Economic risk assessment of AC/DC hybrid distribution network planning

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Abstract

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Economic risk assessment of AC/DC hybrid distribution network planning

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Abstract: The growing use of direct current (DC) load demands and distribution generations (DGs) has led to changes in the distribution network. Due to DC and alternating current (AC) loads and generators, switching to an AC/DC distribution network is an effective solution. In this paper, the AC/DC distribution network planning problem is discussed. Uncertainties in the load demand and power generation of renewable sources cause probabilistic behavior of the distribution network, which leads to risk in the network. Therefore, the technical risks related to the node voltage and the line loading constraints dominate the problem. By modeling the cost of damage due to technical risks, these risks have become economic risks. Using the conditional value at risk (CVaR) method, the economic risk assessment of planning has been addressed. In addition, the modeling of hard and soft constraints for technical constraints has been discussed. The K-means algorithm has been used to model the uncertainties in the problem. The goals of planning are: minimizing planning costs and reducing economic risk. The proposed mathematical model has been solved in MATLAB and general algebraic modeling system (GAMS) hybrid space using a non-dominated sorting genetic algorithm (NSGA-II). Numerical results are presented for a 13-node distribution network.

NOMENCLATURE

Acronyms

AC	Alternating current
CVaR	Conditional value at risk
DC	Direct current
DG	Distributed generation
DSS	Distribution substation
DNLP	Nonlinear programming problem with discontinuous derivatives
EV	Electric vehicle
GAMS	General algebraic modeling system
LV	Low voltage
MCS	Monte Carlo simulation
MV	Medium voltage
NSGA-II	Non-dominated sorting genetic algorithm
OPF	Optimal power flow
PV	Photovoltaic
SSE	The sum of the squared error
VaR	Value at risk
VSC	Voltage source converter

Sets

Ω_B	Set of all nodes
Ω_B^{DC}, Ω_B^{AC}	Set of the total of DC and AC nodes respectively
Ω_{vsc}	Set of AC/DC converters in the system
Ω_G	Set of all generators in the system
Ω_G^{AC}, Ω_G^{DC}	Set of AC and DC generators
Ω_S	Set of all scenarios
T	Planning horizon

Indices

i, j	Index of nodes
ω	Index of scenarios
g	Index of generators
t	Index of years

Parameters

r_d	Discount rate, %
X^{mn}, X^{mx}	Minimum and maximum limit of the variable X
N_{con}	Number of lines that can be connected to each node
C_G^g	Energy cost of generator g, \$/MWh
α	Confidence level, %
$P_L^{i,\omega}$	Active power demand at node i for scenario ω, MW
C_{Cond}	Cost of conductor, k\$/mile
$D^{i,j}$	Distance between node i and node j, mile
K	Total number of clusters
N	Number of network nodes
Pr	Probability of scenario, %

Variables

$V^{i,\omega}$, $\theta^{i,\omega}$	Voltage magnitude and phase angle at node i for scenario ω
P_{inj}^i, Q_{inj}^i	Active and reactive power injections at node i for scenario ω
P_{cal}^i, Q_{cal}^i	Active and reactive power calculated at node i for scenario ω

$P_{tr}^{i,j,\omega}$, $Q_{tr}^{i,j,\omega}$, $S_{tr}^{i,j,\omega}$	Active, reactive and apparent power transmitted from node i to node j for scenario ω
$M_{MO}^{i,j,\omega}$	Modulation index of the VSC connected between node i and node j for scenario ω
$P_{G}^{g,\omega}$	Active power of generator g for scenario ω
$C_{Oper}^{\omega,t}$	Cost of network operation for scenario ω at year t
C_{Line}	Cost of network lines
C_{vsc}	Cost of converters
C_{IC}	Investment cost
C_{MC}	Cost of maintenance
C_{T}^{ω}	Total cost of planning for scenario ω
$C_{Dam,O\&UV}^{i,\omega}$	Cost of damage due to node voltage violation at node i for scenario ω
$C_{Dam,OLL}^{i,j,\omega}$	Cost of damage due to line loading violation between node i and node j for scenario ω
$C_{Dam,OLL,AC/DC}^{i,j,\omega}$	Cost of damage due to AC and DC line loading violation between node i and node j for scenario ω
$F_{Pen,O\&UV}^{i,\omega}$	Penalty function for node voltage violation at node i for scenario ω
$CR_{Dam,OLL}^{i,j,\omega}$	Line overload rate between node i and node j for scenario ω
$E(C_{T}^{\omega})$	Expected total cost
$CVaR_{\alpha}(C_{T}^{\omega})$	Conditional total cost
A_{Str}	node type vector
M_{Str}	Matrix of connection between nodes
Q_{Str}	Line-type matrix connected between nodes
μ_k	Center of cluster k
G_k	Cluster k
N_{G_k}	Number of samples in the cluster k
F	Objective functions
N_x	Scenarios whose cost value is more than $E(C_{T}^{\omega})+\beta$
C_{TNP}	Total net present value of the network costs

1. Introduction

Due to the increased penetration rate of DC load demands, such as electric vehicles (EVs), and DC DGs, such as photovoltaic (PV) panels, the distribution network has undergone significant changes on the production and demand side. Thus, the traditional distribution network includes DC DGs and DC load demands along with the AC load demands and generators. Therefore, the implementation of an AC/DC distribution network in order to eliminate energy-type conversion steps and consequently reduce the investment costs of the distribution network seems to be an attractive solution for planners. On account of the intermittent and uncertain nature, the fluctuation of DGs, load, and EV demand, the distribution network is now faced with challenges severe problems, and risks [1-6].

