INTEGRATED AC/DC NETWORK PLANNING

Saeed MOUSAVIZADEH
Tarbiat Modares University – Iran
Saeed.mousavizadeh@modares.ac.ir

Mahmoud Reza HAGHIFAM
Tarbiat Modares University – Iran
haghifam@modares.ac.ir

ABSTRACT

Proliferation of DC output type Distributed Energy Resource (DER) units in the utility power systems, mostly at the distribution voltage levels, and also recent advancement in the power electronics devices have motivated the integration of DC microgrids as an integral part of AC grids. LVDC system is one of the newest technologies in the field of distribution networks. In this paper, economic design of hybrid AC/DC distribution networks are studied for bipolar LVDC system configurations, area with different load densities and different penetrations of distributed generation sources, considering various kinds of loads. Optimal connection configuration of load points and Distributed Generations to the AC and DC substations candidate points is determined by genetic algorithm considering investment, loss and also customer interruption costs. Afterward, final structure of network is designed by branch exchange method.

INTRODUCTION

The demand for higher quality and reliability of power distribution system, role of distribution system in reducing losses and pollutions have increased requirement for utilization of power electronic devices in distribution systems [1]. The low voltage DC distribution (LVDC) system is one of the latest primary technological innovations in electricity distribution and an interesting challenger to the AC low voltage networks. An LVDC distribution system constructs of power electronic converters and DC links between these converters. LVDC distribution system can be made with two basic implementations; unipolar 1500 VDC and bipolar ±750 VDC system. The differences between two connections are the number of voltage levels that costumers could connect to them. The LVDC network concept is discussed further in [2]. The LVDC distribution system entails more complex planning task than in the case of plain AC distribution. Introducing power electronics and DC networks in electricity distribution poses new challenges for the network planning. Partly they are due to the interaction and compatibility issues of the different part of the network and partly of course due to the power electronic converters themselves. In addition, the amount of possible solutions becomes vast, for instance, due to the possibility to combine both DC and AC technologies. In the planning calculations of the LVDC system, it is essential to process both AC and DC systems together to find the optimal solution for each case [3].
In this paper, economic design of hybrid AC/DC distribution networks are studied for bipolar LVDC system configuration, area with different load densities and different penetrations of distributed generation sources, considering various kinds of loads. First, it is assumed that the amount, location and type of AC and DC loads, as well as the production of distributed generation sources, their locations and types have been predicted. Also, the location and capacity of sub transmission substations are also specified. Distribution network design is done into three modes: designed pure AC network, pure DC network and hybrid AC/DC distribution network.
First, several points of study region are selected as candidate location for AC and DC substations. In cases one and two, determining optimal connection configuration of load points and DGs to candidate location is carried out by genetic algorithm considering investment cost, Customer Interruption Cost (CIC) and also loss cost and best locations are selected among candidate substation points. Afterward, branch exchange method is implemented for MV feeder routing and connection of selected substations to sub transmission substations. Finally, optimal LV feeder routing is implemented for each service area of selected substation points by branch exchange method. In designing pure DC network, MV network remains AC and with DC substation placement, LV network will convert to DC.
In the third case the GA algorithm is used to determine the capacity of DC and AC networks, in other words, which of the loads and distributed generation sources is more economic to be connected to AC network and which of them is more economic to be connected to DC network. Behind the works are similar to two previous cases.
By comparing the calculated costs for three proposed networks, it is determined that utilization of which networks for load feeding is economic.

COST FUNCTION

In this study, cost function is composed of installation cost of MV feeders, AC and DC substation construction cost including substation land cost, transformers and converters cost, installation cost of LV feeders, customer interruption cost and loss cost. Cost of equipments such as filters that required for power quality improvement in DC network, are considered on DC substation construction cost. General form of total cost equation can be written as below:

$$CF = \sum_{i=1}^{N_{MV}} MVIC_i + \sum_{j=1}^{N_s} (SCC_j + \sum_{k=1}^{N_{LVj}} LVIC_{jk}) + LC + CIC \qquad (1)$$

where CF is the cost function; N_{MV}, number of MV feeders; $MVIC_i$, the installation cost of ith MV feeder; N_s, number of selected substations; SCC_j, the construction cost of jth substation; N_{LVj}, the number of LV feeders on jth substation; $LVIC_{jk}$, the Installation Cost of kth LV feeder of jth substation; LC, the loss cost; CIC, customer interruption cost. Mentioned cost function is constructed with converting fix and variable cost of loss and reliability to present value during study period.

