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Considering DG in Expansion Planning of Subtransmission System

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***Abstract*— Deregulation has been obtained new options in the design and planning of the power system. One of these options is the integration of Distributed Generation (DG) into the power system. In this paper, the presence of distributed generation is regarded as another alternative for supplying the load of subtransmission system. The effects of DG on expansion planning of subtransmission system have been modeled as an optimization problem where the Genetic Algorithm (GA) and Linear Programming (LP) are employed to solve it. The proposed approach is applied to a realistic subtransmission system and the results are evaluated.**

***Keywords*— Expansion Planning, Distributed Generation; GA; LP; Subtransmission Lines.**

I. Introduction

Subtransmission networks are composed of subtransmission substation and lines which connect the transmission networks with distribution ones. With consumption growth of the loads, the existing subtransmission network must be able to reliably feed the distribution substations. If not, the existing network loses its adequacy and needs to be expanded [1, 2].

The aim of Subtransmission System Expansion Planning (SSEP) is to propose and decide network reinforcements and new installations that minimize the expected total network cost in the horizon year with adequate reliability [1]. In the conventional methods, SSEP is implemented by installation of new substations and lines or by upgrade of existing ones. Up to now, several researches have been done on expansion planning of substations [3, 4]. Transmission and subtransmission network's structures are similar, however the size of subtransmission networks is, in general, smaller than the size of the transmission ones and in subtransmission system, the number of connected generators is fewer. Several researches have formulated the expansion planning of the lines and have employed different methods to obtain optimal solution [5, 6]. Integration of small generators called Distributed Generations (DG) into power system, which are the result of deregulation and advances in technology, has obtained new options for expansion and design of distribution networks [7, 8]. Hence, the design of power system considering the use of DG as a new alternative should be regarded and the related problem must be formulated. In the recent years, different studies have been done on allocation of distributed generations in distribution networks. In most of them, given an existing network, optimal location and size of DGs for installation on different buses of network to reach different goals such as: reduction of losses [8], improving the voltage profile [9] and improvement of the reliability indices [10] have been investigated. Few researches have been done on the expansion planning of subtranmission system considering the use of distributed generation. In 2001, for the first time, a Successive Elimination Algorithm (SEA) for expansion of subtransmission system, considering the use of distributed generation on the substations, was presented [11]. In this work, assuming that the load of each substation is specified, the optimal capacity of substations, location and size of distributed generations as well as transmission lines are investigated and the impact of using the distributed generation on reduction of total expansion costs is discussed. In [12] the same problem is solved using genetic algorithm and the results are compared with those of SEA. In this study, the objective function includes the cost of installed substations, the cost of transformers added to the network and capital cost of DG units. However, the annual variation of load and operational costs of DGs have not been considered in the problem solution.

In this paper, the effects of using the distributed generation on the expansion planning of subtransmission system have been evaluated. This problem has been modeled from viewpoint of electric companies as a static planning [6]. In the proposed objective function the fix and variable costs and constraints related to the network and operation of substations and DGs have been considered. The optimal capacity of DG units and substations and also the optimal configuration of subtransmission lines for supplying the load of subtransmission system are determined so that the total cost of expansion plan is minimized. The proposed objective function and its constraints, compose an optimization problem which is solved using genetic algorithm and linear programming. The effectiveness of the proposed method is shown by its application on a typical subtransmission system and the results are compared with expansion planning of subtransmission system without the use of the distributed generation.

II. Problem Description

A. Components of expansion costs

The aim of subtransmission system expansion planning considering the distributed generation is to provide the needed energy for supplying the load of the system so that the total expansion cost is minimized with respect to the problem constraints. In this paper, this problem has been modeled as a static expansion planning. Problem unknowns include the expanded capacity of existing substations; capacity of new substations; location and capacity of new subtransmission lines; location and size of DG units. Expansion costs can be divided into two parts: investment (fixed) costs and variable (operation and maintenance) costs. Fixed costs are one-time costs that are spent during construction and installation of substations, lines and DG units does not depend on the intended loading variation to be served after operation. Variable costs exist as the system is in service and depends on the loading required [13]. The fixed costs include:

- Cost of land for new substations
- Cost of transformer and substations' equipment
- Cost of new lines construction
- Cost of installation of DG units

The variable costs of plan include:

- Cost of DG unit's operation
- Cost of purchased power from the upward grid (Transmission network)

In section III, the mathematical model of expansion costs and their combination as objective function are given.