An overview of the studies carried out in hybrid distribution network planning is given below. In [7-10], a new model for AC/DC distribution network planning is presented. In this model, the type of lines, nodes, and network structure are determined. In the AC/DC network planning, it is focused on determining the location and capacity of distribution substations, medium voltage (MV) and low voltage (LV) feeders (length and capacity of feeders), location and capacity of converters [11], the location and capacity of EV and DG [12, 14]. A novel two-stage stochastic planning model is proposed in [13]. In this paper, the lifetime of the voltage source converter (VSC) is modelled and it is included in the hybrid planning problem. In [15-18], the planning of the AC/DC microgrid is discussed. The decision variables of the problem are the capacity of DGs [15-16, 18], and the type of feeders (AC or DC) [15, 17]. In [19], a bi-level planning model for the AC/DC distribution network considering N-1 events is presented. The high-level model optimizes the total investment and operating costs in the AC and DC network over the entire planning horizon. In the low-level model, the goal is to improve the reliability of the DC network under the worst case of N-1. In [20], the AC/DC hybrid distribution network planning with different loads and DGs has been studied. In [21], the introduction and advantages of the DC network are discussed. In the end, he added the DC network to the usual AC network and explained the advantages of the combined network. References [22-24] deal with the planning and expansion of the AC/DC distribution network. So far, the AC/DC hybrid distribution network has been studied from different perspectives.

In general, risk includes all technical and economic damages and losses to equipment and networks. Therefore, the definition and application of indices that can be applied to evaluate economic risks are necessary. CVaR has been widely used to model risk aversion in various industries, such as finance or electricity markets. The CVaR is used as a risk assessment tool that identifying severe economic risks [25-31]. The main contributions are listed as follows:

- The uncertainty of load demand, EV, and output power of renewable energy sources is modeled using the K-means clustering algorithm.
- The technical risks related to the node voltage and the line loading constraints have been considered in the planning problem. In addition, the modeling of hard and soft constraints for technical constraints has been addressed. The hard and soft constraints are treated as constraints only and part of the objective function, respectively.
- The cost of damage due to technical risks is modeled in the planning objective function. By using the CVaR method, the economic risk assessment in the AC/DC distribution network planning has been done.
- The problem is formulated as a mathematical model with multiple criteria. The planning goals are: 1) minimizing planning costs and 2) reducing the economic risk due to uncertainties.
- The AC/DC distribution network planning has been tested under different voltage tolerance values and confidence levels.

A comparison of the proposed model with existing studies is shown in Table 1. This comparison highlights the contributions cited above. However, none of the aforementioned works were considered risk in the AC/DC hybrid distribution network planning.

The rest of this paper is organized as follows. AC/DC hybrid distribution network planning model is introduced in Section 2. The formulation and algorithm for solving the proposed model are given in Section 3. Simulation results are illustrated in Section 4. The conclusion is outlined in Section 5.

2. Risk-based AC/DC hybrid distribution network planning model

The hybrid distribution network planning problem includes some parameters that have probabilistic behavior. The possible behavior of the parameters is related to the uncertainties related to some data, such as the forecast of load demand and renewable energy generation. In this paper, among the main factors that have led to the probable behavior of the hybrid distribution network are:

- Uncertainty in forecasting AC and DC load demand
- Uncertainty in the output power of renewable energy sources such as wind and solar energy

The probabilistic behavior of the hybrid distribution network has consequences. These consequences cause additional costs in the network operation or damage to some equipment. On the other hand, these adverse consequences are known as risks [6, 32-33]. In the distribution network planning, without considering uncertainties, constraints such as node voltage and line loading limit are always within an acceptable range. However, considering the uncertainties in the issue, these restrictions may violate their permissible limits. This violation of the restrictions can cause damage to the equipment or subscribers of the distribution network. These consequences, i.e., the risk of exceeding the line loading limit and the node voltage, are technical. The schematic view of risk-based hybrid distribution network planning is drawn in Fig. 1.

2.1. Modeling the uncertainties of the problem

In AC/DC hybrid distribution network planning, the stochastic nature of the renewable energy sources, load demand, and EV demand is considered. The algorithm of K-means is utilized to cluster the uncertainties in the problem. The purpose of this algorithm is to find the center of clusters so that the data distance of each cluster to the center of that cluster is minimized. The process of implementing the K-means algorithm is as follows [34-35]:

Table 1 Comparison with other studies

Reference	Objectives		Uncertainties		The method of modeling uncertainty
	Cost	Risk	Demand	Output power of DGs	
[7]	✓	×	✓	✓	MCS technique
[8]	✓	×	✓	✓	MCS technique
[9]	✓	×	✓	✓	MCS technique
[10]	✓	×	×	×	Not included
[11]	✓	×	×	×	Not included
[12]	✓	×	✓	✓	MCS technique
[13]	✓	×	✓	✓	MCS technique
[14]	✓	×	×	×	Not included
[15]	✓	×	×	×	Not included
[16]	✓	×	×	×	Not included
[17]	✓	×	×	×	Not included
[18]	✓	×	×	×	Not included
[19]	✓	×	×	×	Not included
[20]	✓	×	×	×	Not included
[21]	✓	×	×	×	Not included
[22]	✓	×	✓	✓	Scenario tree approach
[23]	✓	×	✓	✓	Multi-scenario approach
[24]	✓	×	×	×	Not included
Proposed model	✓	✓	✓	✓	K-means algorithm

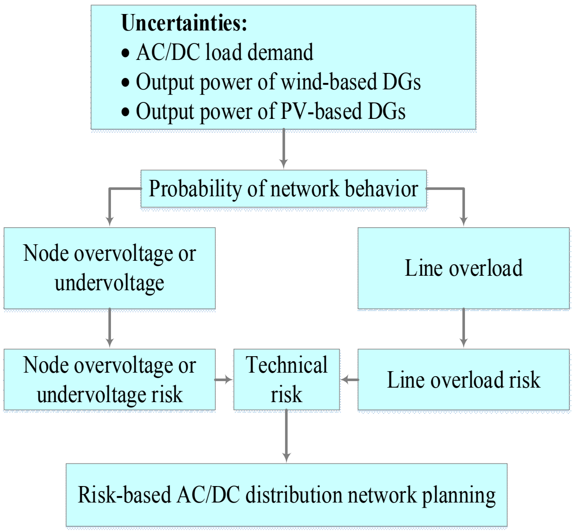

Fig. 1*. Schematic view of risk-based hybrid distribution network planning*

Step 1, determine the number of clusters (K)
Step 2, select K samples as the cluster center. The cluster center is shown by μ_k. μ_k is selected from the input variables, i.e., $X=[x_1,\ldots,x_N]^T$.
Step 3, assign all samples to the nearest cluster center
Step 4, calculate the center of the clusters as follows:

