IJE TRANSACTIONS B: Applications Vol. 37, No. 05, (May 2024) 876-886

International Journal of Engineering

Journal Homepage: www.ije.ir

Risk-Based AC/DC Hybrid Distribution System Planning

Z. Esmaeilzadeh, H. Falaghi*, M. Ramezani

Faculty of Electrical and Computer Engineering, University of Birjand, Birjand, Iran

PAPER INFO

Paper history:
Received 02 September 2023
Received in revised form 14 November 2023
Accepted 12 December 2023

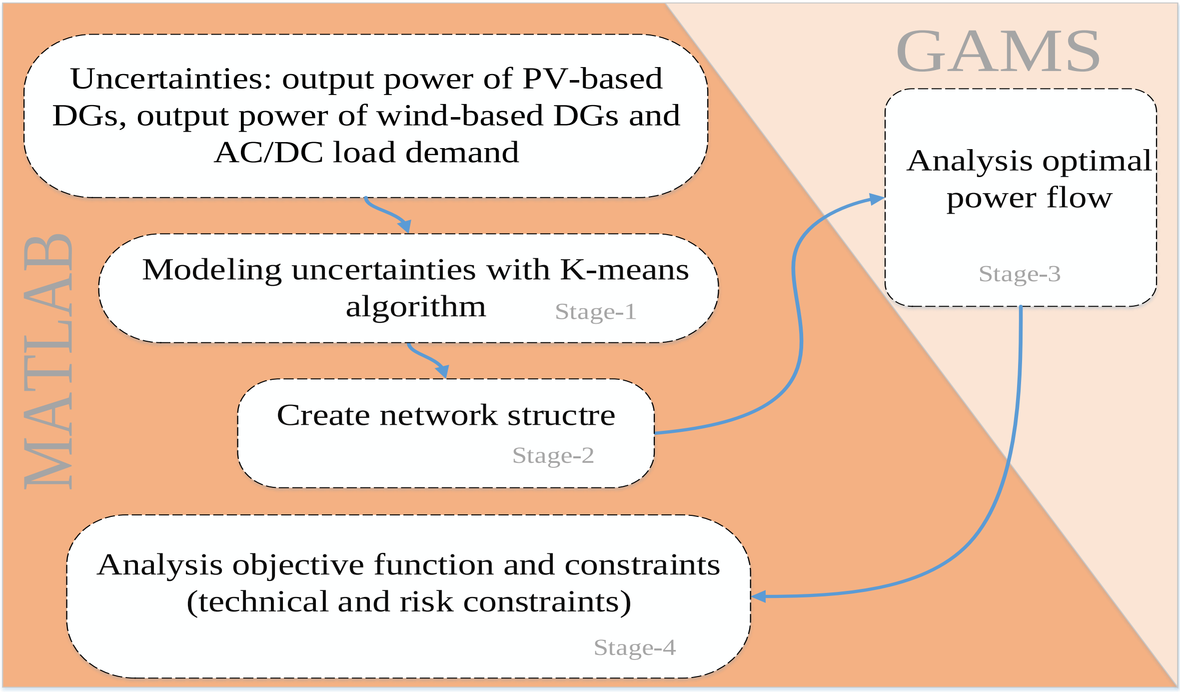
Keywords:
AC/DC Hybrid Distribution System
Distribution Generations
Load Demands
MATLAB/GAMS Hybrid
K-means
Planning
Risk-based

ABSTRACT

With the growing movement of using direct current (DC) load demands, as well as DC distribution generations (DGs), the distribution system has undergone significant changes on the production and demand side. Due to alternating current (AC) and DC generators and load demands, it is not cost-effective to continue in the AC distribution system. Therefore, AC/DC hybrid distribution system planning is economical despite various demands and generations. On the other hand, uncertainty in load demand and output power of DGs cause the possible behavior of the distribution system. This behavior leads to risk in the distribution system. In this paper, the AC/DC distribution system planning is discussed by considering the risk. The planning problem in the matrix laboratory and general algebraic modeling system (MATLAB/GAMS) hybrid space has been formulated and solved. Using the K-means algorithm, the uncertainty related to renewable DG output power and load demand has been modeled. To verify the proposed method, it was implemented in a sample distribution system.

***doi**: 10.5829/ije.2024.37.05b.06*

Graphical Abstract



---

[*] Corresponding Author Email: falaghi@birjand.ac.ir (H. Falaghi)

Please cite this article as: Esmaeilzadeh Z, Falaghi H, Ramezani M. Risk-Based AC/DC Hybrid Distribution System Planning. International Journal of Engineering, Transactions B: Applications. 2024;37(05):876-86.

NOMENCLATURE

Acronyms	
AC	Alternating current
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
MATLAB	Matrix laboratory
MCS	Monte Carlo simulation
MV	Medium voltage
OPF	Optimal power flow
PV	Photovoltaic
PEM	Point estimate method
SSE	The sum of the squared error
VSC	Voltage source converter
IGDT	Information gap decision theory

Sets	
Ω_B	Set of all buses
$\Omega_B^{DC}, \Omega_B^{AC}$	Set of the total of DC and AC buses respectively
Ω_{vsc}	Set of AC/DC converters in the system
Ω_G	Set of all generators in the system
$\Omega_G^{AC}, \Omega_G^{DC}$	Set of AC and DC generators
Ω_S	Set of all scenarios
T	Planning horizon

Indices	
i, j	Index of buses
ω	Index of scenarios
g	Index of generators
nv	Index of converters
t	Index of years

Parameters	
r_d	Discount rate, %
X_{mn}, X_{mx}	Minimum and maximum limit of the variable X
$Ncon$	Number of lines that can be connected to each bus
C_{G_g}	Energy cost of generator g, $/MWh
K	Total number of clusters
N	Number of network buses
$\Pr$	Probability of scenario, %

