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Transforming an Existing Distribution Network into a Sustainable Autonomous Micro-grid

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ABSTRACT: A distribution network with renewable and fossil based resources can be operated as a micro-grid, in autonomous or non-autonomous modes. Owing to industrialization, there has been a steep increase in the electric power demand on contrary to the limited power generation facilities. In this context, a detailed methodology to develop a sustainable autonomous micro-grid is presented. The proposed methodology suggests novel sizing and siting strategies for distributed generators(DGs) and structural modifications for autonomous micro-grids. This paper optimal siting of renewable resources for autonomous operation are obtained using loss sensitivity factor. The proposed methodology is tested on IEEE 33-bus radial distribution systems. Results confirm the usefulness of the proposed loss sensitivity factor approach in optimal siting of renewable resources.

KEYWORDS: Distributed power generation, loadflow, power, reconfiguration, generation planning.

I.INTRODUCTION

A micro-grid is a localized grouping of electricity generation, energy storage, and loads that normally operate connected to a traditional centralized grid (macro-grid). Small micro-grids covering 30–50 km radius and power stations of 5–10 MW will serve the micro-grids, generate power locally to reduce dependence on long transmission lines and cut transmission losses. The Penetration of distributed generators into the conventional distribution system helps in operating the distribution network as a non-autonomous and autonomous micro-grid, reducing burden on efficient transmission of electrical power to long distances.For a presumed number of units, the optimal sizing of the units becomes inevitable for achieving stable operation of the micro-grids.The use of renewable energy sources in the micro-grid is seen as one of the important ways of reducing the carbon dioxide emissions.

In the reference paper [2] titled Alsaadi&Gholami have discussed an effective approach for distribution system power flow solution.An effective approach for unbalanced three-phase distribution power flow solutions is proposed. The bus injection to branch current matrix and the branch current to bus voltage matrix and a simple matrix multiplication are used to obtain power flow solutions for the radial distribution system. In the reference paper [13] Haesenhas et al dealt with the optimal placement and sizing of distributed generator units using genetic optimization algorithms. The authors describe how genetic optimization algorithms can be used to find the optimal size and location of distributed generation units in a residential distribution grid. The method is applied on a system based on an existing grid topology with production and residential load data based on measurements. The obtained optimal location and size prove to depend strongly on the given conditions.In the reference paper [8] Khoaet alhas discussed the Optimizing location and sizing of distributed generation in distribution systems. An algorithm using the primal dual interior point method for solving nonlinear optimal power flow problems is presented. Depending on the ratings and locations of DG units, the optimize location and sizing of distributed generation on distribution systems for reducing line loss was discussed.Paulo M. In the reference paper [11] De Oliveira-De Jesus dealt with the standard backward/forward sweep power flow method.The author describes a convenient formulation of the Backward/Forward (BW/FW) Sweep Power Flow applied to radial distribution systems with distributed generation. In the reference paper [16] SrinivasasRao et al have approached the optimal capacitor placement in a radial distribution system using plant growth simulation algorithm for the radial distribution network system.The solution methodology has two parts: in part one the loss

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sensitivity factors are used to select the candidate locations for the capacitor placement and in part two a new algorithm that employs Plant Growth Simulation Algorithm (PGSA) is used to estimate the optimal size of capacitors at the optimal buses was discussed. In the reference paper [17] VenkataKirthiga& Arul Daniel has discussed a methodology for transforming an existing distribution network into a sustainable autonomous micro-grid. The proposed methodology suggests novel sizing and siting strategies for distributed generators and structural modifications for autonomous micro-grids. The optimal sites and corresponding sizes of renewable resources for autonomous operation are obtained using particle swarm optimization and genetic algorithm-based optimization techniques. Structural modifications based on ranking of buses have been attempted for improving the voltage profile of the system, resulting in reduction of real power distribution losses.