$$\mu_k=\frac{1}{N_{G_k}}\sum_{s\in G_k} d_s \tag{1}$$

where k=1,…,K. d_s denotes to the data s (row s of X).
Step 5, calculate the sum of the squared error (SSE) function as follows:

$$SSE=\sum_{k\in K}\sum_{s\in G_k}\left\|d_s-\mu_k\right\|^2 \tag{2}$$

Step 6, repeat steps 3 to 5 until the stopping criteria of the algorithm are not met. The criteria for stopping in this algorithm are no change in the members of each cluster, no change in the center of each cluster, or minimum SSE. Therefore, in the output of the K-means algorithm, the center of the clusters of all uncertain parameters is obtained.

2.2. Network structure formation

The structure of the AC/DC network consists of a combination of AC and DC distribution networks along with converters. The equipment of these networks is AC and DC loads, AC and DC energy sources, and VSC. VSC is used to convert AC to DC power or vice versa.

Fig. 2a and 2b, respectively, show the types of nodes, lines and converters required in the AC/DC distribution networks [2, 36].

Therefore, in the problem of AC/DC distribution network planning, the network structure consists of 3 parts. In the first part, the connection between the nodes (M_{Str}) is obtained by the N×N binary matrix. So, if there is a connection between the nodes and it is equal to one; otherwise, it is zero. In the second part, the type of connection between the nodes (Q_{Str}) is also determined by the N×N binary matrix. If the communication line between node i and node j is of DC type, then $Q_{Str}^{i,j}$ is one; otherwise, it is zero. The third part also consists of the binary vector of the network node type (A_{Str}). If node i is DC, and then A_{Str}^{i} is one; otherwise, zero.

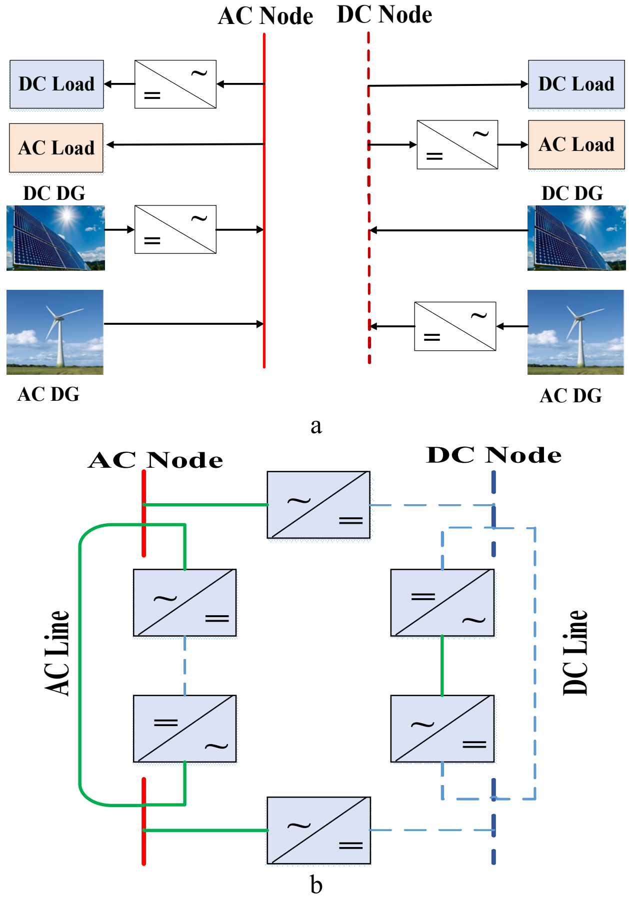

Fig. 2*. Structure of AC/DC hybrid network*
(a) Types of nodes, **(b)** Types of lines

3. Planning problem formulation

In an AC/DC hybrid distribution network, the planning problem is formulated as a stochastic optimization problem with the following objectives, and constraints.

3.1. Objective functions

Two objectives are considered in this work. The first objective is the minimization of the expected total cost, and the second is the conditional total cost.

$$\min F=[E(C_T^{\omega})\ \ CVaR_{\alpha}(C_T^{\omega})] \tag{3}$$

3.1.1 Cost Objective: The first objective is to minimize the expected total planning cost. The total planning cost includes the network investment and operation costs, as follows:

$$C_T^{\omega}=C_{Line}+C_{vsc}+\sum_{t\in T}\frac{C_{MC}+C_{Oper}^{\omega,t}}{(1+r_d)^t} \tag{4}$$

In AC/DC hybrid planning, optimal power flow (OPF) is employed to determine the operating cost of the network structure. The problem of OPF is modeled in GAMS as nonlinear programming problem with discontinuous derivatives (DNLP). CONOPT is one of the nonlinear solvers which has been used to solve the OPF problem. The goal of OPF is to minimize the cost of energy generation, the cost of damage due to node voltage violation, and the cost of damage due to line loading violation, as shown in (5).

$$C_{Oper}^{\omega,t}=8760\times\sum_{g\in\Omega_G}P_G^{g,\omega}\times C_G^g+\sum_{i\in\Omega_B}C_{Dam,O\&UV}^{i,\omega}+\sum_{i\in\Omega_B}\sum_{j\in\Omega_B}C_{Dam,OLL}^{i,j,\omega} \quad (5)$$

$$C_{Dam,O\&UV}^{i,\omega}=C_{Dam,O\&UV}^{mx}\times P_L^{i,\omega}\times F_{Pen,O\&UV}^{i,\omega} \quad (6)$$

$$C_{Dam,OLL}^{i,j,\omega}=M_{Str}^{i,j}\times\left(C_{Dam,OLL,DC}^{i,j,\omega}+C_{Dam,OLL,AC}^{i,j,\omega}\right) \quad (7)$$

$$C_{Dam,OLL,DC}^{i,j,\omega}=2\times CR_{Dam,OLL}^{i,j,\omega}\times C_{Cond}\times D_{Dist}^{i,j}\times Q_{Str}^{i,j} \quad (8)$$

$$C_{Dam,OLL,AC}^{i,j,\omega}=3\times CR_{Dam,OLL}^{i,j,\omega}\times C_{Cond}\times D_{Dist}^{i,j}\times\left(1-Q_{Str}^{i,j}\right) \quad (9)$$