Variables	
$V_{i,\omega}, \theta_{i,\omega}$	Voltage magnitude and phase angle at bus i for scenario ω
$Pinj_{i,\omega}, Qinj_{i,\omega}$	Active and reactive power injections at bus i for scenario ω
$Pcal_{i,\omega}, Qcal_{i,\omega}$	Active and reactive power calculated at bus i for scenario ω
$Ptr_{i,j,\omega}, Qtr_{i,j,\omega}, Str_{i,j,\omega}$	Active, reactive and apparent power transmitted from bus i to bus j for scenario ω
$P_{nv,\omega}, Q_{nv,\omega}, S_{nv,\omega}$	the active, reactive and apparent power of the VSC
$Mo_{i,j,\omega}$	Modulation index of the VSC connected between bus i and bus j for scenario ω
$P_{G_{g,\omega}}, Q_{G_{g,\omega}}$	Active and reactive power of generator g for scenario ω
OC_t	Cost of network operation at year t
LC	Cost of network lines
$VSCC$	Cost of converters
$INVC$	Investment cost
MOC	Cost of maintenance and operation of the system
MC	Cost of maintenance
TC	Total cost of the system
OPC	Cost of system operation
M	Matrix of connection between buses
Q	Line-type matrix connected between buses
A	Bus type vector
n_s^{fs}	The numbers of feasible solutions from the evaluation of system OPF
n_s	The total number of solutions
N_{G_k}	Number of samples in the cluster k
μ_k	Center of cluster k

1. INTRODUCTION

In the distribution system, due to the ever-increasing progress in the field of exploiting renewable energy sources and the multiplicity of DC-type loads, this system has undergone significant transformations and changes. On the other hand, the traditional distribution system is the AC system. Therefore, the distribution system includes additional DC DGs and load demands along with AC loads and generators. With all types of loads and DGs, the implementation of an AC/DC distribution system is an attractive solution for planners. In AC/DC system, load forecasting and power generation of renewable sources such as solar and wind is always associated with uncertainty. Thus, the distribution system has faced risk (1-6).

An overview of the studies carried out in hybrid distribution system planning is given below. A new model for AC/DC distribution network planning is presented in literature (7-10). In this model, the type of lines, buses, and network structure are determined. In the AC/DC system planning, it is focused on determining the location and capacity of DGs (11-15) and electric vehicles (EVs) (12, 14). A novel two-stage stochastic planning model is proposed by Sabzian Molaee et al. (13). In this paper, the lifetime of the voltage source converter (VSC) is modeled, and it is included in the hybrid planning problem. The AC/DC microgrid planning is discussed in literature (16-21). The decision variables of the problem are the capacity of DGs (19, 21), and the type of feeders (AC or DC) (16-18, 20). A bi-level planning model for the AC/DC distribution system considering N-1 events is presented by Wu et al. (22). The high-level model optimizes the total investment and operating costs in the AC and DC system over the entire planning horizon. In the low-level model, the goal is to improve the reliability of the DC system under the worst case of N-1. Yu et al. (23) introduced and disscussed advantages of the DC system. At the end, thye added the DC system to the usual AC system and explained the advantages of the hybrid system. Number of investigators (24-26) dealed with the planning and expansion of the AC/DC distribution system. In general, there are several methods for modeling uncertainties in problems, including interval optimization, robust optimization, stochastic optimization, possibility method, hybrid optimization method, and information gap decision theory (IGDT) (27). However, in the studies conducted in the field of AC/DC planning, the Monte Carlo simulation (MCS) technique (7-9, 12, 13), robust optimization (18), and scenario approach (24, 25) have been used to model the random behavior of load demand and power generation of DGs in the problem.

Among the advantages of the conducted studies, we can mention the implementation of AC/DC distribution system planning. Traditionally, the distribution system is planned as AC. However, due to the large number of DC load demands and DC DGs, the need for a converter to convert power in the traditional system will increase. Therefore, the AC/DC distribution system is one of the solutions in the presence of multiple DC loads and DGs. On the other hand, in several studies conducted in the field of AC/DC planning, the uncertainties in the problem have been modeled. However, one of the disadvantages of studies in this field is not considering the risk. Because the distribution system inherently has probabilistic behavior. This possible behavior leads to risk in the problem. Therefore, it is necessary to model the risk governing the AC/DC distribution system planning problem.

So far, the AC/DC hybrid distribution system has been studied from different perspectives. However, none of the studies conducted were considered risk in the AC/DC hybrid distribution system planning. Risk-based AC/DC distribution system planning is discussed in this paper. Considering the uncertainties in load demand and output power of DGs, the possible evaluation of the system has been done. The K-means algorithm has been used to model the uncertainties of the problem. The planning goal is to minimize the investment and operation costs under the risk of uncertainties. The proposed mathematical model has been solved in the MATLAB/GAMS hybrid space. The effectiveness of the proposed model is demonstrated by applying it to a distribution test system under different risk levels.

2. AC/DC HYBRID DISTRIBUTION SYSTEM PLANNING MODEL

In the AC/DC distribution system planning problem, full knowledge of consumption information leads to reliable planning. On the other hand, due to the different conditions governing the amount of consumption, registration, and collection of cargo information, this information is always associated with uncertainty. Another problem is the existence of renewable sources, such as wind and solar energy, in AC/DC distribution system planning. These resources depend highly on natural factors such as wind speed and solar radiation. For this reason, the output power of these sources is associated with uncertainty. Therefore, the AC/DC distribution system planning problem includes some parameters with possible behavior. The uncertainty related to renewable DG output power and the load variability is the leading cause of this behavior. It is necessary to explain that the possible behavior of these parameters causes risk. Obviously, the greater the uncertainty in the system information, the greater the deviation from the actual values (28, 29).

In this paper, AC/DC distribution system planning is discussed by considering the risk caused by the uncertainty in AC and DC load demands and the output power of renewable sources such as wind and photovoltaic (PV). Figure 1 shows the schematic view of the risk-based planning problem.

2. 1. Modeling of Uncertainties

Among the uncertainty modeling methods, MCS and point estimate method (PEM) have been used in many problems. In the MCS method, the results are highly accurate, but the calculations are time-consuming. In the PEM method, for

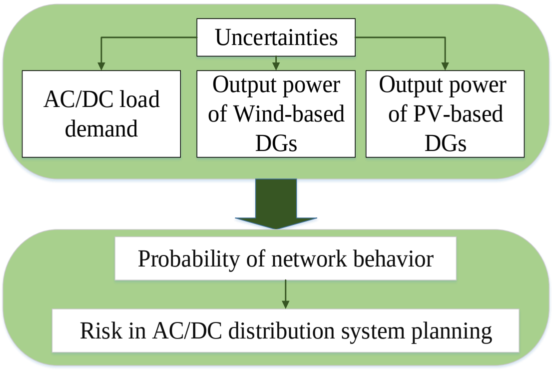


Figure 1. Schematic view of risk-based hybrid distribution system planning

large-scale problems, the volume of calculations is heavy, which is not practical. Recently, clustering methods have been given attention in non-deterministic problems. Among these methods, the K-means algorithm is popular. The reasons for this popularity include very high execution speed, the simplicity of the algorithm, and the ability to use this algorithm for large amounts of data. This algorithm is an iterative algorithm that divides the data set into K distinct non-overlapping clusters according to their characteristics (27, 30). The implementation process of this algorithm is described in the following.