The total loss cost which is obtained during study period, composed of MV and LV feeders loss cost and cost of losses in AC and DC substations with their corresponding equipments. Also, these losses are obtained by implementing load flow in AC/DC distribution network by backward forward sweep and compensation based algorithms. Further information about these algorithms are available in [4-5].

Customer interruption cost is calculated by contingency analysis method during study period and includes cost of no sale of electrical energy during network interruption and customers' damage due to this interruption. To calculate these costs, Energy Not Supplied (ENS) index and Customer Damage Function (CDF) is used. This can show impact of customers' type on LVDC system's economic penetration rate. Also, CIC and loss costs must convert to present value by interest and inflation rate, then added to other costs [6].

OPTIMIZATION METHOD

Determining optimal AC and DC substation location among candidate points and also determination of service area of each substation is carried out by genetic algorithm. Firstly initial population is generated and evaluated by cost function. Each member of population which is called chromosome has a structure similar to Fig. 1.

Each chromosome in initial population has a quadratic structure in which its rows represent number of load points of network and also its columns represent number of candidate locations for substation points. Each array of this chromosome can take 0 or 1 and each row of any chromosome should take just one array with 1 value and other arrays of each row must take 0 values. This is because each load point can belong to just one substation point. This criterion is not necessary for columns and it might be a column with all 0 arrays in a particular chromosome because it is not necessary to select all of candidate substation points and just optimal substation points will be selected during optimization process. Each chromosome of initial population is randomly generated considering mentioned criterion and each chromosome is evaluated by cost function [7].

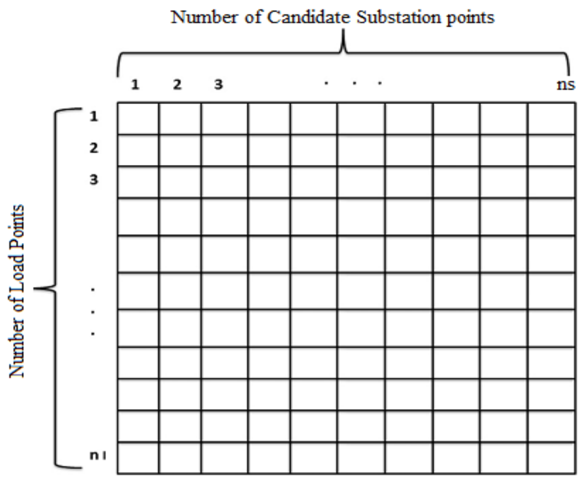

Fig. 1. Proposed structure for chromosomes

Using branch exchange technique which its details will be investigated in next section, optimal routes of equal network with optimal substation points are determined and optimal feeder routing in each substation service area is carried out by branch exchange technique too [7]. After determination of optimal routes of equal network, it is necessary to evaluate its cost. Mentioned stages are implemented for each chromosome of initial population and chromosomes of initial population are sorted based on their cost. Then crossover and mutation genetic operators are implemented to produce new population from initial population and their costs are evaluated similar to initial population. The general conditions for mutation operator are random, high frequency, and with few variations from the original member. The crossover operator is also random, with low frequency and produces new members with combined characteristics. These mechanisms guarantee iterative populations with new characteristics (mutation operator) and combined characteristics (crossover operator). Afterward, best chromosomes with minimum costs are selected among initial population and generated population by genetic operators. In the next iteration, genetic operators are implemented in the selected minimum cost population and new population is generated. Similar to previous stage, minimum cost chromosomes are selected and this procedure is repeated unless satisfying stop criteria [7-8].

Crossover operator

This operator uses two chromosomes as parent and two children are produced. Number of crossover operation is determined by crossover possibility factor [7]. For more details consider Fig. 2. As it is shown in this figure, in each implementation of crossover operator, two chromosomes are randomly selected from initial population and one row is selected randomly from parent chromosomes. Then two parts of chromosomes are replaced to generate child chromosomes. Cost evaluation of generated chromosomes is carried out similar to initial population chromosomes using cost function.

