Optimal Planning of Autonomous Micro-grids

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***Abstract* — Distributed Generators are gaining significant importance in bridging the gap between limited generation capacities and steeply increasing demands. Micro-grids are slowly replacing distribution systems in view of satisfying the needs of select customers without compromising the quality of power. In this regard, an optimal planning has been attempted in this paper in view of transforming an existing radial distribution system into an autonomous micro-grid. An algorithm has been developed to identify the optimal locations of DG units to be placed in the distribution system, based on certain performance indices and also an optimal sizing methodology for the DG units has been formulated. This paper also suggests an optimal structure for the transformed autonomous micro-grid taking into account the reliability issues of the micro-grid and it is found that, weakly meshed architecture is best suited. The Particle Swarm Optimization technique has been used for validating the proposed planning methodologies. The standard 33 bus radial distribution system has been adopted for validation.**

Keywords — Distributed generation, load flow, power generation planning, autonomous micro-grids

I. Introduction

Modern distribution systems are increasingly permitting small generators called Distributed Generators(DGs). These DGs act as electrical interfaces for both conventional and renewable technologies. When different types of electrical sources are introduced in distribution systems, the primary substation is no longer the sole source of power supply to the distribution system and also the fault current contributing source. Therefore, distribution systems with DG units require new approaches in their planning and operation[1-2]. Utility customers have the choice, or will soon have the choice via impending industry deregulation, of whether they wish to purchase their power from existing utilities or to use DG resources to fulfill their power requirements. Any customer or group of customers of the utility in near future will have an option to generate their own power by use of DG as well as sell power back to the grid for purchase. A conglomeration of generation sources and loads forms micro-grids, which operate in autonomous or non-autonomous modes [3].

Studies have indicated that an inappropriate selection of the location and size of DGs, may lead to greater system losses in a micro-grid[4-9]. An algorithm has been developed in this work, for optimal planning of DGs in an autonomous micro-grid in

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view of satisfying its demand by its own generation. After determining the optimal sites and sizes of DGs, it becomes inevitable to investigate the reliability of the micro-grid. Hence reconfiguration has also been attempted in this work, in order to improve the reliability and performance of the system, to avoid formation of accidental islands, on line outages. The standard 33 bus distribution system has been used for validation. MATLAB coding has been developed for the verification of the proposed algorithm.

II. Autonomous Micro-grids

Interconnection of small, modular generation units to low voltage distribution systems forming a self-sustained utility on isolation from the utility mains forms a micro-grid. Micro-grids can be operated in non-autonomous or autonomous modes[2]. An autonomous micro grid is an electrically isolated set of power generators that supply total demand of a group of customers in standalone mode. Hence it becomes inevitable that the DGs connected to the system should be capable of supplying both the real and reactive power demands of the connected customers. This can be achieved by the following different types of DGs:

1) DGs injecting both real and reactive power (ex: synchronous generator)
2) DGs injecting real power alone along with reactive power support (PV cell + capacitor)
3) DGs injecting real power and consuming reactive power along with reactive power support (i.e. induction generator + capacitor).

The following advantages and disadvantages are realized in autonomous micro-grids:

A. Advantages

1) Reliable power supply by providing right energy solution at the right location to enhance power quality.
2) Improved efficiency for on-site applications by minimizing line losses, and using both electricity and heat produced in power generation processes.
3) Savings on electricity rates during peak power periods.

B. Disadvantages

Implementation and control of autonomous micro-grids need extra care from reliability and operational points of view.

III. OPTIMAL SITING AND SIZING

Optimal sizing of DGs and optimal locations to place the optimally sized DGs in an autonomous micro-grid are attempted based on certain performance indices in this work.

A. Load Flow Analysis

The R/X ratio of branches in a distribution system is relatively higher compared to the transmission systems and makes the distribution system ill conditioned. Hence backward and forward sweep algorithm, which exploits the radial nature of the system has been adopted in this work. This method is found to be computationally efficient and possesses a very high rate of convergence[9].

B. Optimal Siting of DGs

(i) Indices adopted in this work

The candidate nodes for the placement of DGs are determined by using various indices as given below:

1. Voltage sensitivity to real power change (*dv/dp*)

A small incremental increase in the real power load is initiated at each of the buses and the sensitivity of the corresponding bus voltage is measured. The buses are ranked with the highest *dv/dp* as top priority[10-12].

2. Voltage deviation factor

For any i^{th} bus of the system under consideration, the deviation factor is determined as follows:

(a) For a generation of 'g', the deviation from nominal voltage at each bus is found and the maximum deviation is computed.

(b) The generation is increased by a constant value and the above step is repeated.

