OPTIMAL MEDIUM VOLTAGE NETWORK PLANNING UNDER LOAD FORECASTING UNCERTAINTY

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ABSTRACT

The long-term expansion planning of distribution networks is a complicated and challenging optimization problem. The complexity of the long –term planning will be increase in the presence of load forecasting errors. This paper presents a probabilistic multistage expansion planning method to overcome the load forecasting error, pseudo dynamic behavior of network parameters and geographical constraints. The optimal route of MV feeders are obtained for both mid and long-term cases with deterministic and probabilistic modeling through the new Imperialist Competitive Algorithm (ICA) developed for the optimal expansion planning of distribution network. In order to check the radial structure of the network obtained in any iteration of ICA, a novel algorithm is employed. The results are compared by Monte Carlo Simulation (MCS) method. Based on the results it is possible to plan the long-term distribution networks more robust and flexible by probabilistic modelling of uncertainty in load forecasting methods.
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INTRODUCTION

Electric power distribution system is one of main subdivisions of electric power system, which is more highlighted in smart grid environment and acts as a connection between the power transmission network and the consumers. Long-term planning of distribution networks encounters with some inevitable problems, such as financial constraints that lead to some uncertainties in the planning development. So it will be an efficient work to evaluate and resolve the planning problem in different distinct periods of time considering the planned network in the previous time periods. This method of planning is called multistage planning which can be helpful in order to overcome the pseudo dynamic behavior of network parameters. In [1]-[3] the complexity of optimal distribution system planning is studied. The ICA optimization algorithm is implemented to obtain the optimal configuration for distribution system [4]. Many attractive paper are prepared about optimal distribution planning [5]-[8]. A multistage expansion planning model is proposed in [9] in order to consider a dynamic behavior for distribution system planning under uncertainties because of asset management and geographical constraints. In the papers [10] a multi-objective model is proposed that aims the distribution system planning with two conflicting objectives. The multi-objective problem solved using tradeoff analysis of the Pareto-optimality principle [11]. A Multistage Distribution network Expansion Planning (MDEP) is presented in the presence of Distributed Generations (DGs) in a multi-objective optimization framework in [12].

FORMULATION OF OPTIMAL FEEDER ROUTING

In this paper a novel algorithm is used to check the radial structure of the network in any iteration of ICA during all simulation process. In the distribution system planning especially from the feeder routing aspect, the first step is to determine the candidate routes for MV feeders based on the cost of construction and operation considering electrical, geographical and asset constraints. Supposing that location MV substations are determined previously, in this stage MV substation is modeled as load points of the network. According to ICA optimization procedure, each country used during optimization is a vector with binary structure as shown in Fig. 1. This vector is represented the candidate MV feeders' route. In order to keep the radial structure of the network and simultaneously preserving the probabilistic nature of the problem, at any iteration of optimization process the vectors (countries) of the ICA is manipulated in a random manner as shown in Fig. 1. All MV substations in the system must be supplied by HV substations. So the feeder route must be contained of all HV and MV substations with a radial structure. In order to check radial structure of the network during simulation process, a novel method is applied.

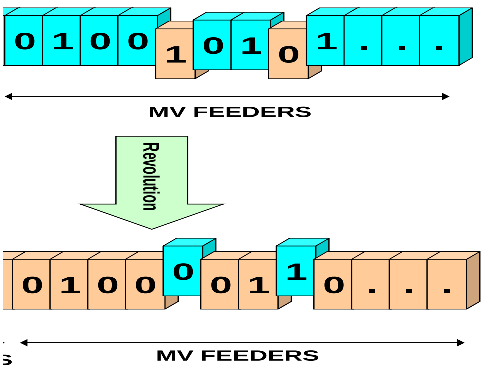


Fig. 1. Revolution process in ICA

During simulation process number of the "1" entries in the any country as shown in the Fig. 1 is fixed and equal to number of the nodes minus one. On the other hand the "1" entries in this vector must be arranged such that the resulted graph be connected. Consider that the new countries are generated such that the above conditions are satisfied. The revolution procedure of each country is shown in Fig. 1. In this procedure the number of "1" in the country should not be changed because of satisfying the above first condition. On the other hand the country must be as a connected graph in order to satisfying the second condition. In this procedure only a solution is accepted that satisfies the above both conditions and the others must be removed from simulation process.