Parent 1

	S1	S2	S3	S4	S5	S6
LP1	1	0	0	0	0	0
LP2	0	0	0	1	0	0
LP3	0	1	0	0	0	0
LP4	0	0	0	1	0	0
LP5	0	0	0	1	0	0

Parent 2

	S1	S2	S3	S4	S5	S6
LP1	0	0	0	0	1	0
LP2	0	0	0	1	0	0
LP3	0	0	0	0	0	1
LP4	0	0	1	0	0	0
LP5	1	0	0	0	0	0

Child 1

	S1	S2	S3	S4	S5	S6
LP1	1	0	0	0	0	0
LP2	0	0	0	1	0	0
LP3	0	1	0	0	0	0
LP4	0	0	1	0	0	0
LP5	1	0	0	0	0	0

Child 2

	S1	S2	S3	S4	S5	S6
LP1	0	0	0	0	1	0
LP2	0	0	0	1	0	0
LP3	0	0	0	0	0	1
LP4	0	0	0	1	0	0
LP5	0	0	0	1	0	0

Fig. 2. Crossover operator

Mutation operator

This operator uses one chromosome as parent and one child is produced. Number of mutation operation is determined by mutation possibility factor. In each implementation of mutation operator, one chromosome is selected from initial population and two randomly selected columns are replaced to generate child chromosome. Afterward, cost of generated population is evaluated [7]. For illustration of this stage of optimization process, consider Fig. 3 in which parent chromosome consist of five load points and six candidate substation points. Then, childe chromosome is generated by genetic mutation operator.

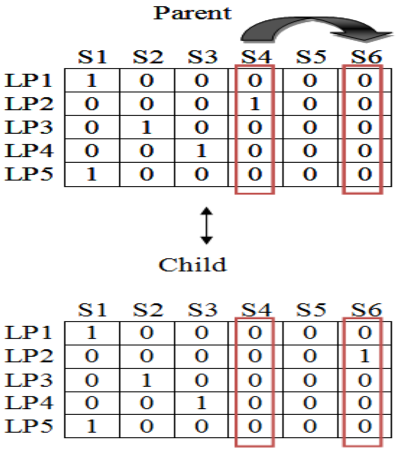

Fig. 3. Mutation Operator

BRANCH EXCHANGE ALGORITHM

In this paper the branch exchange method is used as optimal feeder routing algorithm. The branch exchange technique is one of well known methods for planning of distribution networks. Firstly a feasible configuration is created by connection each load to nearest substation which meets technical constraints (maximum allowable voltage drop and current flow). In this stage all branches are classified as ‘‘unmarked’’. Then, an unmarked branch is selected as Break Branch (BB) and the network is divided into two parts. In the next step, all possible links to connect separated parts together is detected. Each possible link is replaced with BB and overall cost of resulted network is evaluated using cost function. In this step backward– forward sweep load flow method in AC/DC network is used to loss calculation and also voltage drop of network branches. Also, optimal conductor is selected for each branch considering its current that calculated in backward phase. In each iteration of load flow, based on current of each branch, appropriate minimum cost conductor and its Ω/km is considered for that branch and load flow is repeated until convergence. In the final iteration optimal minimum cost conductor is obtained for each branch. Furthermore, contingency analysis is used to calculating CIC of the network [7].
If replacement of one of possible links with BB was not successful, then BB is restored and another branch is selected as BB. Then previous are repeated. But if the replacement was successful, the new branch is replaced with BB and all marked branches are changed to unmarked branches. Then previous steps are repeated. The algorithm is repeated until there is no unmark branch find to replace with new branches [7-8].

