Optimal Placement of Reactive Power Sources for Loss Minimization and Voltage Profile Improvement

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Abstract- **It is demonstrated that compensating of reactive power increases the voltage profile improvement in a distribution system especially in rural networks or industries which are so far from high voltage substation. However, reactive power sources are expensive, needing large scale of investment. This paper presents an applicable method to define the number of static reactive power generating units and their optimal position in a radial network. The proposed method improves voltage profile and power losses simultaneously. To solve the optimization problem, simulated annealing algorithm has been used to minimize a dual fitness function consist of voltage drop and power losses. The method uses an economic criterion to choose the best number and location of reactive power sources. Finally, the proposed algorithm is implemented on a test network called "seda sima" which is one of the middle voltage networks in Bardsir city, Kerman, Iran. The simulation results using Matlab 2009a are presented by verifying the effectiveness of the proposed method.**

Keywords- Reactive Power Source; Distribution System; Voltage Profile; Power Losses; Simulated Annealing Algorithm

I. INTRODUCTION

Avoiding out of variation range in voltage profile and keeping them within specified limits, voltage control should be applied to reduce energy losses and improve voltage regulation. Voltage control is a difficult duty for distribution companies because it is strongly influenced by random and sudden load fluctuations. For this reason, Utilities reinforce their power systems in order to have a direct control over voltage variations [1].

Previous researches about voltage profile enhancement in distribution networks using analytical tools such as voltage stability, optimal power flow, reactive power compensating, failure indicators analysis etc result to install some equipment such as fixed and controlled capacitors banks, automatic reactive power compensators and transformers which have on-load tap changers [1.2].

The large investment cost of new devices has constrained them being used especially in recent years. Therefore, at these conditions the optimal placement of such devices will be most important and noteworthy problem. Researches to define the optimal number, location and sizing of reactive power sources (RPS, hereinafter) to improve voltage profile considering operational constraint at different loading levels, were continued for many years by authors. For the same reason many optimization techniques have been employed as heuristic methods, such as harmony search, ant colony, simulated annealing, neural network, and novel methods [5-7]. Fuzzy logic is another technique that has been laid in attention recently in Iran where the objective function is defined taking into account losses reduction, voltage constraints and total cost including investment and maintenance cost [8, 9]. Authors in [10] have studied to use on-load tap changers to reduce the part of avoidable power losses and improve voltage profile. In [10], an analytical method is used to find optimal tap position and 0/1 state of capacitor banks using optimal power flow (OPF). In [11], Gu and Rizy have solved the above problem considering the loss equation as target and voltage inequalities as constraints using the neural network techniques.

Mahmoudianfard et al in [12] have presented an approach for optimal placement of capacitor banks in a real power network for the purpose of economic minimization of loss and enhancement of voltage with an objective function including the cost of power losses and capacitors.

Sethi and Jain have studied deeply about the reactive power control in distribution network. The work reported by them is carried out with the objective of identifying the optimal locations and sizes of shunt capacitors to be placed in radial distribution system to have overall economy considering the saving due to energy loss minimization and cost of capacitors. They have used loss sensitivity factors to the identification of candidate buses to install capacitors [13]. In [14] a two-stage methodology has been used to solve the optimal capacitor placement problem. In the first stage, fuzzy approach is used to find the optimal capacitor locations and in the second stage, real coded genetic algorithm is used to find the sizes of the capacitors. They have determined the sizes of the capacitors corresponding to maximum annual savings.

In [15] and [16] the optimal number and location of automatic voltage regulators are studied separately from the aspects of placement and sizing of capacitor banks problem, in addition aspects of power approach and energy losses are considered, outside the main problem-solving process. Finally, in the work of Hooshmand and Ataei in [17], a new technique for finding the optimal values of the fixed and switched capacitors in the distribution networks based on the real coded genetic algorithm has been presented and the modeling of radial or loop feeders with unbalanced or balanced network loads have been considered. They have tested their methodology on a region of the distribution network of the city of Ahvaz in Iran.

It seems that a lot of researches about optimal placement and sizing of reactive power injectors have been done in distribution networks. However, only a few papers that have treated the complex problem of optimal location of reactive power sources in real distribution networks.

