 | 200 | 0.072 | 60 | 10 | 1 | Ind |
| **15** | 15 | 16 | 0.7462 | 0.5449 | 200 | 0.09 | 60 | 20 | 10 | Ind |
| **16** | 16 | 17 | 1.2889 | 1.721 | 200 | 0.156 | 60 | 20 | 10 | Ind |
| **17** | 17 | 18 | 0.732 | 0.5739 | 200 | 0.084 | 90 | 40 | 200 | Con |
| **18** | 2 | 19 | 0.164 | 0.1565 | 200 | 0.018 | 90 | 40 | 200 | Con |
| **19** | 19 | 20 | 1.5042 | 1.3555 | 200 | 0.18 | 90 | 40 | 200 | Ind |
| **20** | 20 | 21 | 0.4095 | 0.4784 | 200 | 0.048 | 90 | 40 | 1 | Ind |
| **21** | 21 | 22 | 0.7089 | 0.9373 | 200 | 0.084 | 90 | 40 | 1 | Ind |
| **22** | 3 | 23 | 0.4512 | 0.3084 | 200 | 0.054 | 90 | 50 | 10 | Res |
| **23** | 23 | 24 | 0.898 | 0.7091 | 200 | 0.108 | 420 | 200 | 1 | Ind |
| **24** | 24 | 25 | 0.8959 | 0.7071 | 200 | 0.108 | 420 | 200 | 1 | Com |
| **25** | 6 | 26 | 0.2031 | 0.1034 | 200 | 0.024 | 60 | 25 | 1 | Com |
| **26** | 26 | 27 | 0.2842 | 0.1447 | 200 | 0.036 | 60 | 25 | 1 | Con |
| **27** | 27 | 28 | 1.0589 | 0.9338 | 200 | 0.12 | 60 | 20 | 1 | Con |
| **28** | 28 | 29 | 0.8043 | 0.7006 | 200 | 0.096 | 120 | 70 | 1 | Ind |
| **29** | 29 | 30 | 0.5074 | 0.2585 | 200 | 0.06 | 200 | 600 | 1 | Com |
| **30** | 30 | 31 | 0.9745 | 0.9629 | 200 | 0.114 | 150 | 70 | 1 | Com |
| **31** | 31 | 32 | 0.3105 | 0.3619 | 200 | 0.036 | 210 | 100 | 20 | Ind |
| **32** | 32 | 33 | 0.3411 | 0.5302 | 200 | 0.042 | 60 | 40 | 20 | Res |

*Ind: Industrial; Com: Commercial; Res: Residual; Con: Constant;

Several researches have been demonstrated the effects of different Load models as a critical issue on approaching power system realistically. Commonly, the representation of diverse load models, dependent to the voltage or frequency are studied in power systems. A Static load model is a relation between, the consumption active and reactive power of the installed load in a certain bus and the measured voltage at that bus. Voltage–dependent loads are categorized into three groups: constant impedance, constant current, and constant power, respectively, in these groups, the power dependence on voltage is quadratic, Linear and independent of changes in voltage. But, the ZIP model is an exponential model that represents the sum of these three categories. In this paper, ZIP load modeling for residential, industrial and commercial loads are considered which the required data is borrowed form [41].

$$P_i = P_{0i} \,|\overline{V}_i|^{\alpha} \tag{32}$$

$$Q_i = Q_{0i} \, |\overline{V}_i|^{\beta} \tag{33}$$

Table 2 indicates the proper values of the real and reactive exponents of the considered loads. In a practical situation, a load class mix may be seen; therefore, a load class mix of residential, commercial and industrial loads is also adopted. This is indicated in Table 1 along with the network data including resistance and reactance of branches.

Table 2. Load type and Exponent values

| **Load Type** | $\alpha$ | $\beta$ |
|---|---|---|
| **Industrial Load (IL)** | 0.18 | 6 |
| **Residential Load (RL)** | 0.92 | 4.04 |
| **Commercial Load (CL)** | 1.51 | 3.4 |

Multi-objective optimizations, here, multi objective particle swarm optimization algorithms, is mainly applied where optimal decisions requires to be taken in the presence of trade-offs between multiple conflicting objectives. When speaking about multi-objective optimization problem, there would not be a single optimal solution that simultaneously optimizes all the defined objectives. So, there may be a number of pareto optimal solutions, which with no additional subjective preference information, all the pareto set are equally good. It's clear that, multi-objective optimization is done from different points of view and thus, there exist diverse solutions and aims when setting and solving them.