In this paper the cost function used for optimal distribution network planning is as (1) which is derived from [1].

The network constraints in this planning process are presented in (6).

$$Min\ CF = \sum_{HV=1}^{N_{HV}} FC_{HV} + \sum_{F=1}^{N_F} \left[FC_F + \beta I_F^2 R_F \right] \tag{1}$$

$$S.T \quad not\,(Ring\ in\ the\ network)$$

$$I_F < I_{\max,F} \quad F = 1,2,...,N_F$$

$$\sum_{F=1}^{N_F} (R_F \cos(\phi_F) + X_F \sin(\phi_F)) I_F < AVD_{\max}$$

$$\sum_{MV=1}^{N_{MV}} \sqrt{3} V_{LL} I_{LL,F_{MV}} < S_{HV} \quad HV = 1,2,...,N_{HV} \tag{2}$$

Where:

N_{HV}	Total number of HV substations
HV	HV substation counter
N_F	Total number of MV feeders
FC_{HV}	Fixed cost of HV substation S_h
$\cos(\phi_f)$	Power factor of load in feeder F_f
FC_F	Fixed cost of MV feeder F_f
β and γ	Parameters randomly modify colonies search area
d	Distance between colony and the imperialist
F	MV feeders counter
λ	Energy loss cost factor.
R_F	Resistance of feeder F
X_F	Reactance of feeder F
MV	Medium voltage substations (loads) counter
N_{MV}	Number of MV substations of a HV substation
$I_{\max,F}$	Maximum loading level of MV feeder in pu
$AVD_{\max}$	Acceptable voltage drop at end of feeders
V_{LL}	Line voltage in pu
S_{HV}	HV substation capacity
$I_{LL,F}$	Line voltage in pu

The cost function in (1) is designed such that the cost of loss in the feeders as well as the cost of newly installed feeders should be minimized. This minimization is implemented considering electrical constraints in (2) and some geographical constraints with considering the candidate feeders' routes as input data.

ALGORITHM TO CHECK THE RADIAL STRUCTURE OF THE NETWORK CONFIGURATION

This section presents a novel algorithm to solve the spanning tree problem [13]-[14]. This algorithm investigates two features of a tree in order to diagnose that the graph is tree or not. Any tree has two features:

- Supposing that the number of vertices of the tree is n, so the number of edges is $n-1$.
- The tree is a connected graph.

Supposing that the number of vertices in a simple graph is n, so the number of edges in every tree is $n-1$.

On the other hand, the method used to discover the connectivity or disconnectivity of the graph is described as follows. Considering L and E as the Laplacian matrix and incidence matrix respectively, there is:

$$L = EE^T \tag{3}$$

So it can be concluded that:

$$rank\,(L) = rank\,(E) \tag{4}$$

According to [23], if the graph is connected, then

$$rank\,(\mathrm{L}) = n-1 \tag{5}$$

And if it is disconnected, then

$$rank\,(\mathrm{L}) < n-1 \tag{6}$$

However, matrix L can be obtained through this method: Considering G as a simple graph with n vertices, its Laplacian matrix L is defined as the difference of the graph's degree matrix D (a diagonal matrix with vertex degrees on the diagonals) and its adjacency matrix A (a (0,1)-matrix with 1's at places corresponding to entries where the vertices are adjacent and 0's otherwise):

$$L = D - A \tag{7}$$

Where the elements of L will be concluded as follows:

$$l_{ij} = \begin{cases} \deg(v_i) & if \quad i = j \\ -1 & if \quad i \neq j \quad and \quad v_i \ is\ adjacent\ to\ v_j \\ 0 & otherwise \end{cases} \tag{8}$$

Where $\deg(v_i)$ is degree of the vertex i.

In this paper, these two results are used simultaneously to generate initial countries, assimilate colonies and revolve colonies. A detailed and step by step illustration of this algorithm combined with ICA is shown in Fig. 2.

SIMULATION AND RESULTS

This section contains the results of optimal planning of distribution system based on presented algorithm with probabilistic methods. All simulation and graphical results obtained using MATLAB software. The optimal routes of feeders are implemented in a multistage manner for two cases containing mid (5 years) and long-term (10 years) planning periods. The suitability and efficiency of the proposed method for Optimal Feeder Routing (OFR) should be investigated. The obtained graphical results are important from the network experts and planners view point to have a visualization of the optimally planned network graphically. Hence a graphical representation of the results is used.