COMPUTATIONAL RESULTS

To demonstrate the application of the proposed method we considered the service area in Fig.3. Data of load points are shown in table 1. The loads of those load points which are not considered in table 1 are equal to zero. Two DGs that produce DC power are considered in this network and their powers are assumed 150 kW. AC residential and commercial loads power factor are assumed 0.9. Cost of LV feeders, C_{loss} and cost of energy assumed as 6000 $/km, 1.81 and 0.2 $/kWh, respectively. Furthermore, Customer Interruption Cost (CIC) per kilowatt-hour is considered 1 $/kWh and 10 $/kWh for residential and commercial respectively, but it could be calculated with CIC curves if it is necessary. Failure rate λ is considered 0.1 f/year.km, failure duration is considered 4 h per fault, MV feeder installation cost of conductor types one (Cat), two (Otter) and three (Raccoon) are considered 15,000, 10,000 and 5000 $/km. Cost for MV/LV and DC substations, based on their transformer and converter rating are used from [1-3], [6] and [9]. Interest and inflation rate are assumed as 18% and 15%, respectively. Minimum and maximum allowable loading are 20% and 80% of rated capacity of each substation. Maximum acceptable voltage drop from substation to load point is assumed as 3% of the circuit nominal voltage. Planning period assumed as 10 year. Proposed algorithm in this paper is simulated by MATLAB software and results are obtained as shown in Fig.5 and 6.

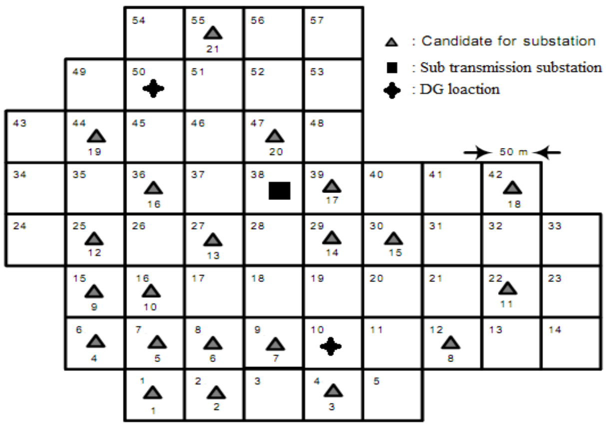

Fig. 4. Tested service area

Table 1 Load point data of selected service area in (kVA)

Residential									Commercial		
N	L	T	N	L	T	N	L	T	N	L	T
1	12	A	16	40	D	31	80	A	48	80	D
3	12	A	17	48	D	32	100	A	49	108	D
4	12	A	18	60	D	33	40	A	50	120	D
7	12	A	20	40	D	36	40	A	51	104	D
8	12	A	21	40	A	37	40	D	52	60	A
10	12	A	22	40	A	40	40	D	53	120	A
11	12	A	23	20	A	41	80	D	54	120	A
12	12	D	26	20	A	42	120	D	56	120	A
13	12	D	27	20	A	45	40	D	57	120	A
14	12	D	28	20	A	46	60	A			
15	40	D	30	60	A	47	68	A			

In table 1 following notation is used.
N: denotes number of load point on tested area.
L: denotes demand of load.
T: denotes load type.

A, D: denotes AC and DC.

Crossover and mutation operators rate are considered respectively 0.3 and 0.8. Maximum number of genetic optimization iteration is considered 60 with initial population of 15,000. Fig. 5 shows best costs for studied three cases.