II. PLANNING OF AUTOMONOUS MICRO-GRIDS

In this paper, a standard radial distribution system has been transformed into a micro-grid on introduction of DGs and is investigated for autonomous mode of operation. The radial structure and a relatively high R/X ratio of branches make any distribution system, ill conditioned. Hence minimization of distribution losses has been considered as the main objective in this paper which is achieved by determining the optimal location of DGs in a micro-grid.

A. Load Flow analysis:

Load flow analysis is essential in a sizing program since constraints such as bus voltage limits are included in the optimization problem to minimize the distribution losses.Backward and forward sweep algorithm exploits the radial nature of the distribution system and it is computationally more efficient when compared with the conventional load flow algorithms for a radial system. Among the many benefits of distributed generation is a reduced line loss, but depending on the ratings and locations of DG units, it is possible to have an increase in loss at very high penetration levels.Hence in this work, the basic Backward and Forward Sweep technique has been modified so as to suit the optimal sizing and siting of the distributed generation on distribution system for an autonomous micro-grid operation [11].

B. Loss Sensitivity factor:

The candidate nodes for the placement of DGs are determined by using the Loss sensitivity factors. The Loss Sensitivity Factors are determined from the losses obtained by base case load flow analysis as denoted by the following equations:-

$$\frac{\partial P_{lineloss\ (q)}}{\partial P_{eff}} = \frac{2 * P_{eff\,(q)} * R_k}{V^2{}_q}$$

$$\frac{\partial P_{lineloss\ (q)}}{\partial Q_{eff}} = \frac{2 * Q_{eff\,(q)} * R_k}{V^2{}_q}$$

$Q_{eff\,(q)}$ - is suppliedQ beyond the node ‘q’.

$P_{eff\,(q)}$ - is supplied P beyond the node ‘q’.

The above sensitivity factors are evaluated at each bus and all buses are ranked in descending order of the values of their sensitivity factors to form a priority list. The top-ranked buses in the priority list are chosen as the optimal locations for placement of DGs [16].

C. Optimal Number of DGs:

It is evident that structural modification of an existing radial distribution system into a partially mesh connected sustainable autonomous micro-grid, requiresDGs to be integrated into the network.The optimal size of these generators and the optimal siting of the same in the network are necessary for its autonomous operation. Hence a hierarchical methodology is attempted fordetermining the optimal sites and sizes of the generators and for transforming the network.

It is mandatory that the total connected DG units are needed to be satisfy the total demand and the system lossesof the distribution system. For obtaining the optimal number of DG units andthe corresponding sites for the DG placements, the followingmethodology is proposed.

1) An optimization problem is formulated for minimizing the distribution losses, including the constraints viz., generator rating constraint and voltage constraint.

2) For “r” generator units, the numbers of different possible combination of sites are taken from the ranking of the loss sensitivity factor methods.

3) The Genetic Algorithm (GA) technique is thenemployed for minimizing the optimization problem of loss minimization function, foreach of the combinations, where initially "r"is set to 1(1 to 6, randomly).
4) The optimal locations corresponding to the minimal distribution losses for each of the DG units are noted down for all the combinations.
5) The minimum distribution losses and hence the corresponding installation cost pertaining to "r" DG locationsare normalized on a ten point scale and the variation of theabove functions have been plotted against a varying "r". The normalized value of the function is

$$F_{norm} = 1 + \left(\frac{(F_x - F_{min})*(b-a)}{(F_{max} - F_{min})}\right) \quad (1)$$

Where,
$F_x$is actual value of the function;
F_{min} &F_{max} Are minimum and maximum values of F_x.
6) The number of DG sites for which both the curves intersects decided as the optimal number of DG units (taking onlyone DG unit at any given site), that is required to convertan existing distribution system into an autonomous micro-grid.
7) The siting combination pertaining to minimum distribution losses and minimum installation cost for the DG units is decided as the optimal siting of the DG units [17].