In [1], the voltage regulators replacement problem has been solved using genetic algorithm by Mendoza and some authors, but they have used Newton-Raphson algorithm for load flow while it has not proper results in radial networks [26]. This paper has extracted the method from [1] that has separated the original problem in two sup problems. The first part consists of determining the optimal position of the RPSs in the system, solving a multi-objective optimization problem (Fig. 1). The second part consists of choosing the optimal number of RPSs. To do this, a decision making process is carried out through a benefit analysis decoupled from the main optimization solving-process.

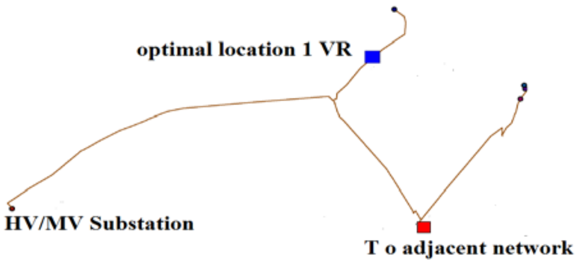

Fig. 1 Schematic of test system and optimal location for one RPS

In this paper, the optimization problem is a multi-objective with minimization of power losses and voltage deviations as target. Locating, sizing of RPSs and determination of optimal tap position of RPSs is solved into a single-objective optimization problem using weighting method. This is suitable for solving combinatorial problems. The objective function is minimized using the simulated annealing algorithm because of its adaptability in complex problem [19]. The proposed method takes into account the discrete nominal power and tap constraints of RPSs. This method is implemented on a real distribution network which validates the efficiency of the proposed method. The nomenclatures are given at the appendix.

II. FORMULATION OF OPTIMIZATION PROBLEM

According the proposed method in [17], placement of RPSs can be studied separately in three sub problems, including: 1) locating the RPSs on the distribution network, 2) choosing the tap position, and 3) selecting the necessary number of RPSs.

The index of voltage profile improvement and the index of power losses reduction are two components of optimal placement of RPSs problem. These two terms are separated from each other, in other word, the minimization of one of them make difficult the improvement of the other one.

It is difficult to formulate the problem in terms of cost incidence of these objectives over the system operation. Because, even if the cost incidence of power losses is clear, it is not the same for keeping the voltage values at the nodes close to the rated value[1,13].

According to the aforementioned important, the objective function to minimize is:

$$Min: F.F = w_1 L.M + w_2 V.I \tag{1}$$

Where:

$$L.M = \sum_{j=1}^{NS} i_j^2 . R_j \tag{2}$$

$$V.I = \sqrt{\sum_{K=1}^{NN} (V_{K_{P.U}} - 1)^2} \tag{3}$$

And (4), (5) are basically the constraints:

$$V_{\min}^j \le V_j \le V_{\max}^j \tag{4}$$

$$Q_{VC_j} \le Q_{\max VC_j} \tag{5}$$

Optimal selection of tap position in locating of RPSs is very important. Tap position is a state variable and optimal value of that would be found by successive displacement and using Forward-Backward sweep load flow (FBs-LF). The FBs-LF is a very useful load flow method in radial distribution networks [26]. This method of load flow reinforces the speed of convergence in load flow problem in a radial network system. In radial distribution networks, the reactance per resistance for a conductor is near 1 or even less than unit. This is important to make inadequate the conventional method such as Newton- Raphson in load flow for radial networks. Speed of convergence in Newton-Raphson method has a direct relation to reactance per resistance ratio(X/R) of the network [27].

Number of RPSs is an effective parameter for utilities because of their much investment. This paper separates the decision making about optimal number of RPSs from locating part.

One of very useful approach in economic engineering is the present cost analysis which consists of primary investment, operating and maintenance costs, interested rate and other economic parameters. The used approach in this paper to economic ranking of alternatives has followed from interested rate that is proposed as below: [1, 17]

$$B.I = \frac{1 - F.F}{N.V.C} \times 100\% \tag{6}$$

Adding a RPS in the system, Eq. (6) is calculated to find optimal number of RPSs based on most gained.