In AC/DC hybrid distribution system planning, the stochastic nature of renewable sources, load demand, and EV demand are 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 (31):

Step 1, determine the number of clusters (K)

Step 2, select K samples as the cluster center coordinates

Step 3, assign all samples to the nearest cluster center

Step 4, calculate the center of the clusters as follows (d_s represents the data s):

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

Step 5, calculate the sum of the squared error (SSE) function in the form of Equation 2:

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

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 systems along with converters. The equipment of these systems is AC and DC loads, AC and DC energy sources, and a voltage source converter (VSC). VSC is used to convert AC to DC power or vice versa. Figure 2 shows the types of buses in the AC/DC distribution system (2, 32, 33).

Therefore, in the problem of AC/DC distribution system planning, the system structure consists of 3 parts. In the first part, the connection between the buses (M) is obtained by the N×N binary matrix. So, if there is a connection between the buses, it is equal to one; otherwise, it is zero. In the second part, the type of connection between the buses (Q) is also determined by the N×N binary matrix. If the communication line between bus i and bus j is of DC type, then Q(i,j) is one; otherwise, it is zero. The third part also consists of the binary vector of system bus type (A). If bus i is DC, then A(i) is one; otherwise, zero.

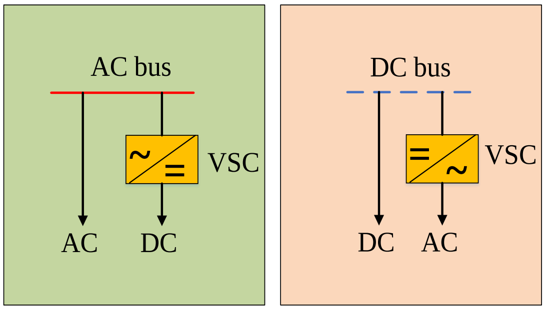


Figure 2. Types of buses in AC/DC hybrid network

3. PROBLEM FORMULATION

The planning problem is formulated as a stochastic optimization problem with the following objective function and constraints.

3. 1. Objective Function

The objective is to minimize the investment and operation costs as follows:

$$\min(TC) = INVC + MOC \tag{3}$$

$$INVC = LC + VSCC \tag{4}$$

$$MOC = \sum_{t \in T} \frac{MC + OC_t}{(1+r_d)^t} \tag{5}$$

$$OC_t = 8760 \sum_{\omega \in \Omega_S} OPC_{t,\omega} \times pr_\omega \tag{6}$$

In AC/DC hybrid planning, optimal power flow (OPF) is employed to determine the operating cost of the system structure. The problem of OPF is modeled in GAMS as a 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 as follows:

$$\min(OPC) = \sum_{g \in \Omega_G} C_{G_g} \times P_{G_g} \tag{7}$$

3. 2. Constraints

The constraints are categorized into two groups: 1) technical constraints and 2) risk constraint.

3. 2. 1. Technical Constraints The technical constraints include the equations of active and reactive power balance, voltage constraints, thermal constraints of the equipment capacity, energy generation constraints, and network structure constraints. Constraints 8-16 are considered the constraints of the OPF problem. Constraints 17-19 indicate the binary variables of the structure matrices. In order to avoid congestion and isolation of each bus, communication is limited to Constraints 20 and 21 (7).

$$Pinj_{i,\omega} = Pcal_{i,\omega} \quad ,\forall i \in \Omega_B, \omega \in \Omega_S \tag{8}$$

$$Qinj_{i,\omega} = Qcal_{i,\omega} \quad ,\forall i \in \Omega_B, \omega \in \Omega_S \tag{9}$$

$$V_{mn} \le V_{i,\omega} \le V_{mx} \quad ,\forall i \in \Omega_B, \omega \in \Omega_S \tag{10}$$

$$\theta_{mn} \le \theta_{i,\omega} \le \theta_{mx} \quad ,\forall i \in \Omega_B, \omega \in \Omega_S \tag{11}$$

$$\sqrt{Ptr_{i,j,\omega}^2 + Qtr_{i,j,\omega}^2} \le Str_{mx} \quad ,\forall i,j \in \Omega_B, \omega \in \Omega_S \tag{12}$$

$$Mo_{mn} \le Mo_{i,j,\omega} \le Mo_{mx} \quad ,\forall i,j \in \Omega_B, \omega \in \Omega_S \tag{13}$$

$$\sqrt{P_{nv,\omega}^2 + Q_{nv,\omega}^2} \le S_{mx} \quad ,\forall nv \in \Omega_{vsc}, \omega \in \Omega_S \tag{14}$$

$$P_{G_{g,mn}} \le P_{G_{g,\omega}} \le P_{G_{g,mx}} \quad ,\forall g \in \Omega_G, \omega \in \Omega_S \tag{15}$$

$$Q_{G_{g,mn}} \le Q_{G_{g,\omega}} \le Q_{G_{g,mx}} \quad ,\forall g \in \Omega_G, \omega \in \Omega_S \tag{16}$$

$$A(i) \in \{0,1\} \qquad \forall i \in \Omega_B \tag{17}$$

$$M(i,j) \in \{0,1\} \qquad \forall i,j \in \Omega_B \tag{18}$$

$$Q(i,j) \in \{0,1\} \qquad \forall i,j \in \Omega_B \tag{19}$$

$$\sum_{j \in \Omega_B} M(i,j) \ge Ncon_{mn} \quad ,1 \le Ncon_{mn} \le Ncon_{mx} \quad ,\forall i \in \Omega_B \tag{20}$$

$$\sum_{j \in \Omega_B} M(i,j) \le Ncon_{mx} \quad ,Ncon_{mn} \le Ncon_{mx} \le N-1 \quad ,\forall i \in \Omega_B \tag{21}$$

3. 2. 2. Risk Constraint In general, the behavior of the distribution system is inherently probabilistic. This possible behavior is related to the uncertainties in the load demand and the output power of renewable energy sources. On the other hand, this behavior is the main source of risk in the distribution network. In this paper, risk is considered as one of the constraints of the problem, and it is calculated based on the following steps:

Step 1, modeling random parameters in the planning problem using the K-means algorithm.
Step 2, generation of scenarios (combines the center of clusters of random parameters of the set of scenarios).
Step 3, run OPF for each scenario.
Step 4, repeat step 3 for all scenarios.
Step 5, calculates the percentage of system risk (based on the ratio of the total number of feasible solutions of OPF to the total number of solutions). The mathematical model of risk is defined by (an infeasible OPF solution due to the violation of one or more of the constraints):

$$Risk = 1 - \frac{n_s^{fs}}{n_s} \tag{22}$$

In this paper, a genetic algorithm (GA) is used to solve the optimization problem. In the AC/DC hybrid distribution system planning, the connection of lines between buses, the type of connection, and the type of buses (the type means AC or DC) are 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 Figure 3. The first part of the chromosome, which consists of two substrings, has the Nc gene. The first substring (M) represents the connection between buses. The value of zero and one in the genes of this substring M(i,j) indicates the lack of connection and connection between the buses i and j, respectively. The second substring (Q) indicates the type of communication between the buses, So the value of zero and one in the gene Q(i,j) represents the type of AC and DC line between buses i and j, respectively. The second part of a chromosome (A) has the number of N genes that indicate the type of network buses. The values of zero and one in these genes represent AC and DC buses, respectively.

4. TEST SYSTEM AND SIMULATION RESULTS

The proposed model and method for the planning problem of the AC/DC distribution system have been tested on a sample distribution system of 13 buses, as shown in Figure 4. In this system, there is a variety of AC

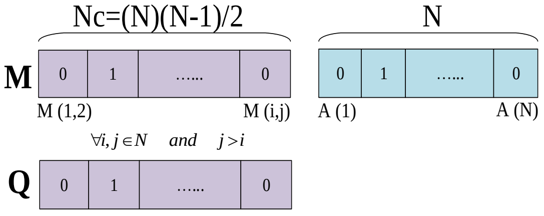


Figure 3. Proposed chromosome structure

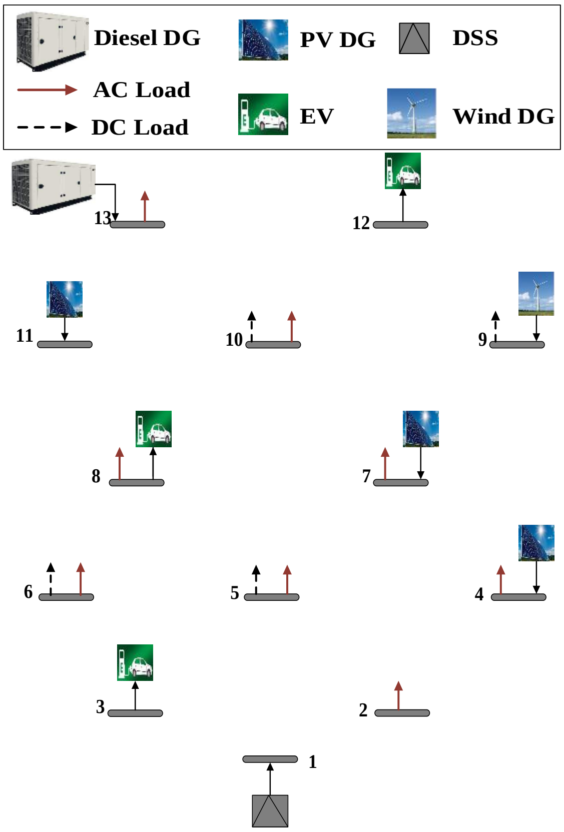


Figure 4. The studied system

and DC-type loads and sources. The distribution substation (DSS) is connected to bus 1. All input information required in this system is extracted from literature (7). 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 300, 150, 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. In the following, the AC and AC/DC distribution system planning under 4 cases have been discussed.

4. 1. Case 1: Distribution System Planning and Comparison

In this case, the AC and AC/DC system planning problem has been addressed without considering the risk constraint. The purpose of implementing this case is to show the validity of the proposed method. By implementing this case, the optimal structure of AC and AC/DC distribution system planning has been achieved, similar to the optimal structure of the AC and AC/DC distribution system (7). Also, the results were compared with the reported data in literature and also presented in Table 1. Therefore, the sameness of the optimal structure of the AC and AC/DC distribution system, as well as the comparison of the cost results of this case with the mentioned reference, shows the correctness of the optimization method.

In Tables 1 and 2, a and b show AC and AC/DC distribution system planning, respectively.

4. 2. Case 2: Distribution System Planning under Risk Less than 20%

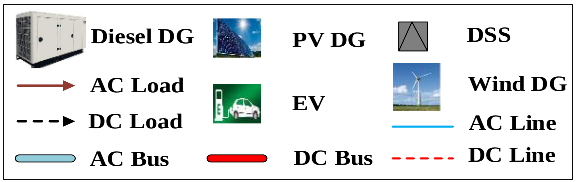
In this case, the distribution system planning has been done considering the risk of less than 20%. From the implementation of this case, the optimal planning structure of the AC and AC/DC distribution system has been obtained according to Figures 5 and 6, respectively. The results of planning costs under a risk of less than 20% are given in Table 2. In AC system planning, all buses and lines are of AC type. Therefore, in this planning, only the system structure is the decision variable of the optimization algorithm. However, in AC/DC system planning, the type of lines and buses, as well as the system structure is determined by the optimization algorithm. In AC planning, because all lines and buses are of AC type, more converters are needed in this planning. This increase in the number of converters leads to increase in investment costs and total planning costs. The results in Table 2 under the risk of less than 20% show that the lowest planning costs are related to AC/DC network planning. According to the studied network, buses 11 and 12 are composed of PV and EV, respectively. In the optimal AC network planning (Figure 5), a converter is

TABLE 1. The results of costs in the distribution system from the implementation of case 1

Type	Case	LC M$	VSCC M$	INVC M$	TC M$
a	Case 1	1.7136	2.0485	3.7621	47.3564
	[7]	1.7136	2.0485	3.7621	47.3567
b	Case 1	1.2264	1.7595	2.9859	45.6586
	[7]	1.2264	1.7595	2.9859	45.6596

TABLE 2. Cost of different distribution systems under different conditions

Case	Type	LC M$	VSCC M$	INVC M$	TC M$
Case 2	a	1.5120	2.0485	3.5605	44.7625
	b	1.2152	1.5725	2.7877	39.4667
Case 3	a	1.6128	2.0485	3.6613	45.1517
	b	1.2152	1.5725	2.7933	42.4984
Case 4	a	1.6464	2.0485	3.6949	46.6823
	b	1.2208	1.6575	2.8783	45.1494