(c) The rate of change of maximum deviation with increase in generation, which would give the Voltage Deviation Factor of the i^{th} bus is found.

(d) The buses are ranked in descending order of the values of their Voltage Deviation Factor.

3. Thermal limit

Load at each of the bus is increased by a constant incremental value and the order in which the lines reach their thermal limit is noted. The lines are ranked based on the values of the thermal limit.

4. Voltage collapse

(a) Load at each bus (as Receiving end) is increased uniformly until the corresponding bus voltage collapses.

(b) The buses are ranked in ascending order of the values of their voltage collapse point to form a priority list.

5. Loss sensitivity factor

The Loss Sensitivity Factors are calculated from the base case load flows at each bus. The buses are ranked in descending order of the values of their sensitivity factors to form a priority list[13-14].

(ii) Algorithm for optimal siting of DGs

The following steps have been followed to determine the optimal locations of DGs for Autonomous Micro grids:

1) Run base case load flow. Calculate the voltage magnitude at all buses and the distribution line flows.

2) Find the value of the above indices for each bus or line and rank them.

3) Group the factors into two categories viz., one based on losses and the other based on voltage levels.

4) Select the top 15 ranks in both categories and find all possible combinations for three number of locations

5) Adopt the following criteria for identifying the candidate locations for DG placement:

a. Number of locations should be 3[13]

b. Atleast one location should be on the main distributor

c. Atleast 3 buses should be there between two consecutive locations

d. Indices should not be violated

e. Current drawn from substation feeder should be zero (for assuring autonomous operation of the micro-grid).

6) Based on the above criteria the feasible locations are identified.

7) The optimal sizing problem formulated (eqn.(1)) is solved for all the above identified feasible combinations and the one with minimum losses is finally identified as the optimal location for placement of DGs

C. Optimal Sizing of DGs

An objective function has been formulated as shown in eqn. (1), to determine the optimal sizes of the DGs to be connected to transform a distribution system into an autonomous micro-grid.

$$MinF = \sum_{i=1}^{n}\sum_{k=1}^{n} P_{loss_{ik}} \quad (1)$$

Subject to

(i) Voltage constraint

$$V_{min} < V_i < V_{max} \quad (2)$$

(ii) Power balance constraint

$$\sum_{i=1}^{n} P_{DG_i} \geq \sum_{i=1}^{n} P_{D_i} + P_{loss} \quad (3)$$

(iii) Feeder current constraint

$$I_{feeder} < 0.0001 p.u. \quad (4)$$

The multi-objective function has been solved by applying the PSO technique for previously identifies optimal locations.

IV. Optimal Reconfiguration

The transformed autonomous micro-grid is subject to accidental islands on line outages. Hence it is suggested that a weakly meshed configuration would improve the reliability of the micro-grid as well as the performance of the system.

A. Reconfiguration Strategy

Distribution systems are provided with two types of switches namely sectionalizing switches and TIE switches which are initially in CLOSED and OPEN positions, respectively. On reconfiguration, these positions are altered, resulting in the redistribution of loads among the branches of the system. Following steps are followed to find the best reconfigured structure:

1) All the terminal buses except feeder bus (bus 1) and buses that are close to these terminal buses are initially identified.

2) TIE switches are provided at the ends of lines connecting terminal and other buses that are geographically closer.

3) Each of the terminal buses are connected, to any one of the buses in such a way that buses which are connected do not belong to the same branch and all the terminal buses are connected (except feeder bus).

4) As many combinations as possible are identified in such a way that each terminal bus should be connected to only one bus in a combination.

5) Load flow is done for each of these feasible combinations and the one with minimum length, least losses and minimum voltage deviation is chosen as the optimal choice.

After finding the reconfigured structure, contingency analysis is done to assure the stability of the reconfigured autonomous micro-grid.

B. Case study

To analyze the reliability and stability of the system single line and bus outages (being most common occurrences) are considered for analysis:

1) Single line outage

The reconfigured structure is subject to single line outage by adopting the following steps for each line:
(a) A line outage is simulated.
(b) Load flow analysis is performed. The system losses, power generations and voltage deviations for each line outage are determined.
(c) The increase in system loss is found to be supplied by the largest generator(Slack).

2) Single bus outage

The reconfigured structure is subject to single bus outage by adopting the following steps for each line:
(a) A bus outage is simulated - the lines and loads connected to the bus are removed.
(b) Load flow analysis is performed. The system losses, power generations and the voltage deviations for each bus outage are determined.
(c) The increase in system loss is found to be supplied by the largest generator available(Slack).