III. SIMULATED ANNEALING ALGORITHM

The simulated annealing algorithm is based on a thermodynamic principle: if a metal be energized by warming and be cold slowly, it would be more strengthened from mechanical point of view. In the other words, simulated annealing (SA) simulates energy system variations until it becomes a solid material on a stable state. Optimization process is started from a basic point and fitness function will be calculated at the same point. Then, the algorithm continues on adjacent points. If the new points be better according to fitness function, the new point will be accepted certainly as new start point [19]. Otherwise, SA goes to adjacent point considering a probability that is calculated using Relation (7).

$$P = \exp\left(\frac{-\Delta E}{KT}\right) \tag{7}$$

Where T is temperature, K is Boltzmann constant and ΔE is energy deviation within two points.

It should be noted while the cooling is undergoing, the value of T parameter is reducing, so probability of acceptation of non valuable points will be converged to zero and algorithm is finished when T=0 [19]. At this optimization technique, selection of first value of T parameter is very important. Small values make convergence on around local optimum and large values make the algorithm's progress slow. The below code shows the procedure of SA algorithm [21]:

Procedure Simulated Annealing

1. Initialization

 1.1 Set cooling schedule

 1.2 Define neighborhood solution

 1.3 Generate initial solution(x0)

2. Evaluate initial solution and set x'=x0

3. Generate new neighborhood solution (xi)

4. If f (xi) <f (x') set x'=xi

Or if p>r set x'=xi

5. Reduce primary temperature

6. Stop if convergence criteria met; otherwise go to 3

IV. CALCULATION OF WEIGHT COEFFICIENT OR PARTICIPATING FACTORS

It is a fact that cost reduction due to voltage profile improvement or other power quality parameters is not possible or at least very difficult. On the other hand the power losses reduction can be calculated in cost simplify. So Weighting method can be used in such cases to compromise between importance of voltage improvement and loss reduction. Weighting the objectives to obtain non-inferior solutions is a method derived from necessary conditions of non-inferiority developed by Kuhn and Tucker [23].

This method uses scalar coefficients and participates to objectives to generate an equivalent single-objective optimization problem. These coefficients that multiplies each objective function is called weight and be interpreted as the relative weight or worth for one objective when be compared to the other objectives [24].

Weights must be normalized using Eq (8).

$$\sum_{j=1}^{n} W_j = 1 \tag{8}$$

In [25] to normalization, a decision matrix (values of objectives are drays of this matrix) has been used. Where, each objective is divided by maximum possible value of the same objective. So, Relation (1) can be rewritten as below:

$$OF = w_1 \frac{L.M}{L.M_{\max}} + w_2 \frac{V.I}{V.I_{\max}} \tag{9}$$

Where, L.Mmax & V.Imax are maximum values of power losses and voltage deviation in initial system (without VCs). In order to simplify the analysis, standard form can be recast as below from (9):

$$w_1' = \frac{w_1}{L.M_{\max}}, \quad w_2' = \frac{w_2}{V.I_{\max}} \tag{10}$$

V. LOCATING ALGORITHM

Line parameters (impedances), load values including active and reactive consumptions, number of RPSs and weighting coefficients are the inputs for optimal location. In the beginning, voltage deviation of nominal voltage and total power losses since original system is calculated to find weighting coefficients. Then, with selection of starting point in SA, optimization process will begins.

VI. CASE STUDY

The proposed method has been applied on one of radial 20KVs network of Bardsir city, Kerman, Iran as a test system. Test system is consists of fifty-six nodes.

The impedance and load matrix is extracted from GEO DATA bank of south Kerman electrical distribution company. Values of R & X per ohm and active/reactive power per KW/KVAR are presented in appendix. Replacement studies have been done under cases when the network is exporting active and reactive power to adjacent network. This energy is excited from fifty-sixth node. Results of the optimization process using 1 RPS are shown in Table I.

TABLE I RESULTS FOR ONE RPS

Weight Coefficient	**W1=1 W2=0**	**W1=0 W2=1**	**W1=0.5 W2=0.5**
O.F	0.911	0.8694	0.8937
Location	56	43	37
Tap Position	0.997	0.999	0.99

In the above table, values of objective function are written in three conditions as follows: 1) only power losses optimization; 2) only voltage deviation optimization and 3) simultaneous optimization of voltage deviation and power losses with equal weighting coefficients. The problem was solved for two RPSs using same weighting coefficients; results are shown in Table II.