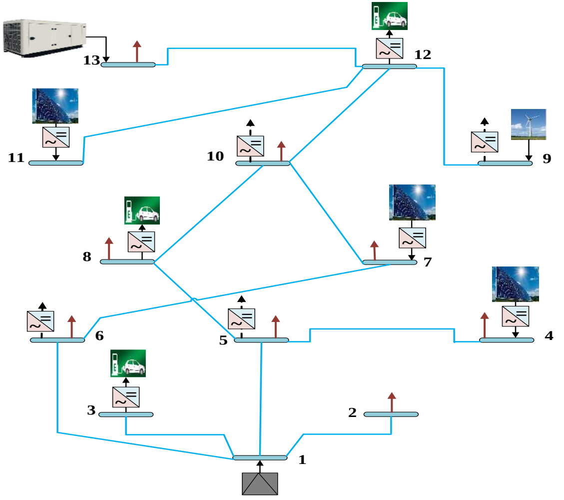


Figure 5. The optimal structure of AC distribution system under case 2

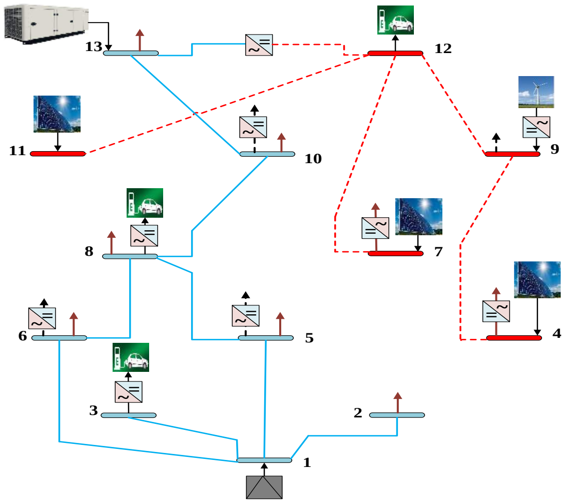


Figure 6. The optimal structure of AC/DC distribution system under case 2

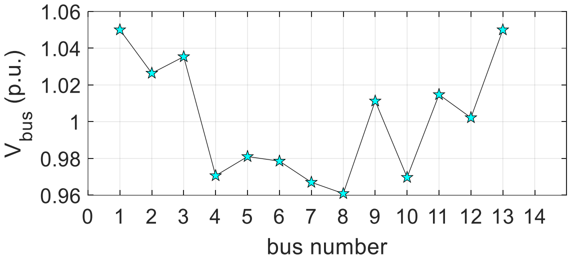


Figure 7. Bus voltage profile for AC distribution system under case 2

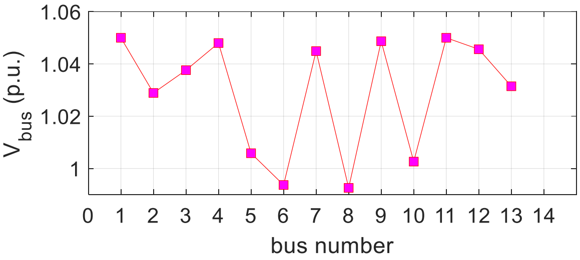


Figure 8. Bus voltage profile for AC/DC distribution system under case 2

4. 3. Case 3: Distribution System Planning under Risk Less than 10%

In this case, the goal is to find the AC and AC/DC distribution system planning where the risk is less than 10%. The results of planning costs from the implementation of this case are given in Table 2. The optimal planning structure of AC and AC/DC distribution system is also shown in Figures 9 and 10, respectively. Also, the bus voltage profile for AC and AC/DC system planning is shown in Figures 11 and 12, respectively. According to the results of this case, AC/DC distribution system planning has lower costs than AC system planning. Therefore, by planning the AC/DC distribution system, it is possible to achieve an optimal structure with minimum planning costs. Also, according to the results of this case, with the reduction of risk, all planning costs have increased compared to the results of the previous case.

4. 4. Case 4: Distribution System Planning under Zero Risk

In this case, the problem of distribution system planning has been discussed, considering the condition of zero risk. Therefore, in AC system planning, the goal is to find an optimal structure in which risk does not occur. Also, in AC/DC planning, the goal is to find the type of buses and lines as well as the system structure so that the risk of the problem is zero. The results of this case are presented in Table 2. The optimal structure and bus voltage profile for AC and AC/DC system planning under zero risk are shown in Figures 13 to 16. According to the results of Table 2, when the planning problem is implemented under zero risk, the costs of AC and AC/DC system planning have increased compared to the previous two cases. Therefore, reducing the risk of the problem leads to an increase in planning costs. The results of this case are similar to the results of cases 2 and 3, indicating that AC/DC system planning has lower planning costs than AC system planning. In AC/DC planning, the type of buses and lines and the system structure are determined by the optimization algorithm with the aim of the lowest planning costs. However, in AC planning, the algorithm only determines the system structure and the type of buses and lines that are fixed AC.

