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Optimal Placement and Sizing of Solar Photovoltaic Generation System in Low Voltage Secondary Distribution Network

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Abstract:
The present trend in distribution regulation pushes distribution utilities to reduce system loss and achieve high efficiency. Different methods to reduce secondary system loss include distribution transformer location shifting, network splitting, changing the secondary line and service drop size, and integration of distributed generation (DG). This paper develops a methodology that minimizes secondary system loss by properly placing and sizing rooftop solar photovoltaic (PV) generation system using genetic algorithm (GA). The method is based on optimal single installation to avoid voltage profile problems. A comprehensive modeling was used in this paper to account different loading and customer's characteristics as well as solar PV generation system. Due to the special features of low voltage secondary distribution network, power flow based on backward/forward sweep approach was used. Different test cases based on actual secondary distribution network characteristics were used to show the robustness of the proposed method.

Keywords: backward/forward sweep; distributed generation; genetic algorithm; modeling; solar photovoltaic generation system

I.INTRODUCTION

The presence of distributed generation (DG) has significant effect on distribution network such as efficiency, reliability, power flow, voltage profile, protection, and stability. It brings challenges to traditional distribution network especially if the DG is installed at the low voltage secondary distribution network. As distributed generation gains popularity, utilities and distribution companies are frequently asked by customers for interconnection of these systems [1]. Distributed generation plays a key role in residential, commercial, and industrial customers on the power system. DG provides an alternative supply of power. A rooftop solar photovoltaic (PV) generation system is an example of DG that can be connected to the utility's service from its low voltage secondary distribution network. When numerous solar PV generation systems are installed, the impact could be detrimental to maintaining normal system operation. [1] presented an update of the work presently being done by a range of organizations in the area of policy, technology and practices for interconnection of various types of distributed generation (DG) systems to the utility distribution network grids. They presented a description of a new initiative being sponsored by the Massachusetts Technology Collaborative's (MTC) DG Collaborative for novel design for control and coordination of DG sources on secondary distribution network systems. [2] presented a paper discussing the basic policy, perspective planning, and benefits of distributed generation in India. [3] presented a new method of describing the electric secondary distribution system by using transformer secondary circuit archetypes and load characterization based on customer consumption. The proposed method has been implemented on a pilot area of the local electric utility, and the results validate its effectiveness. [4] developed a computer software using Microsoft Excel to calculate the losses for all transformer secondary circuits in the pilot area, including energy losses in the service drops, secondary lines, and transformers; thus, the circuits with the greatest losses are identified for further study. The applications of the proposed secondary distribution model and load characterization in [3] on the economic analysis and design of secondary circuits are also presented. [5]-[7] analyzed the impacts of distributed generation installation on distribution network operation including voltage profile, electrical losses, reliability, and harmonics. [8]-[11] analyzed the impacts of distributed generation on voltage profile problems. They proposed different load distribution models and comprehensive analysis to determine the maximum amount of DG in secondary distribution network to account voltage profile problems. Some of them derived analytical expression to determine the limit value of power that can be injected to the distribution network without causing overvoltage and other investigates the voltage regulation on residential distribution network. [12]-[13] proposed optimal placement and sizing of distributed generation (DG) using genetic algorithm (GA) and particle swarm optimization (PSO) respectively. Their objective is to minimize total real system loss and improved voltage profile of the system. [14] developed a procedure for optimal sizing and location of a single Photovoltaic Distributed Generation (PVDG) unit on three-phase unbalanced radial distribution feeder. They considered the peak mismatch of the feeder load curve and the PVDG production curve. The procedure has been applied successfully on two 11kV feeders within the Abu Dhabi distribution network. In this paper, genetic algorithm (GA) was used to optimize secondary system loss by properly placing and sizing rooftop solar PV generation system. The method is based on optimal single installation to avoid voltage profile problems.