3.1.2 Economic risk: CVaR and value at risk (VaR) are risk tools to represent the economic risk due to uncertainties. VaR represents the most negligible total cost β in the (1-α) times the total cost distribution under α confidence level. Therefore, mathematically VaR can be defined as,

$$VaR_\alpha(C_T^\omega)=[\beta|Pr(C_T^\omega\leq\beta)\geq\alpha] \quad ,0\leq\alpha\leq 1 \quad (10)$$

VaR provides no information about the worst potential cost beyond the confidence level. An attractive alternative to VaR is the coherent risk measure CVaR. The CVaR is the weighted average of the lower tail in the total cost distribution. CVaR can be obtained as follows:

$$CVaR_\alpha(C_T^\omega)=\beta+\frac{1}{1-\alpha}\sum_{\omega\in N_x}Pr^\omega(C_T^\omega-E(C_T^\omega)-\beta) \quad (11)$$

In the calculation of CVaR, only the scenarios whose cost value is more than $E(C_T^\omega)+\beta$ are considered. Therefore, the set N_x is defined as follows:

$$C_T^\omega\geq E(C_T^\omega)+\beta \quad ,\forall\omega\in N_x \quad (12)$$

3.2. Soft Constraints

3.2.1 Node voltage magnitude limit: when the node voltage is within the limit of $0.9\leq V^{i,\omega}<V^{mn}$ or $V^{mx}<V^{i,\omega}\leq 1.1$, then the node voltage has exceeded its permissible limit. Therefore, the penalty function for node voltage violation is modeled according to Fig. 3a, as shown in (13) [37-38].

$$F_{Pen,O\&UV}^{i,\omega}=\begin{cases}\dfrac{V^{mn}-V^{i,\omega}}{V^{mn}-0.9} & 0.9\leq V^{i,\omega}\leq V^{mn}\\[2ex] \dfrac{V^{i,\omega}-V^{mx}}{1.1-V^{mx}} & V^{mx}\leq V^{i,\omega}\leq 1.1\end{cases} \quad (13)$$

3.2.2 Line loading limit: when the line power flow is within the limit of $0.9\leq S_{tr}^{i,j,\omega}\leq 1$, then overload takes place in the line. The damage due to line overload is analyzed and modeled in [39]. In this paper, considering the linear model, the cost of damage due to line overload is shown in Fig. 3b [40-41].

These constraints are soft constraints, which are part of the objective of the problem.

3.3. Hard Constraints

3.3.1 Node voltage magnitude limit: the node voltage must be limited as follows:

$$0.9<V^{i,\omega}<1.1 \quad (14)$$

Therefore, this constraint is one of the hard constraints of the problem that must be satisfied in the problem.

3.3.2 Line loading limit: the line apparent power flow must be limited by 100% of the line apparent power flow rating [41]. Therefore, this constraint is also one of the hard constraints of the problem that must be satisfied in the problem.

For each node, when the node voltage is between minimum node voltage (V^{mn}) and maximum node voltage (V^{mx}), the risk value of node voltage violation is zero.

For each line, when the line apparent power flow is no larger than 90% of the rated value, the risk value of line loading violation is zero.

Fig. 3a and 3b show a range of node voltage and line loading limit, which are considered as hard constraint, soft constraint, and zero risk in this study [42]. V^{mn}, V^{mx} minimum and maximum voltage of the node that depends on the value of voltage tolerance considered in the problem.

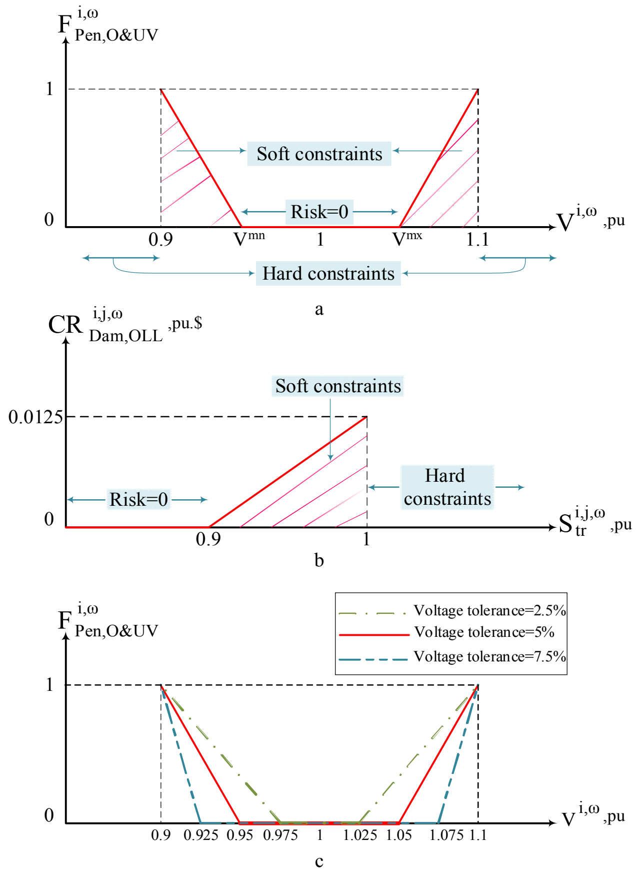

***Fig. 3.** Modeling violation of technical constraints*
(a) Penalty function for node voltage violation, **(b)** Damage cost of line loading violation, **(c)** Penalty function for node voltage violation under different voltage tolerance values

On the other hand, in most of the studies conducted in the field of distribution networks, the value of voltage tolerance is taken as a constant ±5%. In comparison, this value can be changed up to ±10% [43]. In the present study, the voltage tolerance values are ±2.5%, ±5% and ±7.5%. Therefore, the penalty function due to the node voltage violation is shown in Fig. 3c under different voltage tolerance values. As seen from this figure, with the increase of the voltage tolerance, the node voltage will be violated in a smaller range. Therefore, it is expected that the cost of damage due to the node voltage violation will decrease with the increase of the voltage tolerance value.