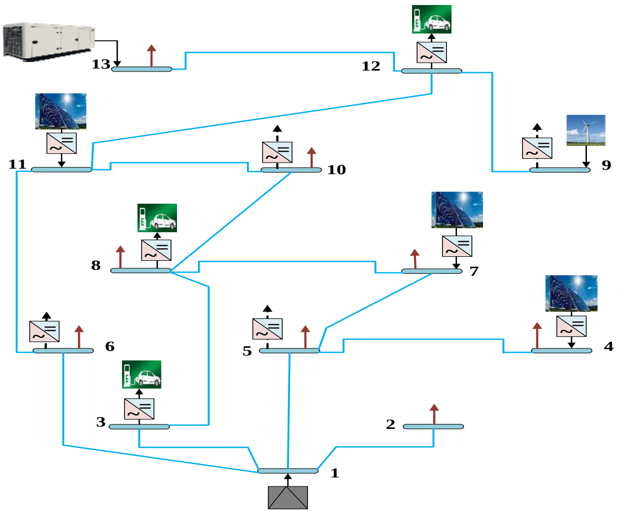


Figure 9. The optimal structure of AC distribution system under case 3

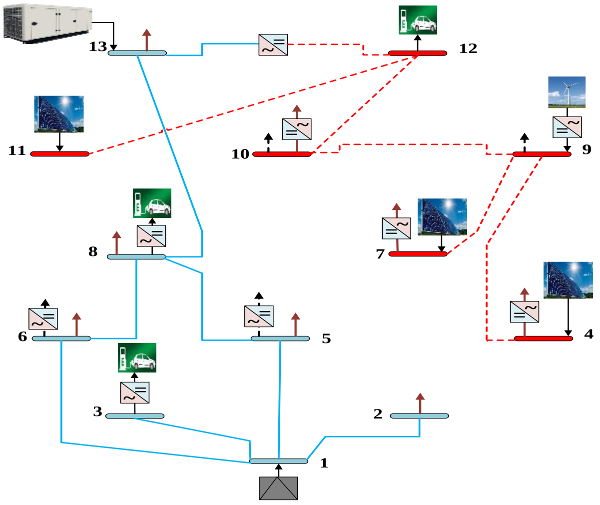


Figure 10. The optimal structure of AC/DC distribution system under case 3

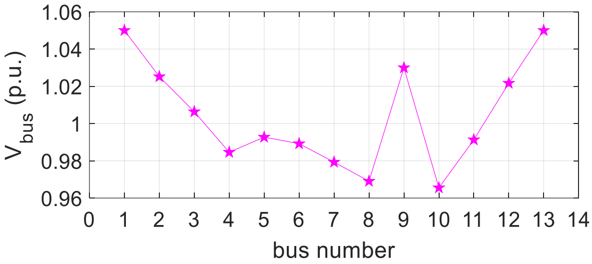


Figure 11. Bus voltage profile for AC distribution system under case 3

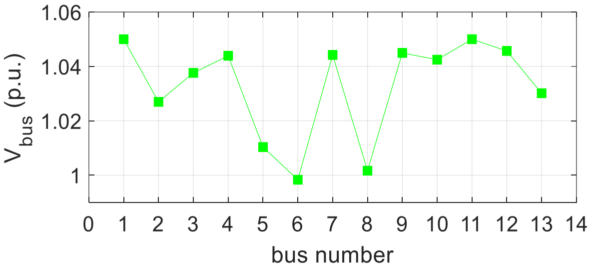


Figure 12. Bus voltage profile for AC/DC distribution system under case 3

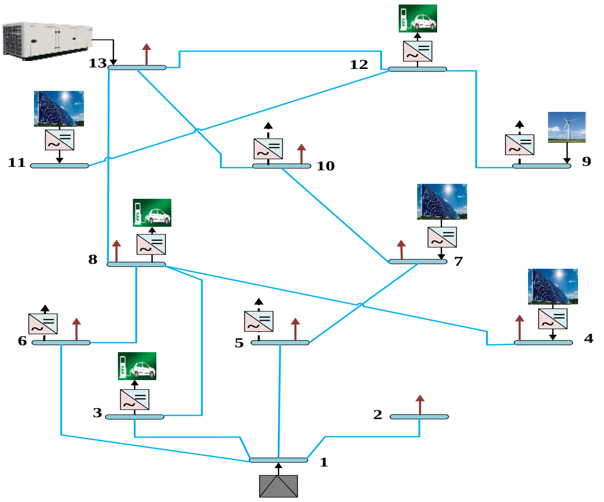


Figure 13. The optimal structure of AC distribution system under case 4

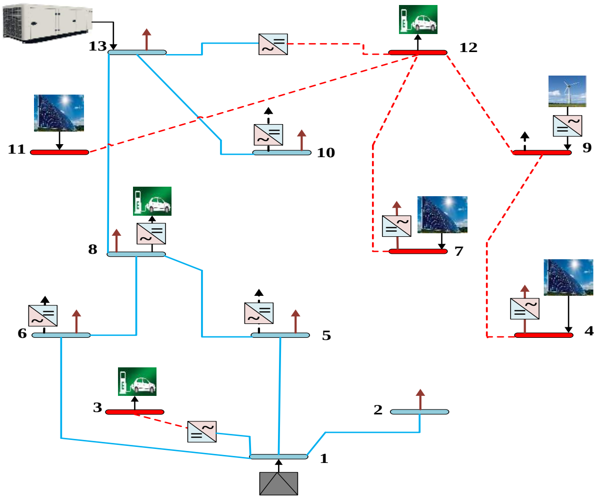


Figure 14. The optimal structure of AC/DC distribution system under case 4

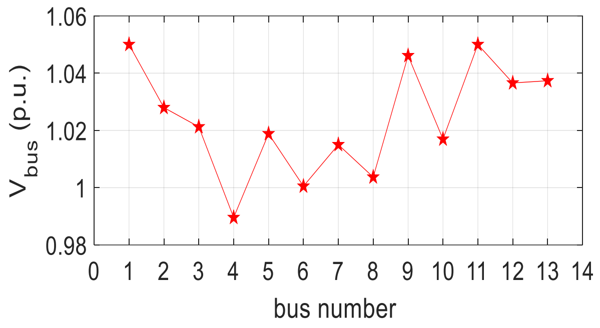


Figure 15. Bus voltage profile for AC distribution system under case 4

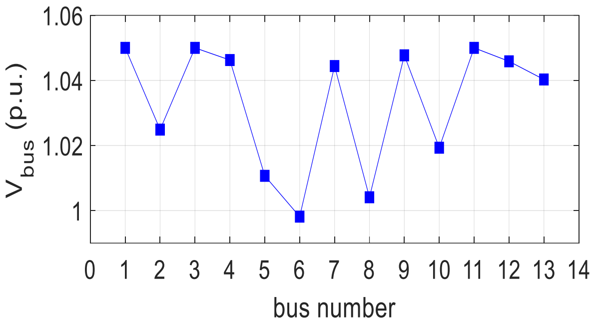


Figure 16. Bus voltage profile for AC/DC distribution system under case 4

In this paper, the planning problem is implemented under 4 cases that include planning without considering risk, considering risk less than 20%, less than 10%, and zero risk. In the first case, the planning results are compared with the mentioned reference results, and the correctness of the proposed method has been demonstrated. In cases 2 to 4, the planning problem has been implemented by reducing risk value. As shown in Figures 17 to 19, planning costs have increased with the reduction of risk. On the other hand, in all implemented cases, the minimum cost is related to AC/DC system planning. Therefore, optimal planning can be achieved by AC/DC planning under different risk levels.