Uncertainty in long-term load forecasting error is one of the major problems. In this sub-section the main contribution of the paper will be presented. The probabilistic multistage expansion planning method results is presented here. In this case the error in mid and long-term load forecasting is modeled as a normal distribution function with zero mean value and the standard deviation of the forecasted errors. The maximum forecasting errors are 5% and 10% for mid and long-term cases respectively. To have a statistic study on this network, 500 load samples are selected based on Monte Carlo Simulation (MCS) method. In this step the ICA is repeated 500 times to obtained 500 optimal network configuration for mid and long-term cases. For each simulation a load sample is obtained from (9). Therefore, electric load is modeled as a normal probability distribution function (PDF) as follows:

$$PDF(P_l) = \frac{1}{\sqrt{2\pi\sigma_L}} \exp\left(-\frac{(P_l - \mu_L)^2}{2\sigma_L{}^2}\right) \tag{9}$$

Where $PDF(P_l)$ is the PDF of the load applied to the network, and μ_L and σ_L are the mean and standard deviation of the forecasted load. Because of different amount of load points (sample) for each time of simulation, different topology of feeders is obtained for each simulation. It is implemented for both mid-term and long-term planning cases. In Fig. 2 and Fig. 3 the best configuration of the planned networks for mid and long-term cases in deterministic planning are given. Beside the best topologies of network in probabilistic planning are indicated in Fig. 4 and Fig. 5 for mid-term and long-term cases respectively. The best configuration for probabilistic long-term planning is represented in Fig. 5 that is relatively different form the long-term deterministic case (Fig. 3).

Table 1 shows the number of selections or repetition for every feeder of the obtained topology in a descending manner for the long-term case under different loading conditions in probabilistic modeling. According to this table for 500 repetitions to evaluate the effects of different load samples at optimal network configuration, there are different selection rate for each feeder. For example feeder number 3 (Bus1-Bus9) is selected for all load sample, while feeder number 39 (Bus14- Bus15) is selected 123 times of 500 samples. Base on the above discussion the capability of the feeder 3 is higher than feeder 39. In other words feeders with higher selections are more change to appear at the final network configuration. This leads to an optimal network with more robustness and flexibility. Feeders with highest number of selections among the obtained different networks for 500 samples are selected while all loads point connected as final best configuration.

A statistical study on the obtained network is implemented. Considering the correlation of input and output network variables, by probabilistic modeling of load forecasting uncertainty, the output variables such as bus voltage and feeder current can show a probabilistic behavior. For example some statistical outputs of the long-term case network are illustrated in Fig. 6(a-d).The sub-figures show the histogram of current in Feeder 1 (From bus 1 to bus 13), loss in feeder 1 (From bus 1 to bus 13), voltage of bus 2 and load distribution respectively for long-term case Fig. 13 depicts the voltage drop of all buses and total loss of the network for long-term case. Regarding the histogram of the output variables, they can be modeled as a normal distribution function. Based on the above discussion the mean and standard deviation of the results for every feeder of the optimal network are given in Tables 2 for the long-term planning case.

Table 1 Number of selections of each feeder at 500 load samples in probabilistic planning in long-term case

Feeder Number	From Bus	To Bus	Number of selections	Feeder Number	From Bus	To Bus	Number of selections
3	1	9	500	39	14	15	123
7	3	7	500	33	12	13	112
53	23	24	500	22	8	9	88
46	18	19	494	42	14	20	83
45	16	21	490	49	20	21	65
2	1	14	485	20	7	11	63
56	25	26	483	32	11	16	59
6	2	6	481	10	4	12	48
8	4	5	481	55	24	25	45
43	15	16	476	65	19	22	38
34	12	17	475	11	4	17	25
23	8	12	473	5	2	5	23
54	23	28	466	59	20	26	13
47	18	22	462	38	13	19	12
50	21	26	461	41	14	19	10
31	11	15	460	48	19	20	9
25	9	10	451	37	13	18	7
19	7	10	443	30	10	14	4
4	1	20	402	64	18	23	4
24	8	13	397	12	5	6	3
17	6	9	366	14	5	9	3
51	22	23	356	62	19	23	3
1	1	13	335	29	10	15	2
44	15	20	332	15	5	12	0
13	5	8	322	16	6	8	0
57	27	28	279	21	7	15	0
26	9	13	262	28	10	11	0
63	27	28	221	35	12	18	0
18	6	10	171	40	14	18	0
52	22	28	171	58	20	25	0
9	4	8	155	60	20	24	0
36	13	14	155	61	19	24	0
27	9	14	153				