TABLE II RESULTS FOR TWO RPSS

Weight Coefficient	**W1=1 W2=0**	**W1=0 W2=1**	**W1=0.5 W2=0.5**
O.F	0.8595	0.7446	0.821
Location	24-56	37-44	37-29
Tap Position	*t1=0.997 t2=0.983*	*t1=0.952 t2=0.897*	*t1=1 t2=0.975*

The results shown in Table II and Table I are very different with each other, but the thirty-seventh node is repeated in both. Fig. 2 indicates that the convergence of SA algorithm occurred after 998 iterations.

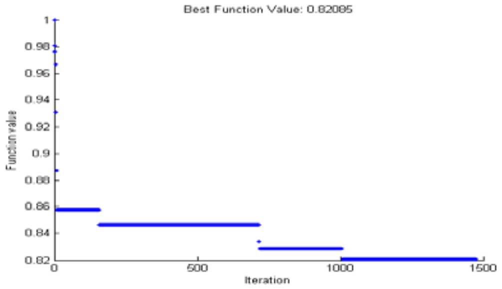

Fig. 2 SA algorithm convergence

In the appendix, the results of optimization process for three and four RPSs are also proposed. The fourth column of TABLE III presents amount of benefits for each number of installed RPSs in percent that is obtained from Eq. (12).

Increasing the number of RPSs on the system has more effect on the voltage deviation index in the comparison with the energy losses reduction. From Table Ⅲ, it can be seen that, if one RPS is used, it is more economical. In the fourth column of Table III, it is the reduced versus increasing in number of RPSs. The analytical results about loss reduction and voltage improvement using one RPS and test system description are proposed in Table IV-VII, in the appendix.

TABLE Ⅲ BENEFITS FOR EACH NUMBER OF RPSS

Weight Coefficient	W1=1 W2=0	W1=0 W2=1	W1=0.5 W2=0.5
1VC	8.89	13.06	10.63
2VC	7.025	12.77	8.75
3VC	5.196	12.09	8.136
4VC	3.91	11.35	6.695

TABLE Ⅳ LOCATION OF 3 RPSS

Weight Coefficient	W1=1 W2=0	W1=0 W2=1	W1=0.5 W2=0.5
O.F	0.8441	0.6373	0.7559
Location	27-56-22	56-39-32	37-44-56
Tap Position	t1=0.906 t2=0.978 t3=0.970	t1=0.957 t2=0.957	t1=0.856 t2=0.955 t3=0.868

TABLE Ⅴ PARAMETERS OF TEST SYSTEM

in	out	R(ohm)	X(ohm)	KW	KVAR
1	2	0.2059318	0.2356908	0	0
2	3	0.2164339	0.2477105	0	0
3	4	0.310245	0.3550783	0	0
4	5	0.1511726	0.1630184	0	0
5	6	0.1768896	0.2024517	0	0
6	7	0.09505584	0.1087923	0	0
7	8	0.1272189	0.1456032	0	0
8	9	0.2593098	0.2967824	0	0
9	10	0.2867356	0.3281715	0	0
10	11	0.3072052	0.3515992	0	0
11	12	0.2819435	0.3226869	0	0
12	13	0.0166606	0.0190682	0	0
13	14	0.06922262	0.07922591	0	0
14	15	0.02256915	0.0258306	0	0
15	16	0.02041055	0.02336005	0	0
16	17	0.022179	0.02542859	0	0
17	18	0.04112737	0.04707071	0	0
18	19	0.2904329	0.3324031	0	0
19	20	0.2543195	0.2910709	0	0
20	21	0.03940813	0.04510296	0	0
21	22	0.02482108	0.02840795	0	0
22	23	0.02682242	0.0306985	0	0
23	24	0.3212596	0.3676845	0	0
24	25	0.01977474	0.02263237	0	0
25	26	0.02628667	0.03008533	0	0
26	27	0.08788547	0.1005857	0	0
27	28	0.2977771	0.3408086	0	0
28	29	0.3544504	0.4056717	0	0
29	30	0.2537736	0.2904462	0	0
30	31	0.330924	0.1442208	0	0
31	32	0.1684398	0.0734082	0	0
32	33	0.04527393	0.01973095	0	0
33	34	0.1806642	0.07873575	0	0
34	35	0.162478	0.0780997	0	0
35	36	0.05720017	0.02492855	0	0
36	37	0.06741013	0.02937819	0	0
37	38	0.1573537	0.06857675	0	0
38	39	0.2065636	0.09002303	0	0
39	40	0.06081075	0.02650209	0	0
40	41	0.05862791	0.02555078	42.3	20.48
41	42	0.2209297	0.09628394	0	0
42	43	0.06885892	0.03000959	21.15	10.24
43	44	0.09431191	0.04110232	266.49	129.07
12	45	0.02969455	0.03398568	0	0
45	46	0.05006409	0.05729881	0	0
46	47	0.1125034	0.128761	0	0
47	48	0.1733688	0.1984221	0	0
48	49	0.2392172	0.2737862	0	0
49	50	0.2123562	0.2430436	0	0
50	51	0.101002	0.1155977	0	0
51	52	0.05654787	0.06471955	0	0
52	53	0.01952691	0.00223487	0	0
53	54	0.05371216	0.06147405	0	0
54	55	0.01886143	0.02158708	84.6	40.97
26	56	0.02281179	0.0261083	4200	2034