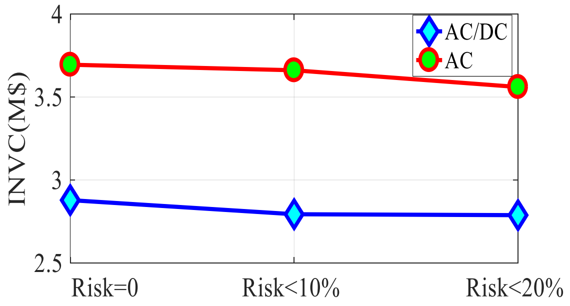


Figure 17. Planning results of investment costs under different risk levels

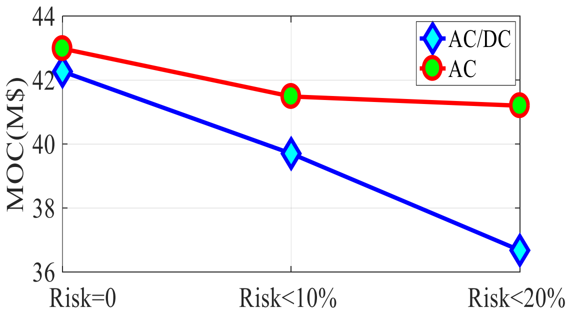


Figure 18. Planning results of maintenance and operation costs under different risk levels

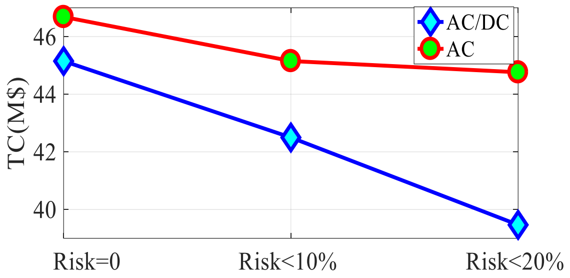


Figure 19. Planning results of total costs under different risk levels

TABLE 3. Values of random variables for a scenario

Type	a	b
Load Demand	54.14 %	48.57 %
EV Demand	44.08 %	37.53 %
Wind-DG Power	84.73 %	84.69 %
PV-DG Power	14.79 %	13.41 %

5. CONCLUSION

Today, in traditional distribution systems (of AC type), the multiplicity of loads and energy sources of DC type has made it uneconomical to continue in this system. Therefore, a solution can be to switch to an AC/DC distribution system due to the presence of various loads and energy sources. In this paper, the AC/DC distribution system planning is discussed. On the other hand, the uncertainties related to the forecasting of load demand and renewable DG output power cause the possible behavior of the distribution system. This behavior leads to risk in the distribution system. The K-means clustering method has been used to model the uncertainties in the problem. The goal of the problem is to minimize the investment and operation costs of the plan under possible risks to the network. The proposed mathematical model has been solved in the MATLAB/GAMS hybrid space. The effectiveness of the proposed model is demonstrated by applying it to a distribution test system. In this paper, the planning problem has been tested under 4 cases. In the first case, the goal is the correctness of the proposed method. In cases 2 to 4, planning has been done by reducing the value of risk. According to the results obtained from these cases, it can be concluded that reducing the value of risk leads to an increase in planning costs. The results of AC/DC system planning show that due to AC and DC buses and lines in this system, optimal planning can be achieved with the goal of minimum planning costs. The results of numerical studies show that changes in the value of risk impact the planning problem.

6. REFERENCES

1. Shahnia F, Arefi A, Ledwich G. Electric distribution network planning: Springer; 2018.
2. Zhang L, Liang J, Tang W, Li G, Cai Y, Sheng W. Converting AC distribution lines to DC to increase transfer capacities and DG penetration. IEEE Transactions on Smart Grid. 2018;10(2):1477-87. https://doi.org/10.1109/TSG.2017.2768392
3. Liu X, Liu Y, Liu J, Xiang Y, Yuan X. Optimal planning of AC-DC hybrid transmission and distributed energy resource system: Review and prospects. CSEE Journal of Power and Energy Systems. 2019;5(3):409-22. https://doi.org/10.17775/CSEEJPES.2019.00540
4. Wang L, Yuan M, Zhang F, Wang X, Dai L, Zhao F. Risk assessment of distribution networks integrating large-scale distributed photovoltaics. IEEE Access. 2019;7:59653-64. https://doi.org/10.1109/ACCESS.2019.2912804
5. Bhuiyan MZA, Anders GJ, Philhower J, Du S. Review of static risk-based security assessment in power system. IET Cyber-Physical Systems: Theory & Applications. 2019;4(3):233-9. https://doi.org/10.1049/iet-cps.2018.5080
6. Wawrzyniak K, Urresti Padrón E, Gomulski K, Korab R, Jaworski W. Methodology of risk assessment and decomposition in power grid applications. IET Generation, Transmission & Distribution. 2018;12(15):3666-72. https://doi.org/ 10.1049/iet-gtd.2017.1731
7. Ahmed HM, Eltantawy AB, Salama MM. A planning approach for the network configuration of AC-DC hybrid distribution systems. IEEE Transactions on Smart Grid. 2016;9(3):2203-13. https://doi.org/10.1109/TSG.2016.2608508
8. Ahmed HM, Eltantawy AB, Salama M. A reliability-based stochastic planning framework for AC-DC hybrid smart distribution systems. International Journal of Electrical Power & Energy Systems. 2019;107:10-8. https://doi.org/10.1016/j.ijepes.2018.11.003
9. Wang C, Ding Z, Zhang X, He Z, Liu H, Xu Z, editors. Bi-level Programming of AC/DC Hybrid Distribution System. 2021 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia); 2021: IEEE.
10. Wang Z, Zhong L, Pan Z, Yu T, Qiu X. Optimal double Q AC-DC hybrid distribution system planning with explicit topology-variable-based reliability assessment. Applied Energy. 2022;322:119438. https://doi.org/10.1016/j.apenergy.2022.119438
11. Huang L, Chen Z, Cui Q, Zhang J, Wang H, Shu J. Optimal planning of renewable energy source and energy storage in a medium-and low-voltage distributed AC/DC system in China. The Journal of Engineering. 2019;2019(16):2354-61. https://doi.org/10.1049/joe.2018.8546
12. Sabzian-Molaee Z, Rokrok E, Doostizadeh M. An optimal master-slave model for stochastic planning of AC-DC hybrid distribution systems. Journal of Renewable Energy and Environment. 2023;10(2):27-38. https://doi.org/10.30501/jree.2022.323167.1309
13. Sabzian-Molaee Z, Rokrok E, Doostizadeh M. An optimal planning model for AC-DC distribution systems considering the converter lifetime. International Journal of Electrical Power & Energy Systems. 2022;138:107911. https://doi.org/10.1016/j.ijepes.2021.107911
14. Wang J, Zhao H, Hu E, Zhang Z, Shen Z, Zhao G, et al., editors. Distributed Generation Capacity Planning Method of AC/DC Hybrid Distribution Network Based on Different Functions of Energy Storage. 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2); 2020: IEEE.
15. Yin D, Mei F, Zheng J. An AC/DC distribution network DG planning problem: A genetic-ant colony hybrid algorithm approach. Applied Sciences. 2019;9(6):1212. https://doi.org/10.3390/app9061212
16. Wu X, Wang Z, Ding T, Li Z. Hybrid AC/DC microgrid planning with optimal placement of DC feeders. Energies. 2019;12(9):1751. https://doi.org/10.3390/en12091751
17. Sun Z, Yan Z, Sharen G, Liang T, Liu X, Yin H, editors. Network Planning of AC/DC hybrid microgrid with Power Electronic Transformers. 2020 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC); 2020: IEEE.
18. Rezaei O, Mirzapour O, Panahazari M, Gholami H. Hybrid AC/DC provisional microgrid planning model considering converter aging. Electricity. 2022;3(2):236-50. https://doi.org/10.3390/electricity3020014
19. Ghiasi M. Detailed study, multi-objective optimization, and design of an AC-DC smart microgrid with hybrid renewable energy resources. Energy. 2019;169:496-507. https://doi.org/10.1016/j.energy.2018.12.083
20. Yang Y, Pei W, Huo Q, Sun J, Xu F. Coordinate planning of multiple microgrids and distribution network with mixed AC/DC interconnection method. Energy Procedia. 2018;145:313-8. https://doi.org/10.1016/j.egypro.2018.04.057
21. Rousis AO, Konstantelos I, Strbac G. A planning model for a hybrid AC–DC microgrid using a novel GA/AC OPF algorithm. IEEE Transactions on Power Systems. 2019;35(1):227-37. https://doi.org/10.1109/TPWRS.2019.2924137
22. Wu Z, Liu P, Gu W, Huang H, Han J. A bi-level planning approach for hybrid AC-DC distribution system considering N-1 security criterion. Applied energy. 2018;230:417-28. https://doi.org/10.1016/j.apenergy.2018.08.110
23. Shen Y, Wu G, Zheng H, Deng J, Shi P, editors. Research on key technology of planning and design for AC/DC hybrid distribution network. AIP Conference Proceedings; 2018: AIP Publishing.
24. Wu Z, Sun Q, Gu W, Chen Y, Xu H, Zhang J. AC/DC hybrid distribution system expansion planning under long-term uncertainty considering flexible investment. IEEE Access. 2020;8:94956-67. https://doi.org/10.1109/ACCESS.2020.2990697
25. de Barros HF, Alvarez-Herault M-C, Raison B, Tran QT. Optimal AC/DC Distribution Systems Expansion Planning from DSO's Perspective Considering Topological Constraints. IEEE Transactions on Power Delivery. 2023. https://doi.org/10.1109/TPWRD.2023.3277089
26. Liu P, Wu Z, Gu W, Lu Y, Yang X, Sun K, et al. Security-constrained AC–DC hybrid distribution system expansion planning with high penetration of renewable energy. International Journal of Electrical Power & Energy Systems. 2022;142:108285. https://doi.org/10.1016/j.ijepes.2022.108285
27. Fan H, Wang C, Liu L, Li X. Review of uncertainty modeling for optimal operation of integrated energy system. Frontiers in energy