3.4. Optimal power flow constraints

The constraints include the equations of active and reactive power balance, and energy generation constraints. Constraints (15-20) are considered the constraints of the OPF problem [7].

$$P_{inj}^{i,\omega}=P_{cal}^{i,\omega} \qquad \forall i\in\Omega_B=\Omega_B^A\cup\Omega_B^D \;,\; \forall\omega\in\Omega_S \qquad (15)$$

$$Q_{inj}^{i,\omega}=Q_{cal}^{i,\omega} \qquad \forall i\in\Omega_B \;,\; \forall\omega\in\Omega_S \qquad (16)$$

$$\theta^{mn} \leq \theta^{i,\omega} \leq \theta^{mx} \qquad \forall i\in\Omega_B \;,\; \forall\omega\in\Omega_S \qquad (17)$$

$$M_{MO}^{i,j,mn} \leq M_{MO}^{i,j,\omega} \leq M_{MO}^{i,j,mx} \qquad \forall i,j\in\Omega_B \;,\; \forall\omega\in\Omega_S \qquad (18)$$

$$P_G^{g,mn} \leq P_G^{g,\omega} \leq P_G^{g,mx} \qquad \forall g\in\Omega_G=\Omega_G^A\cup\Omega_G^D \;,\; \forall\omega\in\Omega_S \qquad (19)$$

$$Q_G^{g,mn} \leq Q_G^{g,\omega} \leq Q_G^{g,mx} \qquad \forall g\in\Omega_G \;,\; \forall\omega\in\Omega_S \qquad (20)$$

3.5. Network structure constraints

Constraints (21-23) indicate the binary variables of the structure matrices. In order to avoid congestion and isolation of each node, communication is limited to (24-25) [7].

$$A_{Str}^{i}\in\{0,1\} \qquad \forall i\in\Omega_B \qquad (21)$$

$$M_{Str}^{i,j}\in\{0,1\} \qquad \forall i,j\in\Omega_B \qquad (22)$$

$$Q_{Str}^{i,j}\in\{0,1\} \qquad \forall i,j\in\Omega_B \qquad (23)$$

$$\sum_{j\in\Omega_B} M_{Str}^{i,j} \geq N_{con}^{mn} \qquad 1 \leq N_{con}^{mn} \leq N_{con}^{mx} \;,\; \forall i\in\Omega_B \qquad (24)$$

$$\sum_{j\in\Omega_B} M_{Str}^{i,j} \leq N_{con}^{mx} \qquad N_{con}^{mn} \leq N_{con}^{mx} \leq \Omega_B\text{-}1 \;,\; \forall i\in\Omega_B \qquad (25)$$

In general, the AC/DC distribution network planning consists of 5 steps, as shown in Fig. 4.

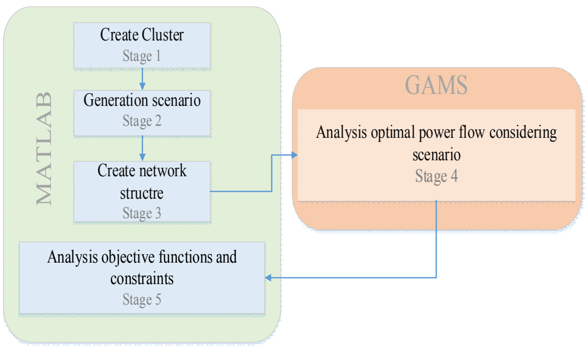

Fig. 4. Process of AC/DC hybrid distribution network planning

Many studies recommend using the NSGA-II, because it is easy to implement, guarantees population diversity in the optimization process, and is a multi-objective optimization algorithm [44]. Thus, it was the chosen method to solve the optimization problem in this study.

In the AC/DC hybrid distribution network planning, the connection of lines between nodes, the type of connection, and the type of nodes (the type means AC or DC) are among the decision variables of the problem. Each chromosome, which is a member of a population, shows a network structure. The structure of the proposed chromosome contains several substrings, as shown in Fig. 5. The first part of the chromosome, which consists of two substrings, has the Nc gene. The first substring (M_{Str}) represents the connection between nodes. The value of zero and one in the genes of this substring ($M_{Str}^{i,j}$) indicates the lack of connection and connection between the node i and node j, respectively. The second substring (Q_{Str}) indicates the type of communication between the nodes, So the value of zero and one in the gene $Q_{Str}^{i,j}$ represents the type of AC and DC line between node i and node j, respectively. The second part of a chromosome (A_{Str}) has the number of N (the number of network nodes) genes that indicate the type of network nodes. The values of zero and one in these genes represent AC and DC nodes, respectively.

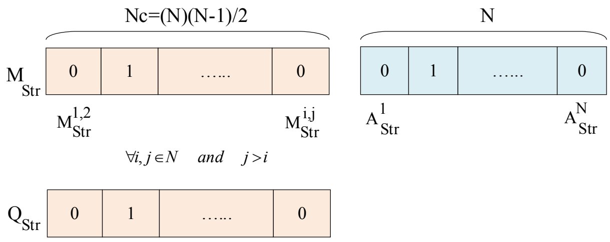

Fig. 5. Proposed chromosome structure

4. Test system and simulation results

The effectiveness of the proposed model and economic risk assessment has been tested on the 13-bus test system, shown in Fig. 6. In the system under study, there are various AC and DC-type loads and sources. The distribution substation (DSS) is connected to bus 1. All input data is extracted from [7]. The maximum cost of damage due to node voltage violation is (112000 $\$/_{MW}$) [45]. The proposed planning method was implemented in the MATLAB/GAMS hybrid environment. By performing numerous experiments in this numerical study, the population, number of generations, probability of crossover, and mutation operator were set to 200, 100, 0.9, and 0.125, respectively. It should be noted that in this paper, the number of clusters for all random parameters in the system is 3 clusters. Three different cases are presented in this work which are:

- Case 1. Base case without risk assessment
- Case 2. Risk-based distribution network planning under different confidence levels
- Case 3. Risk-based distribution network planning under different voltage tolerance values

4.1. Case 1: distribution network planning and comparison

First, to show the efficiency of the optimization method, the AC and AC/DC distribution network planning has been implemented on the network under study. In this case, the objective is to minimize the net present value of the distribution network costs, including network investment and operation costs. The results obtained from the implementation of this case are compared with reference [7] and presented in Table 2. On the other hand, the optimal structure of AC and AC/DC distribution networks obtained from the implementation of this case is the same as the optimal structure of the networks mentioned in the reference. Therefore, the results of costs in AC and AC/DC distribution networks indicate the correctness of the optimization method.

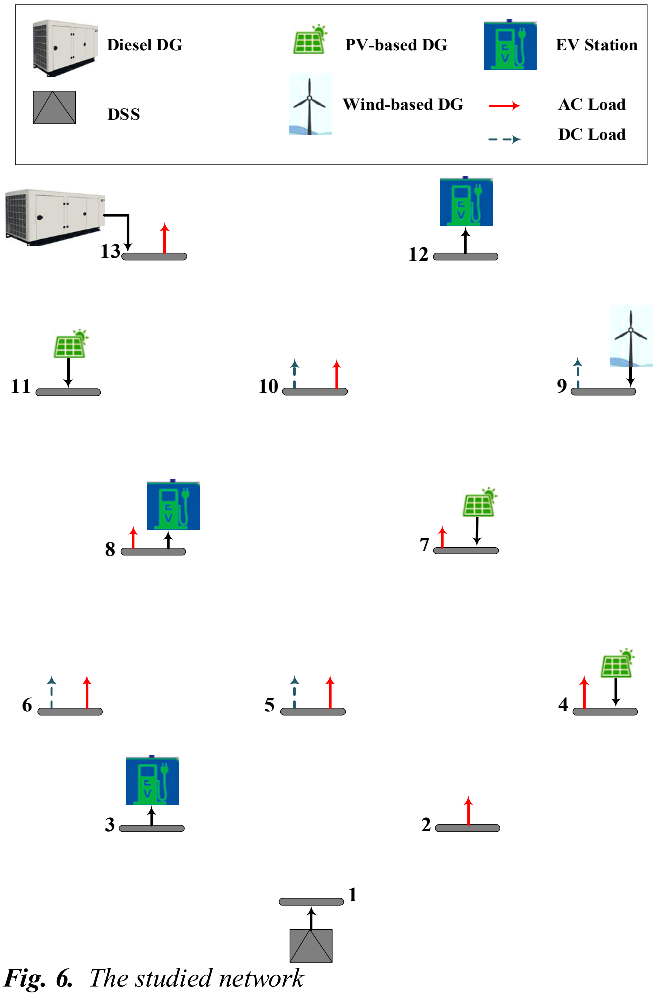

Fig. 6. The studied network

4.2. Case 2: Economic risk assessment of distribution network planning under different confidence levels

In this case, the economic risk assessment of the AC and AC/DC distribution networks planning under different confidence levels has been discussed. The confidence levels are 0.92, 0.95, and 0.98, respectively. Therefore, using the proposed planning and the search method based on NSGA-II, the Pareto front solutions in AC and AC/DC distribution networks under different confidence levels have been obtained according to Fig. 7a and 7b. The Pareto front solutions space obtained using the proposed multi-objective model is displayed in a two-dimensional graphic format. The axes of these Pareto front solutions show the values of expected total cost and conditional total cost. Each point of these solutions is the geometric location of the corresponding Pareto front solutions according to the values of the corresponding objective function. On the other hand, in AC distribution network planning, all nodes and network lines are of AC type. Therefore, the presence of DC loads and output power in this network means that a converter is needed to connect these loads and output power to the nodes, which increases the investment cost of the network and, ultimately the total cost of the network in the AC distribution network planning. However, in AC/DC distribution network planning, lines and nodes can be chosen as AC or DC. In this network, in addition to the network structure, the type of nodes and network lines are also determined. Therefore, because the optimization algorithm can choose the type of nodes and lines, unlike the AC network, we can achieve optimal planning in the presence of various loads and output power. On the other hand, according to the Pareto front solutions obtained for AC and AC/DC distribution networks, in this case, the values of expected total cost and CVaR in AC/DC distribution network planning are lower compared to the AC distribution network. Therefore, according to the results obtained in this case, with the increase in the confidence level, the values of the objectives in the Pareto front solutions for AC and AC/DC distribution networks have increased. Based on the model presented in this paper, for the optimal structure of AC and AC/DC distribution networks obtained in [7], the values of the objectives have been obtained under the confidence level of 0.98 according to Table 3. Comparing the values obtained in this table with the Pareto front solutions under the confidence level of 0.98 indicates the improvement of Pareto front solutions. On the other hand, according to the user's opinion, any of the Pareto front solutions can be selected as the final solution to the problem. In this paper, fuzzy decision-making is used to choose the proposed solution. The results of the proposed solutions of AC and AC/DC distribution networks are depicted in Fig. 8a and 8b and are shown in Table 4.

4.3. Case 3: Economic risk assessment on distribution network planning under different voltage tolerance values

In this case, the AC and AC/DC network planning has been done considering different voltage tolerance. The voltage tolerance values are 2.5%, 5%, and 7.5%, respectively. The set of Pareto front solutions obtained for AC and AC/DC distribution networks under different voltage tolerance values are shown in Fig. 7c and 7d. According to these figures, it can be seen that with the increase of the voltage tolerance value, the set of Pareto front solutions decreases; In other words, the values of the objectives of the solutions are reduced. In this case, as in the previous case, the values of the objectives for the optimal structures of the mentioned reference under the voltage tolerance of 7.5% have been obtained in Table 3. Based on the Pareto front solutions obtained under the voltage tolerance of 7.5% and the values of this table, the improvement of the Pareto front solutions for AC and AC/DC distribution networks will follow. The results of the proposed solutions of AC and AC/DC distribution networks are depicted in Fig. 8c and 8d and are shown in Table 4.