It is inferred from the above case studies that some extra power is needed to satisfy the voltage constraint. So the largest generator is to be resized to avoid over sizing of any or all other generators, in view of avoiding load shedding. This excess power requirement is added to the rating of the Slack generator and hence the sizing is updated.

V. Results and Discussions

The standard 33 bus radial distribution system is used as the test system, with a winter demand of 4.456 MW. A base kV of 12.66 and base MVA of 100 are adopted for analysis.

A. Optimal Siting of DGs

Ranking of Buses Based On Indices

The candidate nodes for the placement of DGs in the standard 33 bus distribution system are determined by using various indices as explained in section III. The values of the various voltage sensitivity based indices are tabulated in Table I and the ranking of distributors based on thermal limit is shown in Table II.

TABLE I. Comparison of Buses based on Voltage Sensitivity based Indices

Bus Num ber	dv/dp (p.u.)	Voltage collapse loading (p.u.)	VDF	dploss/ dpeff (p.u.)	dploss/ dqeff (p.u.)
2	-0.05789	4.451	-0.06429	0.0045	0.00
3	-0.37831	3.494	-0.41334	0.0216	0.0126
4	-0.62347	4.316	-0.6751	0.0112	0.0073
5	-0.88599	5	-0.95083	0.0112	0.0074
6	-1.48874	4.779	-1.56247	0.0238	0.0164
7	-1.63456	0.51	-1.70739	0.0029	0.0013
8	-2.89228	0.369	-2.96395	0.0089	0.0041
9	-3.66917	0.245	-3.72259	0.0101	0.0045
10	-4.47313	0.195	-4.49287	0.0094	0.0044
11	-4.62323	0.058	-4.63637	0.0016	0.0008
12	-4.90888	0.149	-4.90876	0.0028	0.0013
13	-6.0717	0.146	-5.99112	0.0098	0.0044
14	-6.52028	0.118	-6.39615	0.0031	0.0014
15	-6.98831	0.108	-6.82274	0.0024	0.0008
16	-7.57335	0.102	-7.35363	0.0023	0.0009
17	-8.61428	0.098	-8.26686	0.0029	0.0012
18	-9.19122	0.08	-8.77358	0.001	0.0004
19	-0.16074	2.378	-0.06435	0.0007	0.0003
20	-1.11283	1.72	-0.06475	0.0051	0.0023
21	-1.37396	0.633	-0.06482	0.0009	0.0004

22	-1.82525	0.518	-0.06486	0.0008	0.0004
23	-0.67129	4.066	-0.41627	0.0055	0.0026
24	-1.26713	2.78	-0.42178	0.01	0.0047
25	-1.86166	0.511	-0.42438	0.005	0.0024
26	-1.63169	0.481	-1.56792	0.0026	0.0026
27	-1.83291	0.44	-1.57508	0.0035	0.0036
28	-2.61282	0.367	-1.6045	0.0123	0.0134
29	-3.22641	0.272	-1.62531	0.0087	0.0103
30	-3.60874	0.22	-1.63458	0.0046	0.006
31	-4.34248	0.2	-1.64901	0.0061	0.003
32	-4.57406	0.159	-1.65196	0.0012	0.0006
33	-4.81778	0.151	-1.65213	0.0003	0.0002

TABLE II. RANKING BASED ON THERMAL LIMIT

Rank	Line number	Loading (p.u.)	Rank	Line number	Loading (p.u.)
1	5	0.00140	17	19	0.00720
2	2	0.00150	18	27	0.00760
3	7	0.00170	19	28	0.00790
4	3	0.00190	20	11	0.00820
5	4	0.00190	21	29	0.00900
6	8	0.00230	22	30	0.00900
7	9	0.00240	23	16	0.00920
8	1	0.00260	24	22	0.01290
9	12	0.00280	25	23	0.01340
10	6	0.00300	26	17	0.01380
11	13	0.00380	27	31	0.01480
12	14	0.00420	28	18	0.01600
13	10	0.00430	29	32	0.01860
14	15	0.00440	30	20	0.01870
15	26	0.00490	31	24	0.02280
16	25	0.00490	32	21	0.02540

TABLE III. OPTIMAL LOCATIONS AND SIZING OF DGS IN AUTONOMOUS MICRO-GRID

Bus number	Real power rating (MW)	Reactive power rating (MVAr)
3	2.3	1.42
14	0.8	0.5
30	1.39	0.86

It is significant from the tables (I and II) that the ranking of the buses reflect different scenario for different performance indices. Since there is no deliberate similarity in ranking, it is difficult to decide the candidate locations for placement of DGs based on ranking pertaining to a single performance index. Hence the performance indices are categorized into two groups, viz., based on voltage sensitivity (dv/dp, voltage collapse VDF) and loss sensitivity (thermal limit and LSF). The top 15 buses in each category of ranking are considered for further analysis.