B. Load model of subtransmission substations

Further to transmission network, DG units, as another alternative, can serve some part of the load. Thus, in addition to determining the location and size of DG units, their way of operation must be determined. Therefore, modeling of the substation's loads with their peak value is not sufficient but the annual load variation must be considered. In this paper, the loads of substations have been modeled as linear three-level approximation of Load Duration Curve (LDC) according to Fig. 1. This curve can be obtained from power consumption history of substations in the load forecasting studies [14].

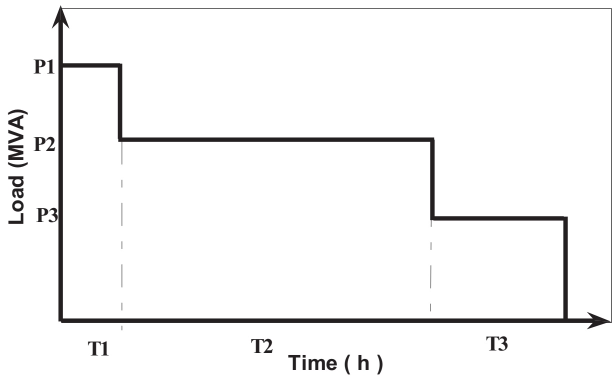

Fig. 1. Load-Duration Curve for substation's load

III. Mathematical Modeling

A. Problem variables

The decision variables of problem are:

- Location and size of DG units
- Amount of supplied power by transmission network and DG units in each load level
- New subtransmisson lines

B. Objective function

Mathematical model of the proposed objective function is (1):

$$\begin{aligned} MinF = SIC + SEC + DGIC \\ + LCC + DGOC + EC \end{aligned} \tag{1}$$

In the objective function, economic evaluation is based on present-worth cost of the plans. Thus, the fixed costs are imported in the objective function without any change, but the variable costs are considered as their present-worth value in the objective function. The objective function includes six parts which are described below in details.

1) Substations Installation Cost (SIC)

This part of objective function includes the cost of land, equipment and transformers for new substations.

2) Substation Expansion Cost (SEC)

This part is the cost of additional transformers for increasing the capacity of existing substations.

3) Distributed generations Installation Cost (DGIC)

The cost of DG unit's forms this part of objective function is:

$$DGIC = \sum_{i=1}^{ns} C_{DG} S_i^{DG} \tag{2}$$

DG units are installed as modules of particular capacities e.g. 5 MW.

4) Lines Construction Cost (LCC)

Construction cost of the lines between subtransmission substations and also between subtransmission substations and transmission network composes LCC according to (3):

$$LCC = \sum_{i,j=1, i \neq j}^{ns} cl_{ij} . n_{ij} \quad (3)$$

Cost of each line ($cl_{ij} . n_{ij}$) is dependent on its type (capacity and impedance), length and number of its circuits.

5) DGs' Operation Cost (DGOC)

DGs Operation Cost is the cost of maintenance and also fuel for DG units. The present-worth cost of DGs operation cost is calculated using (4) [15]:

$$DGOC = \beta^t \sum_{i=1}^{ns} \sum_{d=1}^{nld} P_{i,d}^{DG} T_d K_{DG} \quad (4)$$

6) Electricity Cost (EC)

Electric companies must pay for the electric energy which they receive from the transmission system via subtransmission substations. In addition, the cost of active power can be different in different load levels. Usually it is high in the peak hours and is low in other times. The present-worth cost of providing the energy of subtransmission system from the transmission network is given by (5).

$$EC = \beta^t \sum_{i=1}^{ng} \sum_{d=1}^{nld} P_{i,d}^{G} T_d K_d^{G} \quad (5)$$

C. Problem constranits

With regards to the limitations governing the network and operation of equipment, it is essential to consider the following constraints in the model.

1) Limitation on substations loading

In this paper, the possibility of single contingency on the transformers of substations has been regarded in choosing the substations' capacity. In this way, in the case of single contingency on the transformers of a substation, other transformers of that substation must not be overloaded.