II. PROBLEM FORMULATION

In distribution system, installation of solar PV generation system can be used to minimize secondary system losses while satisfying electrical constraints. Secondary system loss is composed of losses from secondary line and service drops. For the optimization problem, the objective function F is the secondary system loss. The objective of this study is to minimize secondary system loss. The latter is the measure of how efficient the secondary distribution network is. The optimization problem is formulated as:

$$\min F = re\left[\sum_{k=1}^{b} I_k (V_m - V_n)^*\right] \qquad (1)$$

Where V_m is the line voltage at node m, I_k is the line current along section k between nodes m and n, and b is the total number of section in the system. Section may be secondary line or service drop. Due to the special features of secondary distribution network, that is, radial structure and single-phase, the conventional power flow solution may become inapplicable in the analysis of the secondary distribution network. The backward/forward sweep power flow was used to calculate secondary system losses [15]. Due to its low memory requirements, computational efficiency, and fast convergence characteristic, this power flow method has gained attraction for radial distribution systems power flow analysis [12].

III. LOW VOLTAGE SECONDARY DISTRIBUTION NETWORK MODELING

This section presents a new method of low voltage secondary distribution network modeling. It employs a procedure of identifying secondary distribution circuit model, secondary line and service drop model, load model, and solar PV generation system model.

A. Secodary Distribution Circuit Model

The typical secondary system in the Philippines is 240V, single-phase, three wires with the neutral solidly grounded and connected to the primary neutral. In the secondary distribution circuit layout, each transformer extends radially the number of pole spans to the left and to the right of the transformer. Transformers are usually located to provide two-way, three-way, of four way feeds. The normal preference is a two-way feed as shown in Fig. 1. Fig. 2 shows an example of secondary distribution circuit diagram and the corresponding circuit characteristics is shown in Table I.

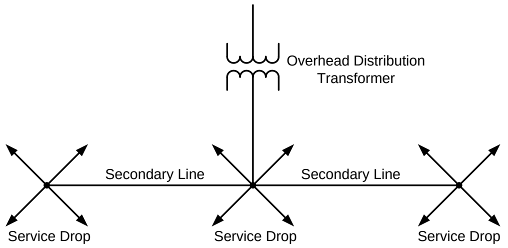

Figure.1. Two-way secondary feed

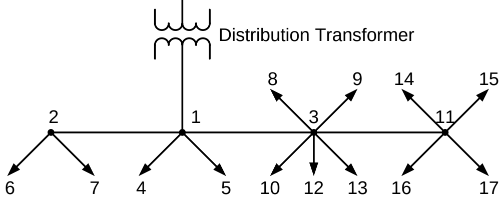

Figure.2. Example secondary distribution circuit diagram

Table .1. Circuit characteristics

From	To	Length (m)	Wire Type
1	2	43	Secondary Line
1	3	59	Secondary Line
1	4	3	Service Drop
1	5	20	Service Drop
2	6	13	Service Drop
2	7	23	Service Drop
3	8	26	Service Drop
3	9	27	Service Drop
3	10	16	Service Drop
3	11	67	Secondary Line
3	12	16	Service Drop
3	13	17	Service Drop
11	14	13	Service Drop
11	15	5	Service Drop
11	16	23	Service Drop
11	17	30	Service Drop

B. Secondary Line and Service Drop Model

The secondary line and service drop model is taken from actual distribution utility standards for overhead secondary line and service drop. The secondary line is composed of 3/0 AWG black polyethylene (PE) insulated triplex cable with an impedance of 0.4143+j0.0868 Ω/km and a current carrying capacity of 215A. The service drop is composed of #6 AWG black polyethylene (PE) insulated triplex cable with an impedance of 2.6488+j0.0999 Ω/km and a current carrying capacity of 70A. Since majority of single-phase loads are connected in 240V system, the model of secondary line and service drop is simply twice the impedance.

C. Load Model

This paper uses a method of load characterization based on customer monthly load consumption. The sum of the energy consumption was divided by the total number of hours to obtain average real power for each customer. This paper uses a load power factor of 85% to get the reactive power of each customer. Residential and Commercial loads comprise of end-use electrical appliances and equipment related to the household and commercial activities such as lighting, entertainment, cooking, drying, etc. Modeling of these appliances and equipment involves finding voltage dependencies of each of the appliances and equipment in a household and commercial establishment. Voltage dependency of loads can be modeled by using standard ZIP parameters which are proportions of constant impedance (Z), constant current (I), and constant real and reactive power (PQ) type of load in any given load model. Each of the customers, residential and commercial, would have different type of load variations. This paper uses 8.3% constant PQ, 26.7% constant Z, and 65% constant I for residential customers and 13% constant PQ, 34% constant Z, and 53% constant I for commercial customers.