B. Optimal Sizing of DGs

After identifying the optimal locations, it becomes inevitable to determine the optimal sizing of the DGs to transform the system to an autonomous micro-grid. The objective function represented by the eqn.(1) is solved using PSO technique for all the possible combinations of the locations. The sizing of DGs which result in minimal real power loss is considered as the optimal sizing and the corresponding locations to place the three DGs are identified as the optimal locations for realizing an autonomous micro-grid.

C. Optimal Structure for the autonomous micro-grid

After obtaining the optimal sites for DG placements and their optimal sizes, an optimal structure is to be determined for the micro-grid. The reconfiguration algorithm explained in section IV is implemented for micro-grid after deciding the optimal sizing and siting of DGs. The top 10 combinations of reconfiguration are tabulated in Table IV. From the above combinations, the one with the minimal loss and voltage deviation is chosen and it is noted that both losses and voltage deviation has reduced on reconfiguration.

TABLE IV. RANKING OF POSSIBLE COMBINATIONS OF RECONFIGURATION FOR AUTONOMOUS MICRO-GRID

Rank	Tie switch position	Real power losses (MW)	Reactive power losses (MVAr)	Voltage deviation
1	8-22,25-26,18-33	0.0231	0.0179	1.1139
2	7-22,25-26,18-33	0.0232	0.0179	1.1585
3	8-25,25-26,18-33	0.0233	0.0179	1.1643
4	7-25,8-22,18-33	0.0232	0.0183	1.1251
5	7-25, 25-26,18-33	0.0234	0.0181	1.2268
6	7-25,7-22,18-33	0.0233	0.0183	1.1674
7	7-25,8-25,18-33	0.0234	0.0184	1.2064
8	8-22,8-25,18-33	0.0240	0.0187	1.2408
9	7-22,8-25,18-33	0.0242	0.0187	1.278
10	7-22,8-22,18-33	0.0252	0.0197	1.6245

D. Comparison of distribution losses

It has been observed that a radial system with no DG and single substation feeder causes high losses in the system but when optimally sized DGs are placed at optimal locations the losses reduce by 90%. Further these distribution losses are found to decrease by 25% with respect to the radial structure as shown in Table V.

TABLE V. COMPARISON OF DISTIRBUTION LOSSES IN AUTONOMOUS MICRO-GRID

Cases	Real power losses (MW)	Reactive power losses (MVAr)
Without DG	0.31	0.21
With DG	0.031	0.0248
After Reconfiguration	0.0231	0.0179

E. *Comparison of voltag profile*

It has been observed that in a radial system with no DG and single substation feeder voltage, most of the buses are found to violate the voltage limits (preferred to be within ±5 %.) .With optimally sized and optimally located DGs voltage deviation is found to have reduced to merely 1.7% and reconfiguration helps in reducing it further to 1.11%

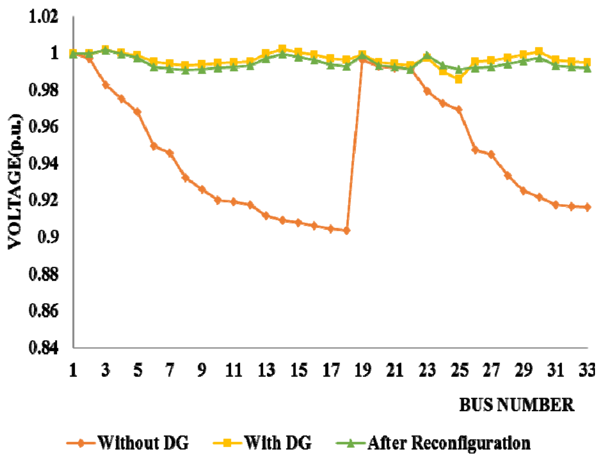

Fig. 1. Voltage profile of the 33 bus Autnomous Micro-grid

F. *Evaluation based on reliability*

To analyze the reliability and stability of the system, single line and single bus outage is simulated and following results are obtained.