2) operational constraint of DG units

The loading of each DG unit must be less than its capacity as (6).

$$0 \le P_i^{DG} \le S_i^{DG} \qquad i = 1,2,..., ndg \quad (6)$$

In the design of distribution networks in the presence of distributed generation, it is tried to provide the majority of the load from transmission network via subtransmission system not from DG units [15]. Therefore, in this study, the maximum amount of power generated by DGs is considered as (7).

$$\sum_{i=1}^{ns} P_{i,d}^{DG} \le 0.3\, D_d \quad d = 1,2,..., nld \quad (7)$$

3) Capacity limitation of new installed substations and existing expanded substations

Usually, there is a limitation on installing the new substations or expanding the existing ones, such that we can not install or expand a substation more than a specific capacity due to technical and geographical constraints. This limitation is expressed by (8).

$$0 \le S_{s,i} \le S_{s,i}^{\max} \qquad , i = 1,2,..., ns \quad (8)$$

Despite that DG units need small site area; however there is a limitation for installing DG units which can be regarded as:

$$0 \le n_i^{DG} \le n_{i\max}^{DG} \qquad i = 1,2,..., ns \quad (9)$$

4) Maximum constructible circuits for the subtransmission lines

This constraint is expressed as (10) and states that the constructed circuits in each corridor must be fewer than the maximum constructible circuits in that corridor.

$$0 \le n_{ij} + n_{ij}^0 \le n_{ij}^{\max} \qquad i, j = 1,2,.., ns \quad (10)$$

5) Loading limit of subtransmission lines

The reliability for subtransmission lines is considered as reserve factor [16]. Loading of the lines in different load levels must be less than maximum loading limit as follows:

$$\left| P_{ij,d} \right| \le (1 - rfl) \left| P_{ij}^{\max} \right| \quad (11)$$

Where, *rfl* is the reserve factor for the lines. The reserve factor is considered to make sure that the lines are not overloaded in the case of contingency on the other lines. Moreover, for prevention of substations islanding in single contingencies of lines, at least two lines must be connected to each substation [17].

D. Chromosome structure in genetic algorithm

The flowchart and operators of genetic algorithm have been thoroughly discussed in [18-20]. The chromosome considered in this problem is consisted of two parts as shown in Fig. 2. In the first part of the chromosome, the value of i[th] gene expresses the number of DG units (with a predetermined size for each unit) on the i[th] substation. The value of each gene in the second part of chromosome is the number of circuits of subtransmission lines in the corresponding corridor.

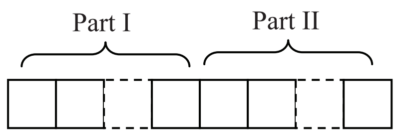

Fig. 2. The structure of the proposed chromosome

E. Chromosome decoding and calculation of objective function components

With respect to the proposed chromosome, the optimal capacity of existing and new substations and their related costs and also the cost of installed DGs are calculated with decoding part I of the chromosome and regarding the load of each substation. The cost of lines also is calculated by decoding part II. Now it is turn to calculate the optimal power generation of DG units and the power purchased from the transmission network. The proposed method for calculation of these components of objective function is explained in the next subsection.

F. Performing the Linear Programming (LP)

Providing the needed energy of subtransmission system from the transmission network imposes an expense for the electric companies. In addition, supplying the whole load of subtransmission system by DGs is not economical.

Therefore, the participation degree of transmission system and DG units in providing the energy of subtransmission system must be determined. For a given chromosome (the number of DG units on each substation, the number of lines, and also the load of each substation are known), a subsidiary optimization in each iteration of genetic algorithm is performed using linear programming to find the optimal generated power of DG units and also the optimal amount of power provided from the transmission system in each load level. The objective function of LP is the sum of DGs' operation cost and electricity cost of purchased power from the transmission network as (12).

$$\textit{Minimize} \quad F_{LP} = DGOC + EC \qquad (12)$$

The constraints of LP are as follows:

$$PG_{id} - PD_{id} - \sum_{j=1}^{ns} P_{ij,d} = 0 \qquad (13)$$

$$P_{ij,d} = \frac{\theta_{id} - \theta_{jd}}{X_{ij}} \qquad (14)$$

$$\left| P_{ij,d} \right| \le (1 - rfl) \left| P_{ij}^{\max} \right| \qquad (15)$$

$$0 \le P_{i,d}^{DG} \le S_i^{DG} \qquad d = 1,2,\ldots,nld \qquad (16)$$

Equations (13) and (14) are the relations of DC load flow. By performing the LP, the generated power by DG units and power purchased from the transmission network in each load level are determined and the related costs are calculated. The flowchart of the proposed method is shown in Fig. 3.