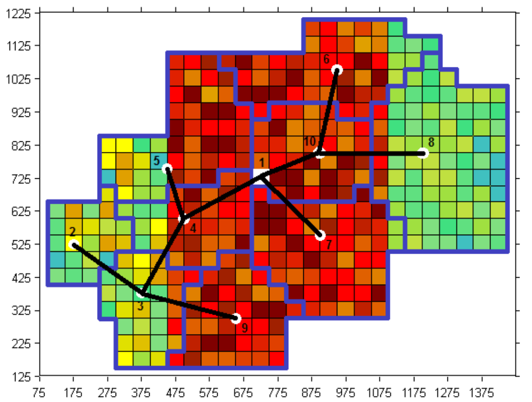


Fig.2. Optimal network configuration for -Mid-term -(deterministic)

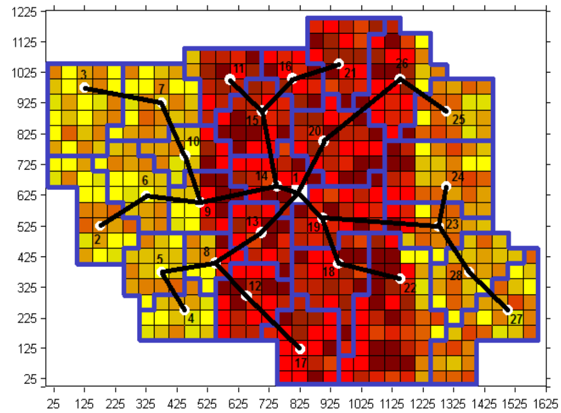


Fig. 3. Optimal network configuration for long-term -(deterministic)

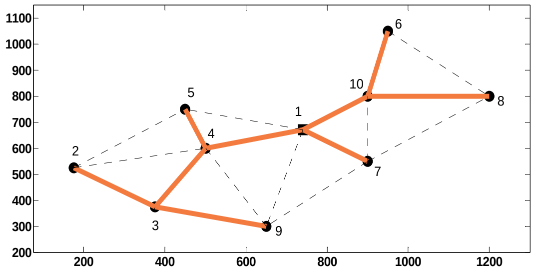


Fig. 4. Optimal network configuration for mid-term -(probabilistic)

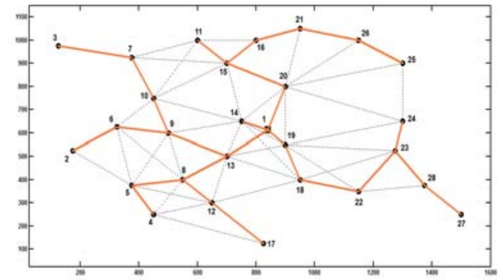


Fig. 5. Optimal network configuration for long-term -(probabilistic)