1) Single Line Outage

After determining the optimal siting, sizing and structure for the autonomous micro-grid, single line outage is conducted. Generator 3 is the largest generator capable of supplying the extra power required when there is change in power flow in addition to its optimally sized value but the rest generators are not altered as shown in Table VI

From the Table VI it is noted that if slack bus is given an additional generation of 0.2 MW, then the system can handle any single line outage without load shedding. It is up to the designer to decide if the small addition is achieved in terms of a reserve generator or to resize the SLACK generator

2) Single Bus Outage

Largest generator capable of supplying the extra power required when there is change in power flow in addition to its optimally sized value but the rest generators are not altered and load shedding is done if load is more than maximum generation (optimally sized value + additional generation). It is noted that with an additional reserve of 0.2 MW in generator 3, load shedding is only necessary when the generator bus outage occurs and for other cases, load shedding can be avoided.

VI. CONCLUSIONS

In this paper, an optimal planning has been attempted for an autonomous micro-grid, formed by transforming a radial distribution system. A heuristic algorithm for optimal siting of DGs based on various voltage losses based indices, has been formulated in this work. This algorithm is found to reduce the computational time when compared to the other methodologies suggested in the literature as it reduces the feasible combinations of the locations.

On identifying the candidate locations for placement of DGs, a PSO based optimal sizing of DGs has been carried out. A drastic reduction in power losses and improved voltage profile has been noticed as a result. The voltage has been improved and found to be within limits and the losses has been reduced to a great extent by 90% in 33 bus system compared to system with no DGs.

The formation of accidental islands is more prominent in radial micro-grids, even for a single line outage and hence the reliability and sustainability become the major challenges in autonomous micro-grids. It has been identified that a weakly meshed structure is optimal for an autonomous micro-grid. A methodology for reconfiguration of a radial autonomous micro-grid has been attempted in view of improving the system performance. The suggested architecture is found to be stable for single line and single bus outages provided the largest (SLACK) generator is resized taking into account the transient stability analysis of the system.

Thus the proposed work suggests an algorithm for transforming an existing radial distribution system into an autonomous micro-grid with optimally sized DGs placed in optimal locations with optimal structure.

TABLE VI. COMPARISON OF DIFFERENT SINGLE LINE OUTAGES IN MICRO-GRID

Rank	Line number	Real power losses (MW)	Reactive power losses (MVAr)	Voltage deviation %	Generation at bus 3 (MW)	Generation at bus 30 (MW)	Generation at bus 14 (MW)
1	30	0.0393	0.0312	5.7589	2.2986	1.39	0.8
2	13	0.0375	0.03	4.941	2.482	1.39	0.8
3	29	0.0364	0.0286	4.5308	2.4541	1.39	0.8
4	12	0.0327	0.0259	4.0906	2.4499	1.39	0.8
5	14	0.0291	0.0229	3.6799	2.2684	1.39	0.8
6	11	0.0288	0.0226	3.3344	2.4187	1.39	0.8
7	31	0.0268	0.0207	3.3076	2.2753	1.39	0.8
8	2	0.0369	0.0285	3.0357	2.2656	1.39	0.8
9	28	0.0287	0.0223	2.8519	2.4066	1.39	0.8
10	15	0.0256	0.0199	2.7718	2.233	1.39	0.8
11	22	0.0417	0.0312	2.7545	2.3977	1.39	0.8
12	10	0.0262	0.0205	2.7092	2.3878	1.39	0.8
13	18	0.0314	0.0239	2.433	2.2748	1.39	0.8
14	23	0.0367	0.0274	2.4145	2.3838	1.39	0.8
15	3	0.0381	0.0303	2.3472	2.1803	1.39	0.8
16	27	0.0263	0.0204	2.2455	2.3818	1.39	0.8
17	9	0.0242	0.0187	2.1325	2.3563	1.39	0.8

18	6	0.0261	0.0209	2.1046	2.3378	1.39	0.8
19	16	0.0238	0.0184	2.0686	2.2536	1.39	0.8
20	19	0.0278	0.0211	1.9632	2.2845	1.39	0.8
21	4	0.0326	0.0259	1.9536	2.2035	1.39	0.8
22	5	0.0305	0.0242	1.8156	2.2156	1.39	0.8
23	34	0.0249	0.0193	1.7355	2.2541	1.39	0.8
24	26	0.0245	0.0189	1.7228	2.3446	1.39	0.8
25	20	0.0251	0.019	1.6413	2.2954	1.39	0.8
26	8	0.0227	0.0175	1.6104	2.3251	1.39	0.8
27	17	0.0227	0.0174	1.4495	2.2749	1.39	0.8
28	21	0.0233	0.0177	1.364	2.3075	1.39	0.8
29	25	0.0232	0.0179	1.3407	2.3107	1.39	0.8
30	7	0.0222	0.0172	1.3123	2.2914	1.39	0.8
31	24	0.0234	0.0178	1.3111	2.323	1.39	0.8
32	33	0.0224	0.0171	1.1646	2.3208	1.39	0.8

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