III.SIZING OF DISTRIBUTED GENERATORS

A. Problem Formulation:

The minimization objective function has been formulated with two objectives as given below equations.F_1 -corresponds to cost function of the generators and F_2 is for loss minimization. In this scenario, to exploit the complete potential of distributed generation, proper siting and sizing of DGs become important and the following motivated objectives are:

$$F_1 = \sum_{j=1}^{r} C_j * P_{gj} \quad (2)$$

$$F_2 = \sum_{i=1}^{N} \sum_{k=1}^{N} P_{loss\ jk} \quad (3)$$

Subject to

1. Generator rating constraint: Based on cost per unit peakpower generation, the minimum and maximum limits have been imposed on the generation capacity as

$$P_{gi\ min} \leq P_{gi} \leq P_{gi\ max} \quad (4)$$

2. Voltage constraint: The optimal sizing has to be obtainedsuch that there are no bus voltages limits violations. Hence the following constraint is included:

$$V_{min} \leq V_i \leq V_{max} \quad (5)$$

The multi-objective problem has been converted to a single objective function is:

$$F_x = \left(\sum_{i=1}^{N}\sum_{k=1}^{N} P_{loss\ jk}\right) + (V_{min} - V_{i\ min})^2 + (V_{max} - V_{i\ max})^2 \quad (6)$$

The above constraints have been included in the main objective function without any scale factors and the resultant unconstrained formulation is given in equation (6), both the objectives give to minimize the total installation cost and also minimize the total distribution losses [10].

B. Sizing of the DGs:

System data and the resource data are taken as input and load flow analysis is performed with DG units. Population size, length, and number of the variables, initial constants of the various optimization techniques, and minimum and maximum limits pertaining to the variables are decided. In this problem, the number of variables equals the number of DG sites (r). Each variable indicates the size of each generator at a particular site. GA sizing parameters are given in the appendix given below.

C. Type of the DG adopted:

DG units capable of injecting both real and reactive powers (Type 2) are planned to be connected to the distribution network. A power factor controller is assumed to be present at every bus to which DGs are connected. The real power rating of the DG unit is obtained by using the genetic algorithm and the corresponding reactive power rating of the DGs is determined by:

$$Q_{DGi} = a*P_{DGi} \quad (7)$$

Where, $a= (\text{sign})\tan (\cos^{-1}(PF_{DG}))$ (8)

The power factor controller is assumed to maintain the power factor at 0.85 lagging. Number of locations at which DGs are to be placed in view of transforming the distribution network into a micro-grid is decided.

IV.SIMULATION STUDY

This chapter discusses the results obtained for the distributed load flow analysis and loss sensitivity factor. The IEEE 33 bus radial distribution system has been used for the testing the algorithm. Simulation was carried out in the MATLAB environment.

A. Test system Details:

The proposed algorithm is tested on IEEE 33 bus radial distribution system. It had 32 sections, the total load for this test system are 3715 kW during summer and 4458kW during winter, 2300kVAr of reactive power. The sub-station bus nominal voltage is 12.66 kV and the base of power is 100 MVA. The line and bus details are taken from the IEEE 33bus radial distribution system. Single line diagram of the IEEE 33 bus radial distribution system (with DG units) is shown in the Figure.1. The ranking of the buses are obtained from the base case load flow analysis and loss sensitivity factor method shown in Table .1.

B. Ranking of the bus based on LSF:

The need of load flow of this work is to determine the losses and voltage profile of the system. The LSF are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system.

Bus Rank	**Bus No.**	**Voltage in pu**	**P_{loss} in pu**	**Q_{loss} in pu**	**LSF (P_{loss})**	**LSF (Q_{loss})**
1	6	0.9497	0.0004	0.0003	0.0233	0.0168
2	3	0.9829	0.0005	0.0002	0.0207	0.0132
3	28	0.9337	0.0001	0.0001	0.0121	0.0136
4	4	0.9755	0.0002	0.0001	0.0107	0.0076
5	5	0.9681	0.0002	0.0001	0.0107	0.0077
6	24	0.9727	0.0001	0	0.0099	0.0047
7	9	0.9351	0	0	0.0099	0.0046
8	13	0.9208	0	0	0.0097	0.0044
9	10	0.9292	0	0	0.0093	0.0044
10	8	0.9413	0	0	0.0088	0.0041
11	29	0.9255	0.0001	0.0001	0.0087	0.0103
12	31	0.9178	0	0	0.0061	0.003
13	23	0.9794	0	0	0.0055	0.0026
14	20	0.9929	0	0	0.0051	0.0023