D. Solar PV Generation System Model

Solar PV generation systems used in residential and commercial customers are typically rooftop PV installations that consist of solar PV modules and an inverter and are operated at unity power factor, that is, only real power is produced. This paper modeled the solar PV generation system as negative injected real power (AC output power).

IV. OPTIMAL PLACING AND SIZING OF SOLAR PV GENERATION SYSTEM USING GENETIC ALGORITHM (GA)

The starting operator of the GA is the generation of initial population, which was randomly generated. The representation of an individual is a single-level string. The length of chromosome string is equal to the number of nodes in the system. In the example secondary distribution circuit, the length of chromosome string is 17. Node 1 is the root node or source node, which is the secondary riser of the distribution transformer. Nodes 2, 3, and 11 are the tapping points of the service drops from the secondary lines. In this paper, the solar PV generation system is installed at every node from 25 W up to the total real power of all connected loads with an increment of 25 W to get the optimal single installation. Using the data of example circuit, the optimal single installation of solar PV generation system is 15.325 kW at node 15. This is the basis for random generation of initial population. Fig. 3 shows an example of how the chromosome strings are encoded. The method avoids the installation of solar PV at source and tapping point nodes (nodes 1, 2, 3, and 11). The summation of multiple installations is equal to optimal single installation capacity, in this case, 15.325 kW. After the generation of initial population, it will call the power flow function and passes the generated population as an input. For each individual, the objective function is then calculated.

The fitness function in this paper is given by [16]:

$$Fitness(x_i) = \frac{(Nind)(X^{(x_i-1)})}{\sum_{i=1}^{Nind}(X^{(x_i-1)})} \qquad (2)$$

$$0 = (MAX-1)X^{Nind-1} + \sum_{n=2}^{Nind}(MAX)X^{Nind-n} \qquad (3)$$

Where X is the computed real-numbered root of the polynomial in (3), x_i is the position in the ordered population of individual i, MAX is the selective pressure or bias towards the fittest individual, and $Nind$ is the number of individuals. Selection is the process of determining the number of times, or trial, a particular individual is chosen for reproduction and, thus, the number of offspring that an individual will produce [16]. The selection used in this paper is the roulette wheel selection. This mechanism is used to probabilistically select individuals based on secondary system loss. The basic operator for producing new chromosomes in the GA is that of crossover. Single-point crossover was used in this paper and is shown in Fig. 4. Child 1and Child 2 has a sum of 13.625 kW and 17.025 kW respectively. They have ±1700 kW discrepancy on the original value. The crossover methodology in this paper introduces a correcting procedure wherein it maintains the summation of multiple solar PV installation to be equal to optimal single installation value to avoid voltage profile problems in the system. If the summation is less than the original value, the discrepancy is added randomly on any node except for the source and tapping point nodes. If the summation is more than the original value, the discrepancy is deducted randomly on any node except for the source and tapping point nodes and nodes without solar PV installation (See Fig. 5). The crossover operation is not necessarily performed on all strings in the population. Instead, it is applied with a probability, *Px*, when the pairs are chosen for breeding. The mutation technique employed is swap mutation based on [17]. It simply selects two random nodes with solar PV installation and swapped their contents. Fig. 6 shows an example of swap mutation. As in crossover, the mutation operation is not necessarily performed on all strings in the population. Instead, it is applied with a probability, Pm, a percentage of the entire population is to be mutated. After the children are mutated, the objective value will be calculated. Fitness-based reinsertion combined with elitism was used in this paper. The termination depends on the maximum number of generations.