IV. NUMERICAL RESULTS

The proposed objective function and its constraints compose an optimization problem where the genetic algorithm is employed to solve it. To evaluate the effectiveness of the proposed method, a basic example has been designed and then some tests have been done on it. The network which is used to test the proposed idea is consisted of nine 63kv substations; three of them are new installed substations which must be connected to the network. These substations are fed by two 230/63kV transmission substations. The one-line diagram of the test network is depicted in Fig. 4 and the specification of its substations is given in Appendix. The loads of substations are given in three load levels in Appendix. All the corridors between substations are regarded as candidate for the construction. The capacities of existing and candidate lines are 25 and 50 MVA. The reserve factor for the lines is considered 30%. The DG units have the size of 5MW, and the maximum number of installable units on each substation is 4. Other required parameters are given in Table 1. To study the impact of the presence of the distributed generation as a new option for supplying the load of the system, considering the input data, the problem is solved in two cases:

- Case1: there are no installed DG units on the substations and the whole load of the subtransmission system is provided from the transmission network.
- Case 2: DG units can be installed on the subtransmission substations and can participate in supplying the load of system.

The results of the test including the capacities of expanded or installed substations, DG units installed on the substations and the constructed lines between substations are listed in Tables 2-4. The costs of the plan in two cases are given in Table 4. It can be seen that installation of DGs has resulted in the decrease in the expanded and installed capacities, such that the substations exist in the plan with lower capacities and costs. The presence of DG units has also decreased the need for more lines and the cost of lines construction has been reduced accordingly. Table 3 shows that in the load levels in which the electricity cost of transmission system is high, some part of the system's load is generated by DG units; in the load levels which the operational cost of DG units is high, most of the system's load is injected from the transmission network into subtransmission system, to reduce total operational cost. Considering the total cost of the plan, the expansion planning of subtransmission system by using distributed generation is more economical.

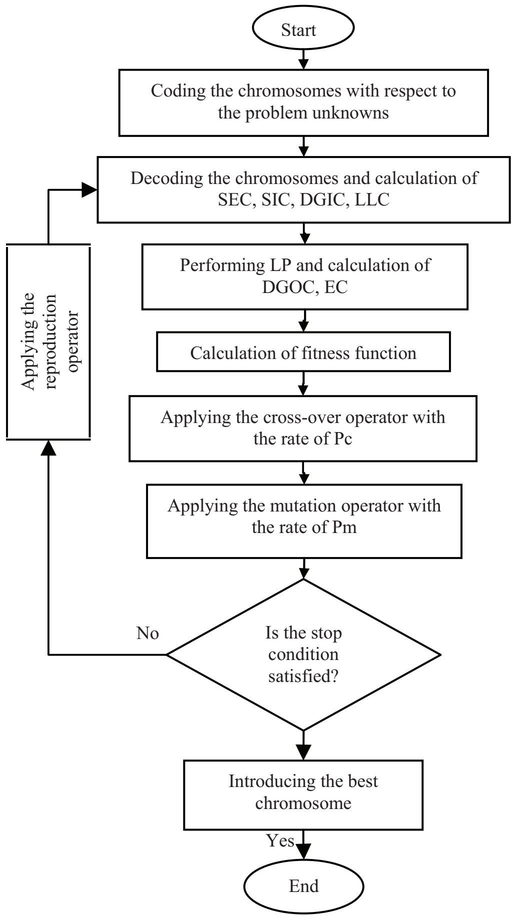

Fig. 3. The flowchart of the proposed approach

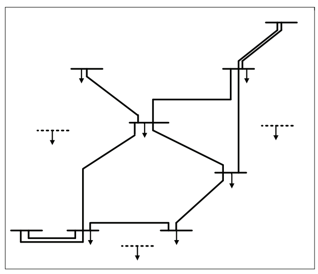

Fig. 4. The one-line diagram of the test network

TABLE I

TECHNICAL AND ECONOMIC DATA FOR THE STUDY

Parameter	Value
Electricity price in the first load level ($/MW-hr)	50
Electricity price in the second load level ($/MW-hr)	30
Electricity price in the third load level ($/MW-hr)	20
Installation cost of DG units ($/MW)	200000
Operational cost of DG units ($/MW-hr)	27
Horizon year	10
Discount rate (%)	12

TABLE II

RESULTS OF SUBSTATIONS EXPANSION IN TWO CASES

Substation name	Proposed capacity (MVA)	
	Case 1	Case 2
1	30	30
2	45	30
3	45	45
4	45	45
5	30	22.5
6	60	45
7	30	22.5
8	45	30
9	22.5	22.5

TABLE III

SPECIFICATION OF INSTALLED DGS ON THE SUBSTATIONS IN CASE 2

Substation name	The proposed capacity of DG (MW)	Loading of DGs in each load level (MW)		
		First	Second	Third
1	0	0	0	0
2	10	9.8	8.48	0
3	10	9.72	8.86	0
4	0	0	0	0
5	10	9.86	7.49	0
6	5	4.76	4.25	0
7	5	4.77	0	0
8	15	14.81	9.11	0
9	0	0	0	0