15	25	0.9694	0	0	0.005	0.0024
16	30	0.922	0	0	0.0046	0.006
17	2	0.997	0.0001	0.0001	0.0043	0.0027
18	27	0.9452	0	0	0.0034	0.0037
19	14	0.9185	0	0	0.0031	0.0014
20	17	0.9137	0	0	0.0029	0.0012
21	7	0.9462	0	0.0001	0.0028	0.0013
22	12	0.9269	0	0	0.0028	0.0013
23	26	0.9477	0	0	0.0026	0.0027
24	15	0.9171	0	0	0.0024	0.0008
25	16	0.9157	0	0	0.0023	0.0009
26	11	0.9284	0	0	0.0016	0.0008
27	32	0.9169	0	0	0.0012	0.0006
28	18	0.9131	0	0	0.001	0.0004
29	21	0.9922	0	0	0.0009	0.0004
30	22	0.9916	0	0	0.0008	0.0004
31	19	0.9965	0	0	0.0007	0.0003
32	33	0.9166	0	0	0.0003	0.0002
33	1	1	0	0	0	0

Table.1 Ranking of the buses for placing the DG units based on the value of LSF

The above table.1 tabulates the ranking of the buses for placing the DG units based on the value of Loss Sensitivity Factors and they are obtained from the base case load analysis.

Thedescending order of elements of vectorwill decide the sequence in which the buses are to be consideredfor placing the DG units. Now for the buseswhose voltage value is less than 0.96p.uis considered as the candidate buses requiring the voltage improvement.

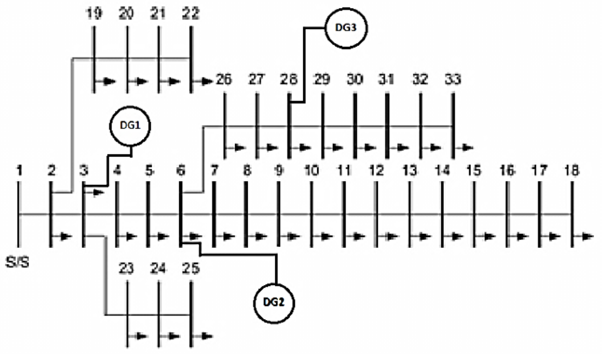

Fig.1 single line diagram of IEEE 33 bus radial distribution system with DG units

In the Fig. 1 Single line diagram of the IEEE 33 bus radial distribution system (with DG units) has been shown.The line and bus details are taken from the IEEE 33bus radial distribution system.

These candidatebuses are stored in ‘bus rank’ vector (Table.1). If the voltageat a bus in the sequence list is healthy (i.e., 1.01<V<0.97) suchbus needs no compensation and that bus will not be listed in the‘rank bus’ vector.
C. Optimal number and sizing of the DG units for autonomous operation of the micro-grid:
The possible size of the Distributed Generation in MW obtained from GA after placing the DG units at the corresponding buses.

Set1 Bus locations	6	3	28	4	5	24
DGs size (MW)	1.13	0.5	0.67	0.5	0.5	0.59
Set2 Bus locations	6	3	28	4	5	
DGs size (MW)	1.14	0.77	0.72	0.64	0.54	
Set3 Bus locations	6	3	28	4		
DGs size (MW)	0.99	1.07	0.97	0.78		
Set4 Bus locations	6	3	28			
DGs size (MW)	1.25	1.6	0.96			
Set5 Bus locations	6	3				
DGs size (MW)	2	1.8				

Table.2 possible size of DG units with respective bus

The total system losses obtained using the proposed distributed load flow for the set 1 to set 5 and the installation cost also taken for normalize to the 10 point scale. The generation of energy from the respective resources should meet the load. A wind turbine of swept area $0.5m^2(\pi r^2)$ supplies 2250Wh at standard conditions, 1050Wh during winter and 450Wh during summer. The gas turbine will supply a constant output both during summer and winter. The costs coefficients wind and gas (cost per 200Wh)are taken as \$250 and \$312.5 respectively.