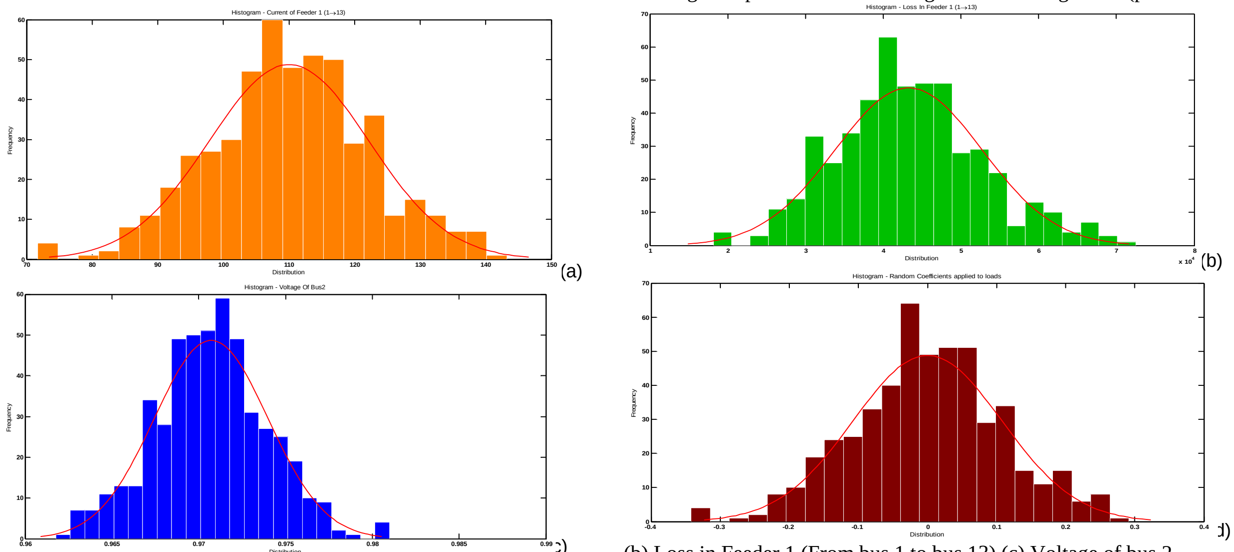
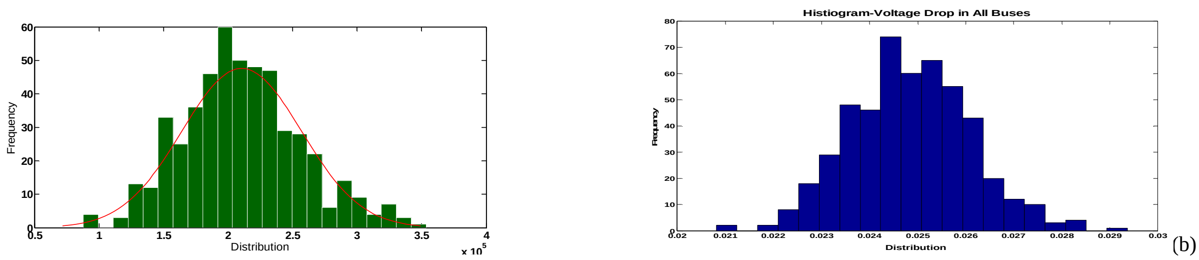


Fig. 6. Histogram of (a) Current in Feeder 1 (From bus 1 to bus 13) (b) Loss in Feeder 1 (From bus 1 to bus 13) (c) Voltage of bus 2 (d) Load distribution– In long-term case



(a) (b)

Fig. 7. Histogram of (a) Total network losses (b) Voltage drop in all buses–Long-term case – (probabilistic)

Table 2 Mean and Std of current of feeders in obtained network for long-term case (probabilistic)

Feeder Number	From Bus	To Bus	Mean	Std	Feeder Number	From Bus	To Bus	Mean	Std
1	1	13	110.019	12.181	31	11	15	9.356	1.033
2	1	14	9.8559	1.062	34	12	17	12.772	1.413
3	1	19	100.957	11.226	43	15	16	43.441	4.849
4	1	20	79.645	8.825	44	15	20	64.241	7.145
6	2	6	10.222	1.134	45	16	21	36.322	4.059
7	3	7	12.551	1.401	46	18	19	88.786	9.907
8	4	5	6.5434	0.722	47	18	22	75.107	8.406
13	5	8	13.698	1.511	50	21	26	24.568	2.750
17	6	9	18.689	2.073	51	22	23	48.110	5.407
19	7	10	22.853	2.549	53	23	24	15.391	1.727
23	8	12	24.553	2.714	54	23	28	24.137	2.718
24	8	13	43.652	4.821	56	25	26	9.761	1.093
25	9	10	30.360	3.382	57	27	28	14.388	1.621
26	9	13	57.567	6.397					

CONCLUSION

In this paper a framework for optimal MV feeders routing problem under load forecasting uncertainty is proposed. A novel routing algorithm is proposed to check the radial structure of the network during simulation process. In the proposed method the optimal routes of MV feeders are obtained considering load forecasting error, with the goal of minimization of total investment and operational costs subject to the electrical and topological constraints. In order to overcome dynamic behavior of the planning parameters, multistage expansion planning is implemented in mid and long-term planning cases both for deterministic and probabilistic load model. Optimal network configuration is compared with deterministic results. A statistical analysis is used to determine the main network parameters in the presence of uncertainty. The presented numerical results demonstrate the efficiency and capability of this methodology for real size distribution networks. The results show that it is possible to plan the future network more robust and flexible by probabilistic modelling of uncertainty in load forecasting methods.

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