Figure 5 shows the economic profit and also the amount of PPA of four possible solution derived from pareto-fronts.

Based on the following illustration, not only DisCo benefits from network reconfiguration and capacitor and DG installation, but also DGO benefits from investing on DG's installed in the distribution network.

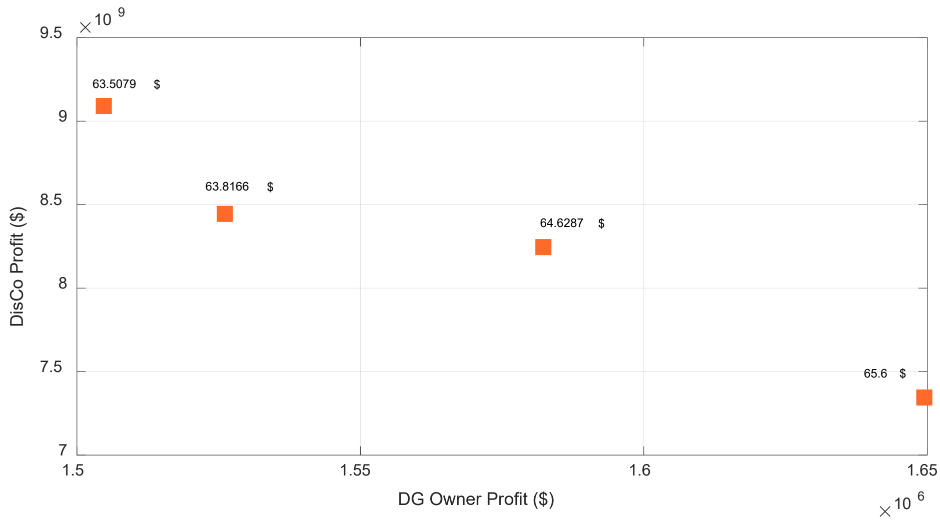


Figure 5. The cost value of each four possible solution chosen from pareto-fronts

Moreover, a statistical investigation has been provided to check the accuracy and high efficiency of the attained optimal solutions. It is evident that, enhancing voltage stability and decreasing the voltage deviation, power losses and energy-not-supplied validate the practicality of proposed strategy. In the following Figure. the ratio of any parameter in the optimal networks obtained from pareto fronts to the value of that parameter in the based case, is represented.

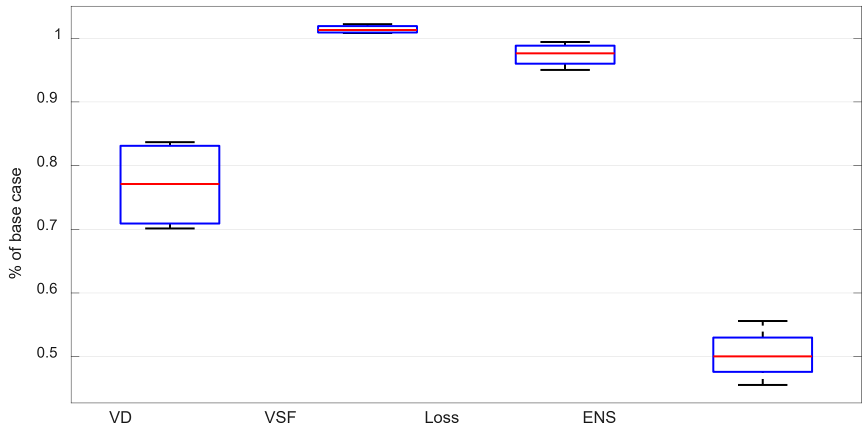


Figure. 6. Comparison of operational parameters of optimal networks versus base case

As shown, the values of VD, Loss and ENS are lower than 1 meaning that, the value of these parameters in the optimal networks obtained from pareto fronts compared to the based case is lower. So, it validates that, the proposed scheme can minimize the defined parameters which they get better in comparison to the base case. However the value of VSF is upper than 1 which shows he efficiency of the proposed approach in maximizing voltage stability compared to the base case. Considering all the pareto-fronts, statistical studies on the obtained structures is provided below. Figure 7 represents the probability of branch selection with consideration of all non-dominated solutions. Selection of a branch means that the existence switch on the branch is in close state and the current is flowing.