Therefore, in this paper, in case 1, the planning problem is solved without considering risk. The purpose of this case is to show the correctness of the results of the proposed model with the desired reference. In case 2 and case 3, the goal is to plan distribution networks under different confidence levels and voltage tolerance values. According to the results obtained in these cases, it can be seen that each of the mentioned factors can affect risk-based planning problems. On the other hand, in this paper, planning is done on AC and

AC/DC distribution networks. Therefore, according to the results obtained from case 1 to case 3 on two types of distribution networks, it can be concluded that optimal planning can be achieved by AC/DC distribution network planning.

Table 2 The results of costs in distribution networks under case 1

Type	AC		AC/DC	
Case	[7]	Case 1	[7]	Case 1
C_{vsc}, M$	2.0485	2.0485	1.7595	1.7595
C_{Line}, M$	1.7136	1.7136	1.2264	1.2264
C_{IC}, M$	3.7621	3.7621	2.9859	2.9859
C_{TNP}, M$	47.3567	47.3564	45.6596	45.6586

Table 3 The results of the optimal structures proposed in [7]

Type	AC		AC/DC	
Case	Case 2	Case 3	Case 2	Case 3
Expected cost, M$	47.3562	47.3403	45.6434	45.6350
CVaR, M$	8.4410	8.2289	7.1542	6.9633
VaR, M$	8.4410	6.8271	7.1542	5.7412

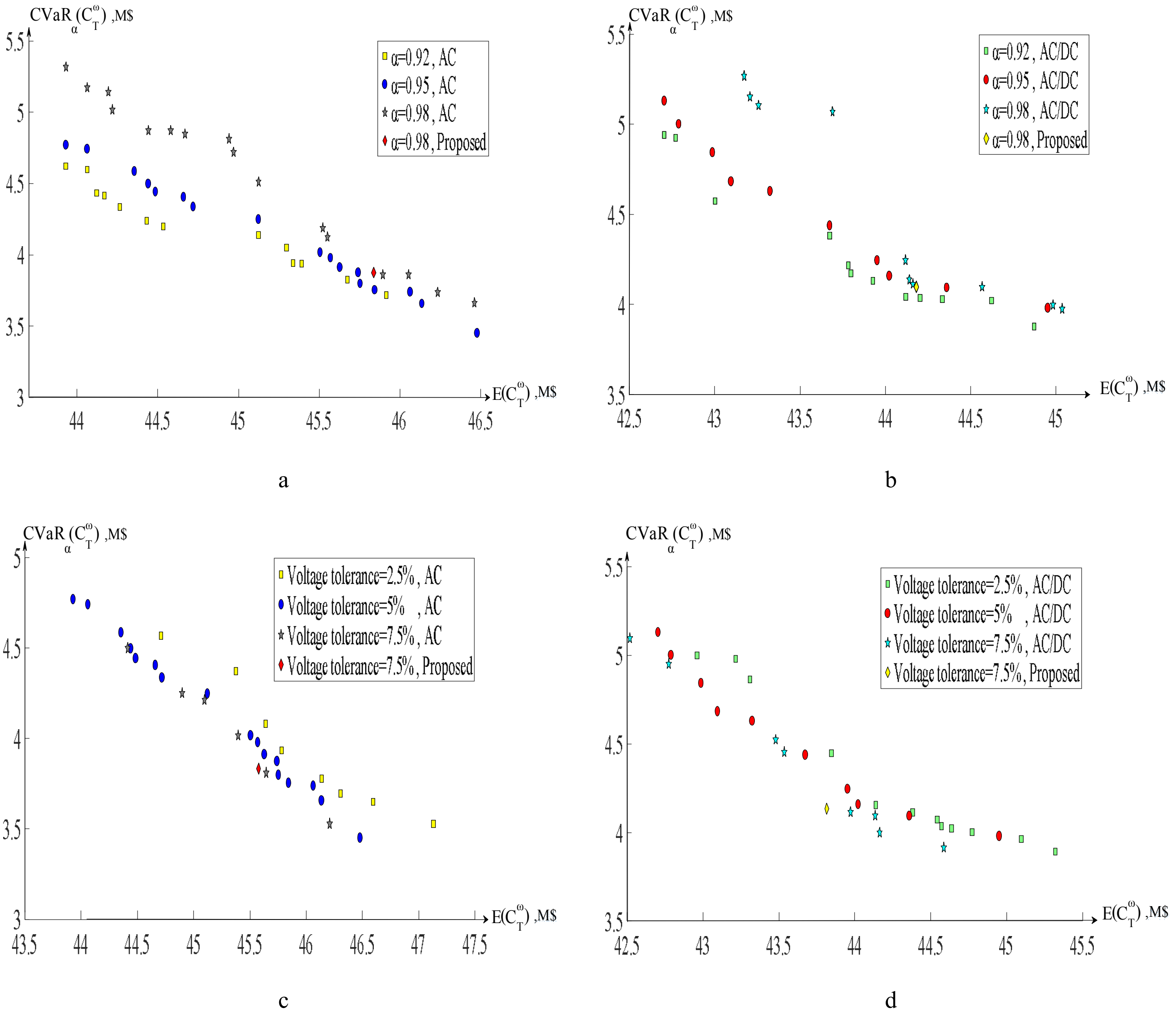

Fig. *7. Pareto fronts*
(a) AC solution under different confidence levels, **(b)** AC/DC solution under different confidence levels, **(c)** AC solution under different voltage tolerance values, **(d)** AC/DC solution under different voltage tolerance values