System adopted for validation, the curves depicting the variationin the distribution system losses and the installation cost arecontradictory in nature and hence cut each other at four DGsites. Hence, for transforming the system under considerationinto an autonomous micro-grid, DGs are to be placed in threelocations for 100% penetration.

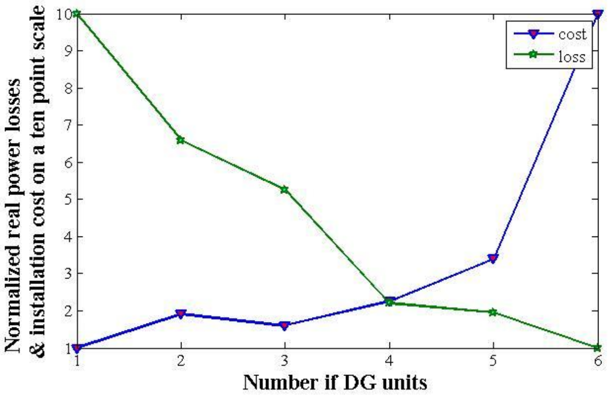

Fig.2 optimal locations of autonomous micro-grid in the variation of real power loss against installation cost

The DG units based on the geographical locations, we take the set 4 instead of taking the set 3for the optimal placing the DG units, because bus no 3 and 4 are near to each other and reduced the installation cost.The optimal cost obtained from the above analysis is \$ 5.4476 $*10^6$ and load flow analysis is carried out for structure of the system of figure.1.

D. Voltage profile improvement:

Network in Figure.1 load flow analysis is carried out with optimized generator size and the voltages are presented in Table.3. Figure.1 shows this variation andvalidates the choice ofthreeDGs as the optimal number of DGsites/units (considering one DG unit/site).

Bus No	Voltages	Bus No	Voltages	Bus No	Voltages
1	1	12	0.98	23	0.9985
2	1	13	0.9742	24	0.9919
3	1.002	14	0.9721	25	0.9887
4	1.0016	15	0.9707	26	1.0013
5	1.0015	16	0.9694	27	1.0011
6	1.0015	17	0.9675	28	1.0003
7	0.9982	18	0.9669	29	0.9926
8	0.9936	19	0.9995	30	0.9893
9	0.9877	20	0.9959	31	0.9854
10	0.9822	21	0.9952	32	0.9846
11	0.9814	22	0.9946	33	0.9843

Table.3 voltages for set 4 DG sizes and locations

Table.3 has been chosen for analysing the voltage profile. The voltage at each bus is foundto improve considerably placing the DG units and the comparison is shown in Figure.3

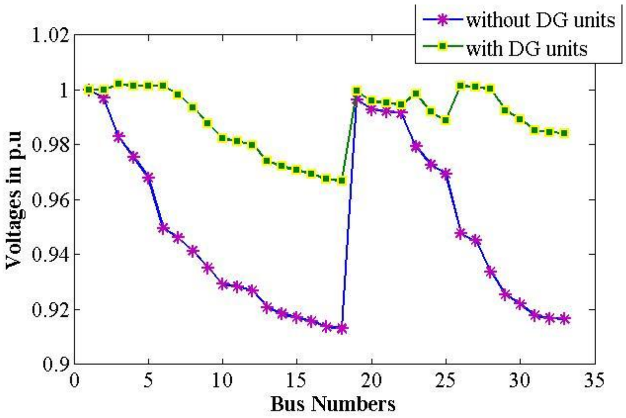

Fig.3 voltage profile of autonomous micro-grid after introduction of DG units and without DG units

From the Figure.3 the minimum and maximum voltages of micro-grid before introduction of the DG units are 0.9131p.u and 1p.u respectively and after introduction of the DG units are 0.9669p.u and 1.002p.u respectively. In particular, there is a significant improvement in the voltagemagnitude of bus 18 (one of the terminal buses) after introduction of the DG units.