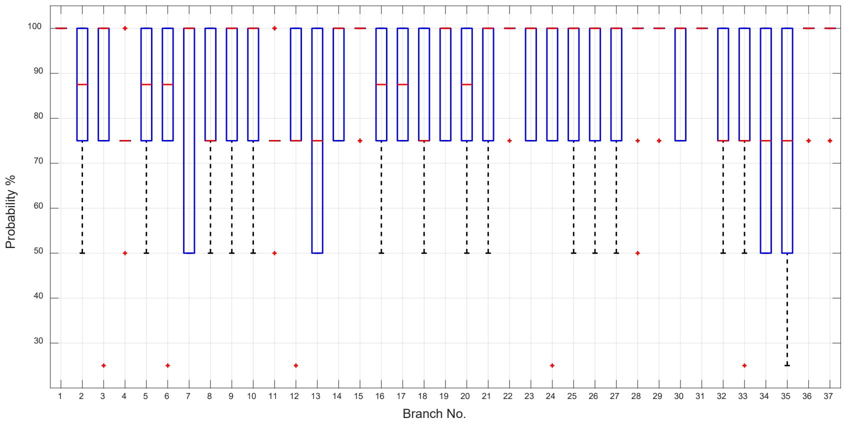


Figure 7. The probability of selection for each branch

*Best Compromise Solution*

In practical operation, there is a need for only one solution to put into practice. Also, evaluating all the pareto-fronts is time consuming and not necessarily helpful. So, decision maker must select one best compromised solution among the pareto-fronts which fuzzy set theory is able for it [34]. In this regards, fuzzy membership function, describing the corresponding satisfaction degree of each objective function of each pareto-fronts must be calculated, so:

$$h_i = \begin{cases} 1 & ; obj_i \le obj_i^{\min} \\ \dfrac{obj_i^{\max} - obj_i}{obj_i^{\max} - obj_i^{\min}} & ; obj_i^{\min} \le obj_i \le obj_i^{\max} \\ 0 & ; obj_i \ge obj_i^{\max} \end{cases} \tag{34}$$

$$h = \frac{1}{N_{obj}} \sum_{i=1}^{N_{obj}} h_i \tag{35}$$

In (35), $h_i$ varies between 0 to 1, indicating the degrees of satisfaction to the $i$-th objective function value. Finally, the best compromise solution is the one among the pareto-fronts which has the greatest value of $h$. Finally, the following results are attained based on the fuzzy set theory applied to non-dominated solutions obtained from MOPSO in order to find the best compromised solution which the details are as follows.

Regarding to the economical approach of the proposed method for DSR and installation of DGs and capacitors in each year of planning period, DisCo and DGO can put their investments in practice. Dynamic modeling of network reconfiguration provides a specific strategy for each year of planning period to be implemented. In the case of network configuration, due to the cost of switching process, optimization tries to change the less number of switches status according to (9). Hence, the state of each year reconfiguration scheme are gathered in Table 3. This Table depicts the open switches in middle years. As shown in Figure. 4, 33-bus distribution network must have 32-closed switched to be a tree-liked network. So, in each year, the switches of five lines must be in open state as shown in the following Table.

Table 3. The configuration instants in each year of time horizon

| Time (Year) | Lines with opened switch |
|---|---|
| 1 | 5 9 13 19 30 |
| 2 | 8 13 18 26 30 |
| 3 | 4 6 11 12 19 |
| 4 | 2 3 9 32 33 |
| 5 | 3 10 26 32 35 |
| 6 | 6 8 17 28 34 |
| 7 | 8 18 27 32 34 |
| 8 | 12 18 24 33 36 |
| 9 | 7 13 25 29 35 |
| 10 | 2 14 17 21 28 |

Timing, siting and sizing of capacitors installed by DisCo can be seen in Table 4. The main contribution of installed capacitors can be defined as increasing power quality when necessary. As depicted in Table 4, six capacitors must be located in the network in different years. It's clear that, each capacitor when and where with what size must be installed.

Table 4. Optimal capacitors set during planning period

| Timing (Year) | 2 | 3 | 3 | 5 | 5 | 6 |
|---|---|---|---|---|---|---|
| Sitting (Bus No.) | 14 | 10 | 30 | 19 | 29 | 20 |
| Sizing (Nominal Capacity kVar) | 450 | 300 | 300 | 150 | 450 | 150 |

Moreover, consequences related to DGs installed by DGO is detailed in Table 5. It should be taken into account that, in order to prevent imposing high budget, the investments process must be divided in years which guarantees more benefits for DGO. Table 5 represents that each DG when and where with what size must be installed in the distribution network. Also, the PPA value can be found in this Table.