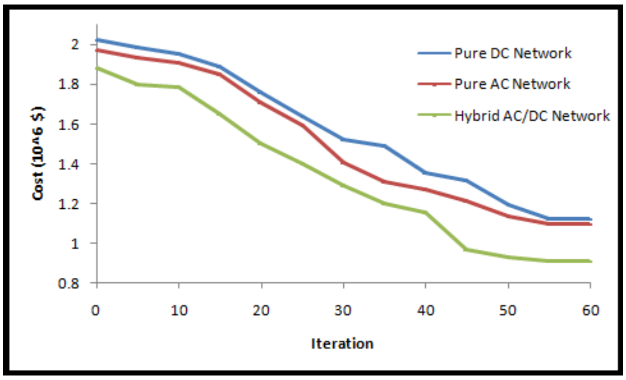

Fig. 5 Best cost of genetic iterations for three cases

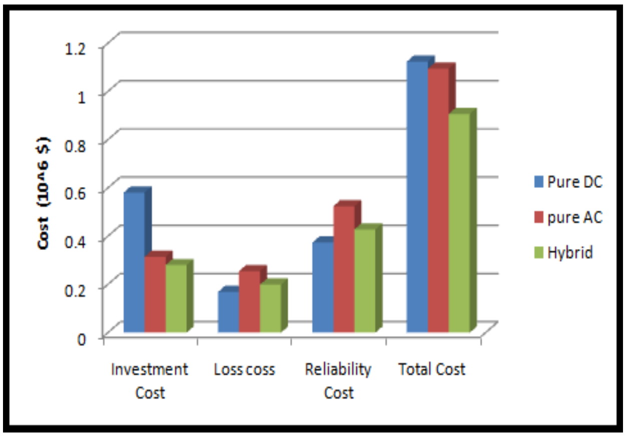

Fig. 6 Comparing cost of three cases

Also, selected location for AC and DC substation and theirs capacity in three mentioned cases are shown in table 2. Following notation is used:
N: Number of selected substation
L: Location of selected substation
C: Capacity of substation

Table 3. Number of Selected substations and their capacities

	AC Substation			DC Substation		
	N	L	C (KVA)	N	Lo	C (KVA)
Pure AC	3	6	250	0	----	----
		11	400			
		21	630			
Pure DC	0	----	----	4	7	300
					11	300
					19	300
					20	300
Hybrid AC/DC	2	7	250	2	14	300
		20	400		21	200

CONCLUSION

In this paper, planning problem is investigated in three cases: designing pure AC network, pure DC network and hybrid AC/DC distribution network. Optimal connection configuration of load points and Distributed Generations to the AC and DC substations candidate points is determined by genetic algorithm considering investment, loss and also customer interruption costs. Afterward, final structure of network is designed by branch exchange method. Simulation results on selected area show that hybrid AC/DC network implementation is more economic than pure AC and DC networks and utilization of power electronic devices in low voltage level, could improve distribution system economic.

REFERENCES

[1] J. Lassila, T. Kaipia, J. Haakana, J. Partanen, and K. Koivuranta, 2009, "Potential and strategic role of power electronics in electricity distribution systems," in *Electricity Distribution, CIRED, The 20th International Conference and Exhibition*, pp. 1-1.

[2] P. Nuutinen, P. Salonen, P. Peltoniemi, T. Kaipia, 2011, "Implementing a laboratory development platform for an LVDC distribution system," in *Smart Grid Communications (SmartGridComm), IEEE International Conference*, pp. 84-89.

[3] Kaipia, T. et al, 2008, "A Planning Methodology For Combined AC and DC Electricity Distribution Networks", *8th Nordic Distribution and Asset Management Conference NORDAC*, Bergen, Norway.

[4] Shirmohammadi, D.; Hong, H.W.; 1988, Semlyen, A.; Luo, G.X.; , "A compensation-based power flow method for weakly meshed distribution and transmission networks," *Power Systems, IEEE Transactions on* , vol.3, no.2, pp.753-762.

[5] Cheng, C.S.; Shirmohammadi, 1995, "A three-phase power flow method for real-time distribution system analysis," *Power Systems, IEEE Transactions on*, vol.10, no.2, pp.671-679.

[6] Ramezani, M.; Falaghi, H.; Haghifam, M.-R.; 2006, "Genetic based algorithm for optimal placement of distribution transformers", *Power Engineering Society General Meeting, IEEE*, vol., no., pp.5 pp.

[7] Javad Salehi, Mahmoud-Reza Haghifam, 2012, "Long term distribution network planning considering urbanity uncertainties", *International Journal of Electrical Power & Energy Systems*, vol 42, Pages 321-333.

[8] M.R Haghifam, M. Shahabi, 2002, "Optimal location and sizing of HV/MV substations in uncertainty load environment using genetic algorithm", *Electric Power Systems Research*, vol 63, Issue 1, Pages 37-50.

[9] Diaz-Dorado, E.; Pidre, J.C.; Garcia, E.M.; 2003, "Planning of large rural low-voltage networks using evolution strategies," *Power Systems, IEEE Transactions on* , vol.18, no.4, pp. 1594- 1600.