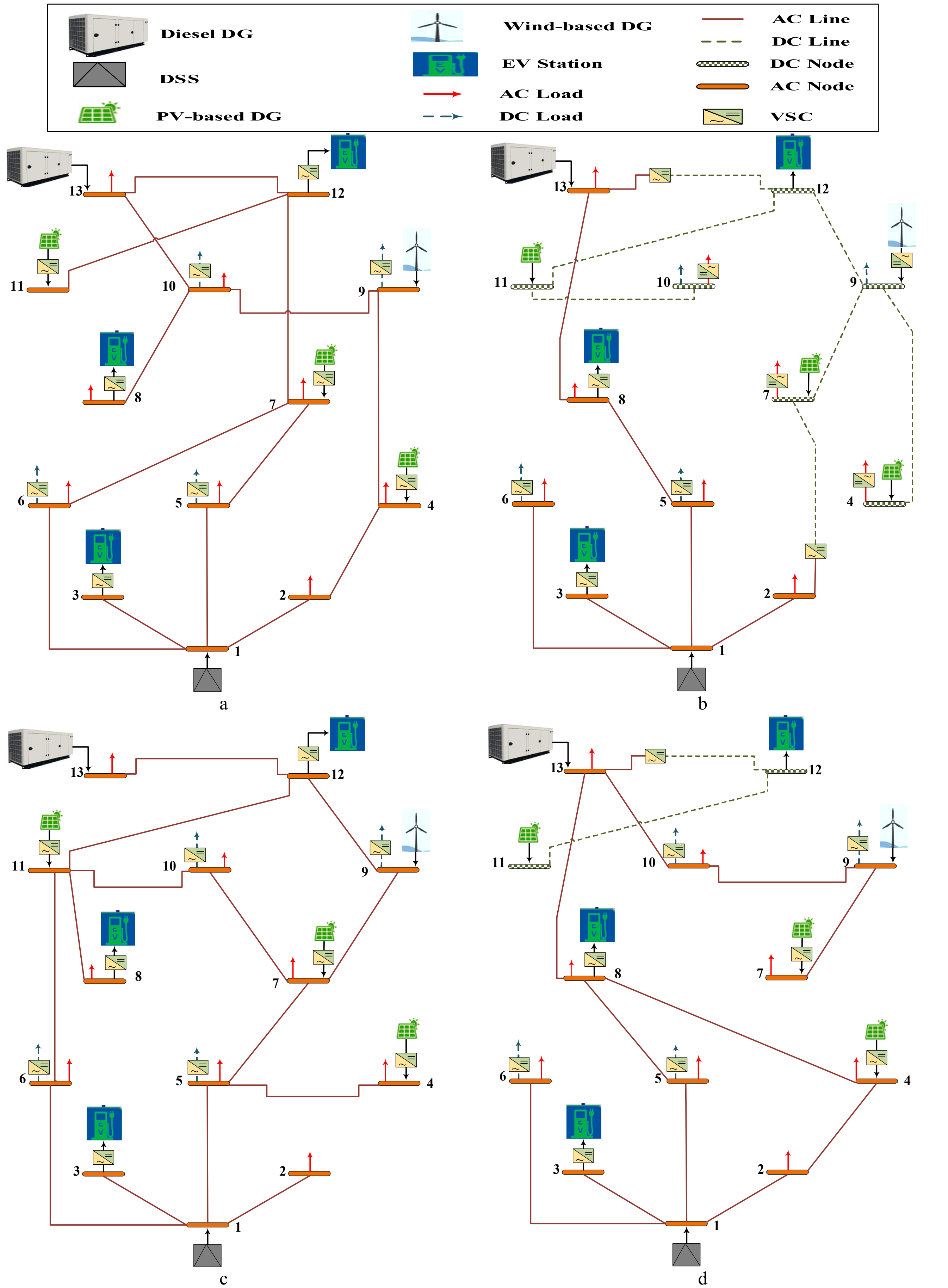

Fig. 8. The optimal structure

(a) AC distribution network under case 2, **(b)** AC/DC distribution network under case 2, **(c)** AC distribution network under case 3, **(d)** AC/DC distribution network under case 3

Table 4 The results of the AC and AC/DC proposed solutions

Type	AC		AC/DC	
Case	Case 2	Case 3	Case 2	Case 3
Expected cost, M$	45.8383	45.5767	44.1804	43.8156
CVaR, M$	3.8757	3.8337	4.0976	4.1335
VaR, M$	3.8757	3.5396	4.0976	3.9801
C_{vsc}, M$	2.0485	2.0485	1.9125	1.8785
C_{Line}, M$	1.5624	1.4448	1.2152	1.4560
C_{IC},M$	3.6109	3.4933	3.1277	3.3345

5. Conclusion

Today, in traditional distribution networks (of AC type), the multiplicity of loads and energy sources of DC type has made it uneconomical to continue in this network. Therefore, a solution can be to switch to an AC/DC distribution network due to the presence of various loads and energy sources. In this paper, the economic risk assessment of AC/DC distribution network planning is discussed. Uncertainties in the forecast of load demand and power generation of renewable energy sources cause probabilistic behavior of distribution networks. This behavior exposes the distribution network to risk. Therefore, the AC/DC hybrid distribution network planning is governed by taking into account uncertainties, and technical risks, including the risk of line loading limit and node undervoltage/overvoltage, which should be modeled in the problem. By modeling the cost of damage due to technical risks, these risks are included in the objective of the planning problem. The K-means clustering algorithm has been used to model the uncertainties in the problem. In this model, risk assessment has been done using the CVaR method. Also, the problem is formulated as a mathematical model with multiple criteria. The goals of planning in the proposed model are: 1) minimizing planning costs and 2) reducing economic risk due to uncertainties. The proposed mathematical model has been solved in the MATLAB/GAMS hybrid space using the NSGA-II multi-objective optimization algorithm. To check the efficiency and application of the presented model, a 13-node distribution network has been used. The AC/DC and AC distribution networks planning has been tested under changes in the values of voltage tolerance and confidence level. The results of the numerical studies show that the changes in each of the mentioned factors impact the problem of risk-based planning.

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