Table. 5. Optimal DG set during planning period

| Timing (Year) | 1 | 1 | 2 | 3 |
|---|---|---|---|---|
| Sitting (Bus No.) | 3 | 17 | 32 | 33 |
| Sizing (Nominal Capacity kW) | 300 | 200 | 500 | 100 |
| Contract Price ($) | | 63.51 | | |

Regarding voltage amplitude as a vital parameter of distribution network, it is considered as the constraints, which any solution had have to maintain the buses voltages in standard range. In addition, due to high cost of power losses as the main result of voltage collapse in distribution network, it seems beneficial for Disco to keep voltage in standard ranges in order to achieve lower current flow in the branches and finally lower losses, as well as higher power quality and voltage stability.

The plotted diagram in Figure 8, is the histogram of the input data contains voltage amplitude of all buses considering all scenarios in planning period; along with a normal density function with parameters estimated from the input data. The number of bars is set to the square root of the number of elements in input data. The x-axis of the mentioned Figure, shows the range of input data, and the y-axis shows the abundance of each bar.

Regarding Figure 8, the PDF curve of input data is fitted by normal distribution function (red highlighted curve) illustrating the behavior of the input data more clearly. Two significant parameters of the normal distribution function are mean and standard deviation. According to the Figure. 1, the greatest probability is related to the mean value, so, it can be treated as an indicator for whole the normal distribution function. Considering Figure. 8, the mean value of the voltage magnitudes is close enough to the slack bus's voltage and the range of x-axis shows that, voltage constraint is preserved efficiently.

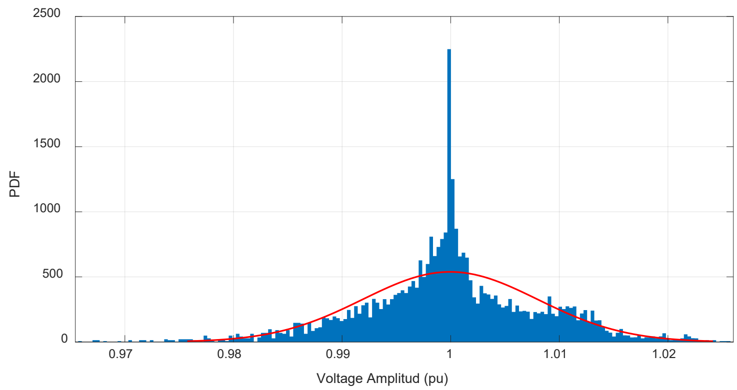


Figure 8. Voltage amplitude of all buses considering all scenarios in planning period in optimum network

Finally, the details of final solution from the economic points of view is given in Table 6.

Table. 6. Details of different terms of objective functions

| | |
|---|---|
| Installation Cost of DGs **($)** | 398334.62521 |
| Installation Cost of Capacitor ($) | 6525 |
| Switching Cost ($) | 1.2374e+04 |
| Cost of purchased power from TransCo ($) | 7.0680e+06 |
| Cost of Power Losses ($) | 4.0450e+04 |
| Reliability (ENS) Cost ($) | 1.6854e+08 |

Above-mentioned improvements in operational features of distribution network, minimizing the DisCo's cost and the gained profits by DGO's, all of them are the outcomes of suggesting a proper scheme. The effectiveness of the proposed method in solving the revealed problem is authenticated by the given simulation results. It is seen that, both the DisCo and DGO's, benefit from adding new DGs and capacitors in the configurable distribution network. Also, the applied strategy has enhanced the operational aspects of the distribution network.

## 4. Conclusion

Distribution Companies suffer from limited financial budget, even sometimes they do not have enough money for tree trimming. So, suppling ever-increasing load demand in acceptable power quality and reliability levels is a great challenge. Network configuration and capacitor allocation are the common approaches for enhancing the operational factors of the network and also can lower the costs. On the other hand, supplying future load demand requires DG installation in the network done by private investments. Regarding to real interest rate and different load levels in time horizon, and because of limited budget; there is a substantial need for annual planning of the network. So, dynamic modelings of simultaneous network configuration, optimal timing and allocation of capacitors and DGs and finding PPA from the DisCo and DGO eco-technical viewpoints, is aimed in this paper. The obtained solution confirms that, the investments must be divided in years. Both the DisCo and DGO benefits from the proposed approach. Also, the proposed scheme improves the power quality of the network and also enhances the reliability.

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