E. Distribution loss reductions

As compared to the distribution system fed from a substationfeeder (without DGs), an autonomous micro-grid has a reduction of its total real power loss by 75.30% (DGs sized using GA) is shown in Figure.4.

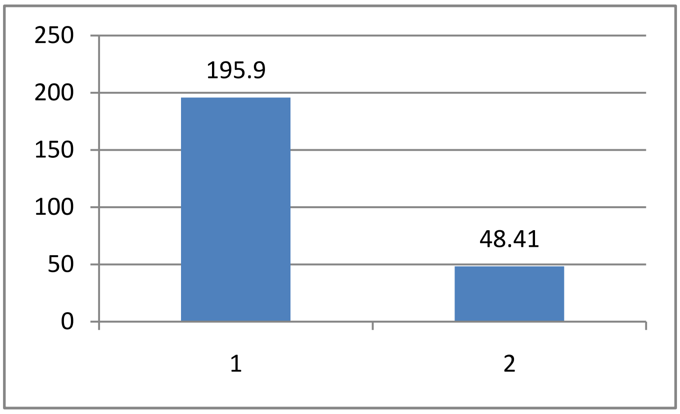

Fig.4 real power distribution losses (kW) of micro-grid before introduction of the DG units and with DG units

After introduction of the DG units, it has been observed that most of the far end buses are within the voltage limits,resulting in reduction of real power distribution losses.

V. CONCLUSION AND FUTURE SCOPE

This proposed method is a comprehensive methodology for optimal location of DGs in the distribution system fed from a substation feeder to an autonomous micro-grid. In the proposed method, the top ranked buses give the optimal location for the DG units. Policy and decision makers and system designers can use the proposed approach for sustainable operation of a distribution system as an autonomous micro-grid. The simplicity of the paradigm is going to identify the strong and weak buses, based on load ability of the buses.Significant improvement in the voltage profile and reduction in losses in the autonomous operationis to be implemented by changing the structure of the radial network. The advantages of conversion of a radial network to meshed architecture by reconfiguration is to be substantiated by bringing out the improvement in the voltage profile, reduction in the distribution losses, and increased reliability of supply. Policy and decision makers and system designers can use the proposed approach for sustainable operation of a distribution system as an autonomous micro-grid. As a future scope of this work, ranking of buses based on reactive power loadable limits has to be attempted to investigate the effect of variations in the reactive power loads upon the bus voltages. Further studies have tobe done for devising methods to reconfigure the system by incorporating both sectionalizing and TIE switches during disturbances in the micro-grid.

VI. APPENDIX

NOMENCLATURE:

P_{gj}	Real power rating of the i_{th} generator.
$P_{gi\ max}$	Max. Generation limit on the ith generator.
$P_{gi\ min}$	Min. Generation limit on the i_{th} generator
Q_{gi}	Reactive power rating of the i_{th} generator.
C_j	Cost co-efficient of the source at the j_{th} bus.
$I_{(1,2)}$	Current drawn from the substation feeder.
$Q_{loss\ jk}$	Q power loss in line between buses i and k
$P_{loss\ jk}$	P loss in line between buses i and k
V_{max}	Max. Limit on the bus voltage magnitude.
V_{min}	Min. limit on the bus voltage magnitude.

V_i	Maximum bus voltage at i_{th}bus of the system
N	No. of buses in the system
R	Resister in Ω
X	Inductance in H
K	Iteration number
P	Sending end bus
Q	Receiving end bus
LSF	Loss sensitivity factor

GA Parameters: Accuracy of the optimization 0.01. Population size 30. Number of variables = 3. Cross over probability 0.8. Mutation probability = 0.01. Number of iterations per run of a function for GA = 30.

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