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Parent 1	0	0	0	225	500	0	0	1875	0	1650	0	200	2125	525	1625	4525	2075
Parent 2	0	0	0	275	2700	200	675	275	175	1500	0	325	1725	4550	1975	125	825

Figure.3. Encoding of chromosome

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Parent 1	0	0	0	225	500	0	0	1875	0	1650	0	200	2125	525	1625	4525	2075
Parent 2	0	0	0	275	2700	200	675	275	175	1500	0	325	1725	4550	1975	125	825

Crossover Point

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Child 1	0	0	0	225	500	0	0	1875	0	1500	0	325	1725	4550	1975	125	825
Child 2	0	0	0	275	2700	200	675	275	175	1650	0	200	2125	525	1625	4525	2075

Figure.4. Single-point crosover

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
New Child 1	0	0	0	225	500	0	0	1875	0	1500	0	325	1725	4550	1975	1825	825
New Child 2	0	0	0	275	2700	200	0	275	175	625	0	200	2125	525	1625	4525	2075

Figure.5. Corrected Child After Crossover

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
New Child 1	0	0	0	225	1500	0	0	1875	0	500	0	325	1725	4550	1975	1825	825
New Child 2	0	0	0	525	2700	200	0	275	175	625	0	200	2125	275	1625	4525	2075

Figure .6. Swap mutation

V. TEST RESULTS AND DISCUSION

The effectiveness of the proposed method is demonstrated using twenty developed test cases based on actual secondary distribution network characteristics. The entire simulation was coded in Matlab platform. The test cases are composed of ten pure residential customers and ten mixed load customers (combination of residential and commercial customers). The crossover and mutation probability are taken as 0.5 and 0.8 respectively, the number of generations and individuals are both 500, and reinsertion rate of 0.5 was used for all simulations. Table II shows the initial and optimized results for the twenty test cases. The result of the simulation shows that optimal single installation can be improved by distributing the total capacity to different nodes on the system. Percent reduction in secondary system loss from 25-50% in single installation to 38-64% in multiple installations is shown in Table II. Secondary system loss and voltage profile improvement is also observed and is shown in Figs. 7 and 8.

TABLE II. CIRCUIT CHARACTERISTICS

Pure Residential

Case Number	Number of Node Points	Total Load (kW)	Initial		Optimal Single Installation				Multiple Installation		
			Loss (W)	Min. Voltage	Optimal Single PV Size	Loss (W)	Min. Voltage	% Reduction in Loss	Loss (W)	Min. Voltage	% Reduction in Loss
Case 1	17	35.281	1152	229.28	15325	624	235.86	46	497	236.63	57
Case 2	25	45.073	1199	231.30	17850	722	234.97	40	513	236.56	57
Case 3	26	55.632	1355	232.49	15150	1025	233.01	24	779	235.73	42
Case 4	26	35.580	510	235.77	10475	367	237.38	28	298	237.82	42
Case 5	24	50.848	1450	230.58	11925	1087	233.14	25	904	235.05	38
Case 6	27	46.448	1533	231.19	13600	1098	234.14	28	901	235.04	41
Case 7	27	34.110	1620	224.98	18175	814	232.44	50	589	236.01	64
Case 8	16	39.351	931	232.33	11350	595	235.13	36	516	236.61	45
Case 9	21	35.070	1185	229.77	12675	702	234.11	41	612	235.68	48
Case 10	27	33.058	642	232.95	8100	447	236.36	30	371	236.61	42

Mixed Load

Case Number	Number of Node Points	Total Load (kW)	Initial		Optimal Single Installation				Multiple Installation		
			Loss (W)	Min. Voltage	Optimal Single PV Size	Loss (W)	Min. Voltage	% Reduction in Loss	Loss (W)	Min. Voltage	% Reduction in Loss
Case 1	26	49.714	1149	232.81	10825	861	235.15	25	735	236.01	36
Case 2	22	40.790	1917	222.29	14300	1075	230.80	44	826	233.39	57
Case 3	23	31.833	1042	228.17	11075	542	234.72	48	473	236.05	55
Case 4	19	29.760	677	234.36	10975	437	235.02	35	357	236.93	47
Case 5	15	29.436	684	231.31	9775	363	236.13	47	324	237.35	53
Case 6	20	52.410	1963	229.66	17675	1285	230.96	35	1045	234.85	47
Case 7	22	42.744	2933	222.60	19675	1707	230.25	42	1284	231.89	56
Case 8	18	35.744	949	231.64	10800	610	235.69	36	523	236.09	45
Case 9	16	22.991	517	232.60	8575	271	235.97	48	238	237.46	54
Case 10	14	17.819	556	230.84	7125	310	234.58	44	249	236.47	55

