Design methodology for autonomous operation of a Micro-grid

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Abstract

The operation of a radial distribution network in an islanded mode has become significant due to an increase in the integration of renewable sources to the utility network. In this project, a computational tool is presented to design the sizes of the distributed resources for an autonomous micro-grid operation of a radial distributor. The technique employs GA optimization, considers the variation in generation and demands in summer and winter. The presented load flow solutions of the designed islanded-Micro-grid shows that the node voltages are within the specified limits during summer and winter.

1. Introduction

Micro-grid is a local grid, which harnesses the energy from renewable energy resources. The micro-grid is a concept based on a cluster of electrical and thermal loads together with small-scale sources of electrical power and heat. The power sources will generally be mixed, including renewable sources such as photovoltaic or wind generators together with fossil-fuelled generators [1] [2]. The interface between this network and the wider electrical power network will be through a well-defined and controlled interface. The micro-grid is responsible for servicing the needs of its consumers, ensuring a quality of power supply that meets the needs of the consumers and possibly controlling some of the non-critical loads. The interface with the local electricity utility will be one of exchanging power, so the micro-grid appears to be a well-behaved load or generator [3]. The use of renewable energy sources in the micro-grid is seen as one of the important ways of reducing the carbon dioxide emissions [4]. Majority of these units can produce relatively small power outputs. This means such generators are conveniently connected at lower voltages with in the distribution system. Micro-grid also provides supply to areas where transmission and distribution network does not exist. In developing countries, they consider micro-grid as an attractive option in remote areas far away from the distribution transformer [5]. Further, micro-grid concept had permitted intentional islanding when required, thereby providing reliable supply to a consumer group [6]. Such autonomous operation requires a stable micro-grid, which can independently supply power to select customers. Such an autonomous operation requires several distributed generators to provide the necessary reliability. Sizing of generators for autonomous operation becomes significant in this context. Earlier, a number of algorithms were developed for sizing the generators in a micro-grid. Edwin Haesen et al proposed a sizing algorithm based on minimizing the losses and not for an autonomous operation [7]. Mallikarjuna et al proposed another algorithm based on simulated annealing and here again sizing for autonomous operation has not been considered [8]. Subsequently, sizing based on detailed annualized cost calculations was proposed [9], which had not also considered sizing for isolated operation. With this background, this paper proposes a sizing methodology for the distributed resources in a micro-grid, where the sizing algorithm also includes criterion for independent operation of the micro-grid. Further, such reliable autonomous operation becomes a necessity during preplanned (intentional) islanding, when maintenance work is carried out. Furthermore, an unplanned (unintentional) islanding is inevitable due to unexpected failure of main grid, caused by a network fault [10].

2. Structure of the micro-grid

A 12kV radial distribution system with 4 laterals and 33 nodes as shown in Fig.1 is taken in this work.

DG's are connected at nodes 2, 5 and 32. Siting of these generators is based on the availability and access to resources and this has not been considered in this work.

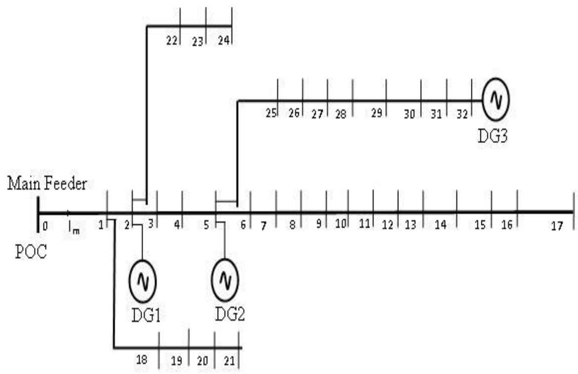

Fig.1. One line diagram of the standard IEEE 33-bus Distribution system with DG's at nodes 2,5 and 32.

The load flow analysis for radial distribution network is carried out using forward sweep method [11]. The line data and load data of the above radial distribution system is taken from Selvan et al [12].

3. Problem formulation

As a matter of fact, micro-grids has the potential to increase the integration of renewable energy sources and other distribution sources into the utility network. Hence, the distributed resources considered in the micro-grid are wind, solar and gas turbines. The objective is to design a system with generators whose sizes are optimally chosen. Such design would reduce the installation cost of generators. Further, these generators should ensure that in the absence of supply from the main point of connection (POC), they can independently feed the demand. In such autonomous operation, the current drawn from the POC should be zero and the voltage magnitudes at all the nodes have to be close to its nominal value.