TABLE Ⅵ ANALYSIS OF LOSS REDUCTION & VOLTAGE DEVIATION FOR ONE RPS

Description	Original System	W1=1 W2=0	W1=0 W2=1	W1=0.5 W2=0.5
Loss	82 kw	71.8 kw	74.4 kw	73.8
Voltage Deviation	0.220256	0.19875	0.19011	0.19403
Location	-	56	41	37

TABLE Ⅶ LOCATION OF FOUR RPSS

Weight Coefficient	W1=1 W2=0	W1=0 W2=1	W1=0.5 W2=0.5
O.F	0.8436	0.5640	0.7322
Location	26-21-28-26	34-35-31-21	40-38-56-20
Tap Position	t1=0.216 t2=0.930 t3=0.834 t4=-0.188	t1=0.405 t2=0.914 t3=0.994 t4=0.904	t1=0.984 t2=0.912 t3=0.984 t4=1

TABLE Ⅷ NOMENCLATURE

B.I	Benefit
V_j	Nominal Voltage
Q_{VCj}	Nominal Reactive Power of RPS
$Q_{VCj\text{-}max}$	Max Reactive Power of RPS
ij	Through Current Line
L.M	Total Losses
N.S , N.N	Number of Sections and Nodes
N.V.C	Number of RPSs
F.F	Objective Function
F.F o.s	Objective Function(original system)
R_j	Resistance of jth Line
V.I	Voltage Deviation
V_K	Voltage of Kth Node
W_1 , W_2	Weighting Coeficients
V.I max	Original Voltage Deviation
L.M max	Original Losses

Although selection of number of RPSs depends on decision maker expectations, the follows can be draw. According to the fourth column of Table I, only one RPS be installed on the thirty-seventh node and each Kilo Watt Hour of energy be equal to 832 Rials (around 0.08$), then around twenty-eight million rials (around 2800$) is saved in annual operation cost, while voltage profile enhancement is another advantage.

VII. CONCLUSION

In this paper, optimal location of reactive power sources in radial distribution networks is studied using SA algorithm based on Geo Data bank. A multi-objective optimization problem is proposed. The multi-objective problem is converted to a single-objective problem using weighting coefficients method.

In the next step, global optimal point is found using simulated annealing algorithm which is one of the most popular heuristic methods. Constraints such as discrete capacity of reactive power sources, lower and upper limits of tap position are also considered in optimization process.

Voltage deviation and energy losses are presented as fitness function components. Tap position is considered as state variable in that, its optimal value has been obtained by successive variations on tap position by using FBS-LF simultaneously. In addition, to compare the influence of numbers of reactive power sources, an especial economical ratio is used. This ratio would make decision-making process easier for system operators. Finally, the proposed method is implemented on a real radial network as a test system.

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