research. 2022;9:641337. https://doi.org/10.3389/fenrg.2021.641337

28. Sheikhahmadi P, Bahramara S, Moshtagh J, Damavandi MY. A risk-based approach for modeling the strategic behavior of a distribution company in wholesale energy market. Applied energy. 2018;214:24-38. https://doi.org/10.1016/j.apenergy.2018.01.051
29. Hemmati M, Mohammadi-Ivatloo B, Ghasemzadeh S, Reihani E. Risk-based optimal scheduling of reconfigurable smart renewable energy based microgrids. International Journal of Electrical Power & Energy Systems. 2018;101:415-28. https://doi.org/10.1016/j.ijepes.2018.04.005
30. Gholami M, Sanjari MJ. Optimal Operation of Multi-Microgrid System Considering Uncertainty of Electric Vehicles. International Journal of Engineering. 2023;36(8). https://doi.org/10.5829/ije.2023.36.08b.01
31. Galvani S, Choogan M. Data clustering based probabilistic optimal power flow in power systems. IET Generation, Transmission & Distribution. 2019;13(2):181-8. https://doi.org/10.1049/iet-gtd.2018.5832
32. Khanalizadeh Eini M, Mirhosseini Moghadam M, Tavakoli A, Alizadeh B. Stability Analysis of AC/DC Microgrids in Island Mode. International Journal of Engineering. 2021;34(7):1750-65. https://doi.org/10.5829/ije.2021.34.07a.20
33. Hamad AA, Nassar ME, El-Saadany EF, Salama M. Optimal configuration of isolated hybrid AC/DC microgrids. IEEE Transactions on Smart Grid. 2018;10(3):2789-98. https://doi.org/10.1109/TSG.2018.2810310

Persian Abstract

چکیده

حرکت رو به رشد استفاده از تولیدات پراکنده و بارهای الکتریکی از نوع DC، منجر به تغییرات قابل توجهی در سمت تولید و تقاضا در شبکه‌ی توزیع انرژی الکتریکی گردیده است. از اینرو به دلیل حضور منابع انرژی و بارها از نوع DC و AC ادامه دادن در شبکه توزیع AC مقرون به‌صرفه نمی‌باشد. بنابراین برنامه‌ریزی شبکه‌ی توزیع AC/DC گزینه مناسبی است که به یک برنامه‌ریزی اقتصادی، مطمئن و ایمن در حضور تنوع بارها و منابع انرژی می‌توان دست یافت. از طرفی عدم‌قطعیت‌های موجود در پیش‌بینی تقاضای بار و توان تولیدی منابع انرژی باعث رفتار احتمالی شبکه‌ی توزیع می گردد. این رفتار، شبکه‌ی توزیع را در معرض ریسک قرار می‌دهد. در مقاله پیش‌رو به برنامه‌ریزی شبکه‌ی توزیع ترکیبی AC/DC مبتنی بر ریسک پرداخته شده است. برای مدل‌سازی عدم‌قطعیت‌های موجود در مسأله از روش خوشه‌بندی K-means استفاده شده است. همچنین مسأله برنامه‌ریزی در قالب مدل بهینه‌سازی با هدف کاهش هزینه‌های طرح تحت ریسک نأشی از عدم‌قطعیت‌ها در فضای hybrid MATLAB/GAMS فرموله‌بندی ریاضی و حل شده است. کارایی روش بیان شده با انجام مطالعات عددی بر روی شبکه‌ی توزیع نمونه نشان داده شده است.