Evidently, there is a constant variation of wind speed, wind direction and irradiation. These variation are pronounced with seasonal changes. So, the varying characteristics of the resources result in varying electrical power output from these sources. Hence, the problem of optimization of the sizes of the generators in the proposed work is to minimize the objective function (hybrid generator cost)

$$z = c_w a_w + c_s a_s + c_g a_g \,;$$

subjected to the seasonal variations in demand and supply along with constraints for islanded operation as stated below:

$$\begin{aligned} D_s &\le W_s a_w + S_s a_s + G s a g \\ D_w &\le W_w a_w + S_w a_s + G w a g \end{aligned} \qquad (1)$$

$I_m < 0.001$ pu (for islanded operation) ; (2)

and $V_i - V_{nom} < €$. i=1,2,3-----33. (3)

where I_m is the current drawn from the POC, D_s and D_w represent the loads in summer and winter, while W_s, W_w and S_s, S_w and G_s represent the energy harnessed by the wind, solar respectively in summer and winter. c_w, c_s, c_g represents the costs of wind, PV per unit area and gas generator per 200Wh respectively. a_w, a_s are area coefficients for wind and solar and a_g represents gas plant capacity.

4. Methodology of sizing

A steady supply of wind with reasonable speed is an essential requirement for harnessing the power in the wind. Modern wind generators are designed to reach rated output at a wind speed of 10 - 15 m/s. The power available to a wind turbine is the kinetic energy passing per unit time in a column of air with the same cross sectional area as the wind turbine rotor. The wind energy (W) harnessed from a wind turbine of unit area of cross section (1 m^2) in terms of wind velocity is given by [13]

$$W = \left(\frac{d}{2}\right)\rho_{air}\left(v^3\right)$$

Where, ρ_{air} is the air density(kg/m^2), v is the daily average wind velocity (m/s) and d is the duration of one day(24 hrs). The net energy that can be extracted from the wind by a turbine is limited by the Betz limit ($C_{p\max}$) and the energy supplied by a wind turbine of radius r is given by

$$\varepsilon_w = C_p(\pi r^2)\, W = a_w W$$

where C_p is the dimensionless power coefficient and $a_w = C_p \pi r^2$ and r is the radius of the rotor.

Similary, if A is the PV array area in m^2 and S is the average solar radiation in Wm^{-2} on the array for a day and η is the conversion efficiency, then the energy supplied by the array is given by

$$\varepsilon_{pv} = S\eta A = a_s S$$

where, $a_s = A\eta$.

4.1 Algorithm

1. The objective function is considered along with the 4 constraints given in equations (1)-(3). Initial sets of a_w, a_s, a_g are generated randomly for optimization.
2. For each set of a_w, a_s and a_g it is checked if demand constraints are satisfied.
3. DG's are connected at nodes 2, 5 and 32 and Load flow analysis is carried out for the distribution system for a given set of a_w, a_s and a_g to check whether the voltages at each node are within specified limits.
4. With sets of feasible solutions, GA algorithm for optimization is employed.
5. After the optimal solution is obtained using GA, load flow analysis is once again performed with the obtained optimal values to check whether all the constraints are satisfied.

5. Case study

The generation of energy from the respective resources should meet the load. The PV array of surface area of 0.5 m^2 (A) supply 1000Wh (ηAS_{std}) at standard conditions; 412.5Wh (ηAS_{sum}) during summer and 67.5Wh (ηAS_{win}) during winter. Also, a wind turbine of swept area 0.5m^2 (πr^2) supply 2250Wh at standard conditions, 1050Wh ($C_p \pi r^2 W_{win}$) during winter and 450Wh ($C_p \pi r^2 W_{sum}$) during summer. The gas turbine will supply a constant output both during summer and winter. The cost coefficients c_w and c_s (cost per unit area of 1 m^2) and c_g(cost per 200Wh) are taken as \$250, \$666.66 and \$312.5 respectively.

The Load during winter and summer are D_S = 3.715 MW, D_W = 4.458 MW respectively.

The proposed sizing algorithm using GA was tested with the above data for variations in solar and wind resources and load in winter and summer. The GA was implemented in MATLAB using the Genetic and Evolutionary Algorithm (GEA) toolbox [14]. The number of chromosomes (N) in the initial population was chosen to be 30. The fitness of each chromosome was evaluated and roulette wheel selection was employed to select the chromosomes for mating. Discrete recombination's in which the variables are exchanged between the individual chromosomes were carried out on the population. The probability of recombination (P_c) occurring between the chromosomes was set to 0.7. Following this, the chromosomes were mutated with a mutation rate (P_m) of 0.01.