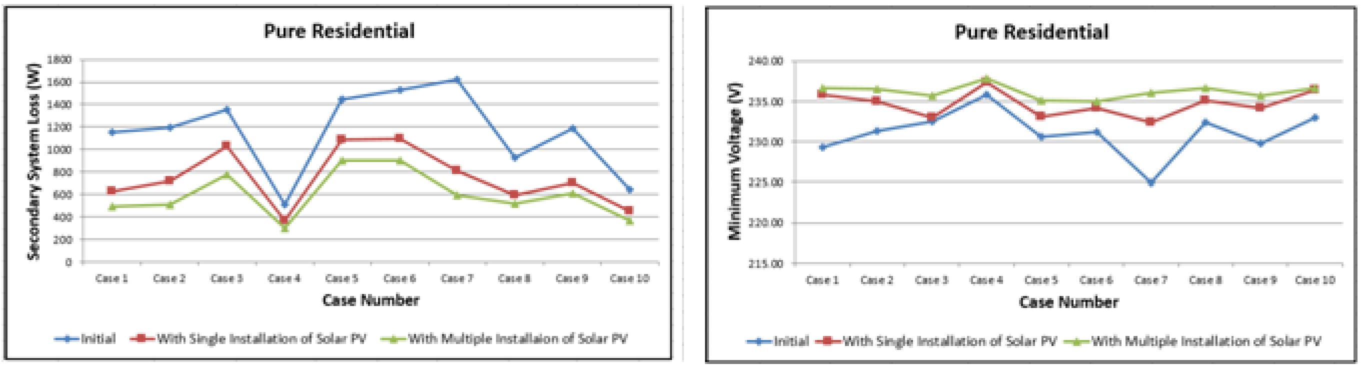

Figure.7. Pure residential secondary system loss and minimum voltage

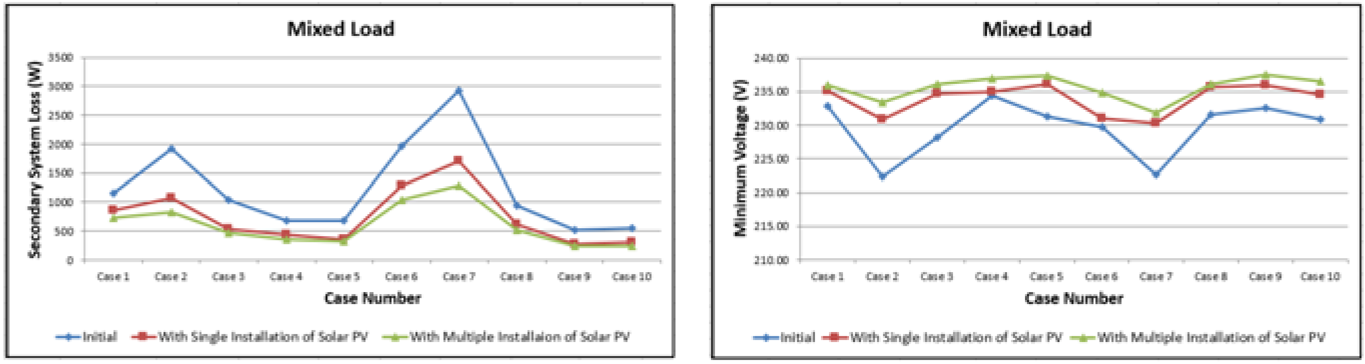

Figure.8. Mixed Load Secondary System Loss And Minimum Voltage

VI. CONCLUSION AND FUTURE WORKS

In this paper, we developed a methodology that minimizes secondary system loss using genetic algorithm (GA). The method is based on optimal single installation to avoid voltage profile problems. The robustness of the proposed method is demonstrated using test cases based on actual secondary distribution network characteristics. The solution shows that improvement of secondary system loss and voltage profile in a much optimal way can be attained by distributing the optimal single installation capacity to different nodes on the system.

Future work may use the methodology described in this paper by properly modeling the solar PV inverter based on actual geographic characteristics considering temperature, irradiance, shading, location, tilt angle, etc. Time-varying loads may be used to minimize annual energy loss.

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APPENDIX

The line and load data of the twenty developed test cases is available upon request.