TABLE IV

THE RESULT OF CONSTRUCTED LINES IN CASE 1 AND 2

Case 1			Case 2		
From bus	To bus	Capacity (MVA)	From bus	To bus	Capacity (MVA)
1	6	1×25	1	7	1×25
1	9	1×25	1	9	1×25
2	9	1×25	3	8	1×25
2	HV1	1×50	5	6	1×25
3	7	1×25	7	9	1×25
3	8	1×25	8	HV2	1×50
4	8	1×25	-	-	-
7	HV1	1×50	-	-	-
8	HV2	1×50	-	-	-

TABLE V

THE COSTS OF TWO PLANS

Parameter (M$)	Experiment	
	Case1	Case 2
The cost of existing substation's expansion	1.45	1.05
The cost of new substation's installation	10	8
The cost of lines construction	23.42	12.01
Installation cost of DG units	0	11
Operational cost of DG units	0	2.19
The cost of purchased power from the transmission system	10.4	7.62
Total cost	45.27	41.87

V. CONCLUSION

The presence of the distributed generation has been provided new options in the design and planning of the power system. This can be had notable economic profits for the electric companies. In this paper, the effects of distributed generation as a new option for supplying the load of system, on the expansion planning of subtransmission system was modeled mathematically and evaluated. The proposed model was expressed by an optimization problem and solved using genetic algorithm and the linear programming. The results for application of the proposed method on the test network showed that the use of distributed generation in the expansion planning of subtransmission system provides more economical plans.

VI. NOMENCLATURE

θ_i	i^{th} substation's phase angle
β^t	Present-worth factor at year t
cl_{ij}	The cost of line installed in corridor *i-j* ($)
C_{DG}	DGs' installation cost ($/MW)
d	Discount rate
D_d	Total load of subtransmission system in d^{th} load level (MW)
F	Value of fitness function
K_d^G	Electricity price of the transmission system in the load level d ($/MW-hr)
K_{DG}	Operational cost of DG including the cost of fuel and maintenance ($/MW-hr)
n_{ij}^0	Number of existing circuits at corridor *i-j*
n_{ij}	Number of new constructed circuits at corridor *i-j*
$n_{ij}^{\max}$	Maximum permissible number of circuits at corridor *i-j*
$n_{i\max}^{DG}$	Maximum number of DG units on i^{th} substation
n_i^{DG}	Number of DG units on i^{th} substation
ng	Number of transmission substations
nld	Number of load levels
ns	Number of substations
$P_{ij,d}$	Flowing power at corridor *i-j* in the load level of d (MW)
$P_{ij}^{\max}$	Capacity of corridor *i-j* (MW)
PD_{id}	Load demand of i^{th} substation in d^{th} load level (MW)
$P_{i,d}^G$	Imported power to subtransmission system from i^{th} transmission substation in d^{th} load level (MW)
$P_{i,d}^{DG}$	The generated power of DG units installed on i^{th} substation in d^{th} load level (MW)
$P_{s,i}$	Loading of i^{th} substation (MW)
S_i^{DG}	Installed capacity of DG on i^{th} substations (MW).
$S_{s,i}$	Capacity of i^{th} substation (MW)
T_d	Duration of d^{th} load level (hr)

X_{ij} Reactance of line at corridor *i-j* (ohm)

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APPENDIX

TABLE VI
SPECIFICATION OF SUBSTATIONS

Substation name	Forecasted load in horizon year (MW)			Geographical position (km)		Existing capacity (MVA)	Expandable or installable capacity (MVA)	Voltage level (kv)	Power factor of the load
	First level	Second level	Third level	X	Y				
1	17	11.9	6.8	20	30	2×7.5	4×7.5	63/20	0.9
2	22	15.4	8.8	50	30	1×15	3×15	63/20	0.9
3	27	18.9	10.8	80	40	2×15	4×15	63/20	0.9
4	20	14	5	90	80	1×15	3×15	63/20	0.9
5	18	12.6	7.2	50	60	2×7.5	4×7.5	63/20	0.9
6	28	19.6	11.2	30	70	2×15	4×15	63/20	0.9
7	14	9.8	5.6	45	30	0	4×7.5	63/20	0.9
8	21	14.7	8.4	100	40	0	3×15	63/20	0.9
9	12	8.4	4.8	20	70	0	4×7.5	63/20	0.9
HV1	–	–	–	0	30	100	–	230/63	–
HV2	–	–	–	100	100	100	–	230/63	–