For a load during winter and summer specified as D_S = 3.715 MW, D_W = 4.458 MW respectively, the following optimal solution was obtained using the proposed algorithm:

$$a_w = 2.08; \quad a_s = 0.24; \quad ag = 0.13$$

From the above value of a_w, the swept area of the wind turbine is found to be 10795.2m^2. The energy supplied by the wind generator is calculated from the data assumed earlier as 4.049 MW during winter and 3.4 MW during summer. Similarly, the surface area of the PV array is calculated as 2229.6 m^2 per unit and the PV array would supply 367.785 kW during summer and 60.183 kW during winter. Gas generator will supply 743 kW during summer and winter. Typical values of C_p (0.3) and η (0.15) are used in the above calculations. The optimal cost obtained from the above analysis is \$16.042*10^6. By using these optimal values for the sizes, load flow analysis is carried out for systems with different loads (i.e. summer and winter).

For the network in Fig.1 load flow analysis is carried out with optimized generator size and the results are presented in Table 1.

Table 1: Voltages in pu for network in Fig. 1. With and without distribution network, using ETAP and without main feeder

Node no	voltage in pu (distribution network without DG's)	voltage in pu(distribution network with DG's and main feeder)	voltage in pu (distribution network-isolated operation) Winter	voltage in pu(distribution network-isolated operation) Summer
0	1.0000	1.0000	0.9972	0.99824
1	0.9970	1.0008	0.9973	0.99825
2	0.9829	1.0071	1	1
3	0.9754	1.0132	0.9868	0.99294
4	0.9680	1.0198	0.9782	0.98597
5	0.9496	1.0385	0.9762	0.97687
6	0.9461	1.0351	0.9690	0.97246
7	0.9412	1.0306	0.9586	0.96768
8	0.9350	1.0247	0.9502	0.96064
9	0.9292	1.0192	0.9462	0.95479
10	0.9283	1.0184	0.9411	0.95405
11	0.9268	1.0170	0.9376	0.95275
12	0.9207	1.0111	0.9354	0.94748
13	0.9184	1.0088	0.9306	0.94553
14	0.9170	1.0073	0.9288	0.94406
15	0.9156	1.0059	0.9265	0.94289
16	0.9136	1.0035	0.9243	0.94115
17	0.9130	1.0028	0.9212	0.94064
18	0.9957	0.9995	0.9945	0.99773
19	0.9921	0.9959	0.9923	0.99422
20	0.9914	0.9952	0.9863	0.99353
21	0.9907	0.9946	0.9822	0.99291
22	0.9802	1.0045	0.9956	0.99655
23	0.9735	0.9980	0.9872	0.99015
24	0.9702	0.9947	0.9801	0.98697
25	0.9444	1.0346	0.9729	0.97517
26	0.9419	1.0327	0.9652	0.97292
27	0.9304	1.0242	0.9611	0.96289
28	0.9221	1.0181	0.9546	0.95569
29	0.9185	1.0156	0.9439	0.95258
30	0.9144	1.0137	0.9387	0.94896
31	0.9135	1.0135	0.9312	0.94816
32	0.9132	1.0140	0.9286	0.94792

5. Conclusions

A 33 bus radial distribution system with distributed resources is taken up for islanded operation. The sizing problem for the distributed resources has been formed by taking isolated operation requirement as one of the constraints. This new constraint included is in addition to other constraints such as variation in generation and demand during summer and winter. The sizing of the generators were carried out using GA. The voltages at the various nodes are within the limits in both summer and winter, when the radial distributor is operated with DGs and the mains and with DGs alone, thus bringing out the significance of the proposed design methodology.

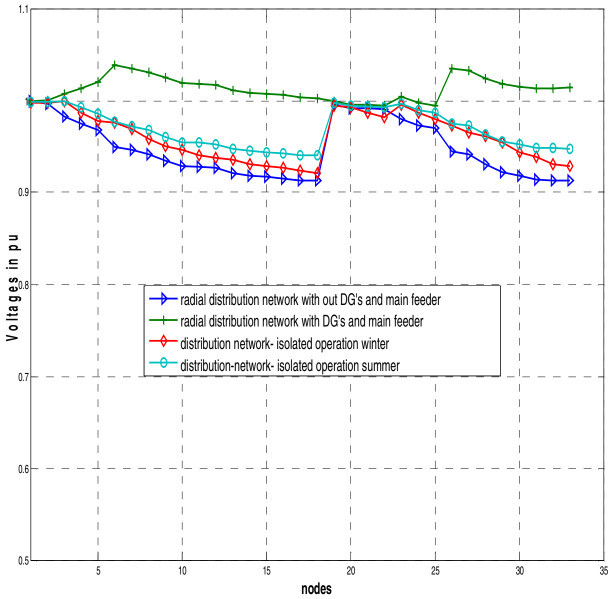

Fig.2. Node voltages in autonomous and non-autonomous modes.

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