APPLICATION OF BINARY VERSION GSA FOR SHUNT CAPACITOR PLACEMENT IN RADIAL DISTRIBUTION SYSTEM

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Abstract

This paper presents a binary gravitational search algorithm (BGSA) is applied to solve the problem of optimal allotment of Shunt capacitors in radial distribution systems. In this work, total line loss (TLL) and the total voltage deviations (TVD) are to be minimized separately by incorporating optimal placement of shunt capacitors with constraints which include limits on voltage, sizes of installed capacitors. This BGSA is applied on the balanced IEEE 12-Bus distribution network and the results are compared with conventional binary particle swarm optimization (BPSO).

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1. INTRODUCTION

It has been seen that as much as 13% of total power generated is wasted in the form of losses at the distribution level [1]. Grainger and Lee [2] developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables. Baran and Wu [3] distinguished capacitor placement problem separately into a master problem and a slave problem. The master problem was used to determine the location of the capacitors while the slave problem was used to determine the type and size of the capacitors. Chen *et al.* [4] considered the mutual coupling effect of conductors to install capacitors in unbalanced distribution systems. Duran *et al.* [5] considered the capacitor sizes as discrete variables and employed dynamic programming to solve the problem. Schmill [6] developed well-known two-third rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder. Grainger *et al.* [7] formulated the capacitor placement and voltage regulator problem and proposed decoupled solution methodology for general distribution system. Placement and sizing of shunt capacitors by using loss sensitivity factors and plant growth simulation algorithm were done in Rao*et al* [8]. The loss sensitivity factor was used to predict which bus has the largest loss reduction when a capacitor was placed. S. G. Saranya*et al.* [9] employed fuzzy expert system (FES) method for determining suitable candidate nodes in distribution systems for capacitor installation. Recently, Rashedi*et al.* [10] proposed a new optimization algorithm called Gravitational Search Algorithm (GSA), which has been demonstrated to be very interesting to find solutions of unimodal and multimodal functions. GSA is based on the law of attraction of masses supported by the Newtonian gravity, which says that “a particle in the universe attracts every other one with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them”. The original version of GSA was designed for search spaces of real valued vectors. However, many optimization problems are set in binary discrete space, such as feature selection and data mining [11] dimensionality reduction [12-16], unit commitment [17], and cell formation [18], in which it is natural to encode solutions as binary vectors. In addition, problems defined in the real space, may be considered in the binary space, too. The solution is to display real digits with some bits in the binary mode. The binary search space is considered as a hypercube in which an agent may move to nearer and farther corners of the hypercube by flipping various numbers of the bits. In the literatures, very few papers use the optimization of voltage profile as objective functions. In this work, a binary version of GSA (BGSA) [19] is utilized to decide the optimal locations of shunt capacitors to obtain an overall better voltage profile for a radial distribution system. In the BGSA, the outcome of these forces is converted into a probability value for each element of the binary vector, which guides whether that elements will take on the value 0 or 1. The objective function is to minimize total line loss (TLL) and maximize the lowest voltage level of the system *i.e.*, nothing but minimize total voltage deviation (TVD) to reach a better voltage profile. The locations of capacitors are formulated by binary variables as decision variables in the constraints.

2. POWER FLOW SOLUTION IN RADIAL DISTRIBUTION SYSTEM

The load flow solution is carried by the following set of recursive equations (1) and (2) derived from the single line diagram as shown in Fig. 1.

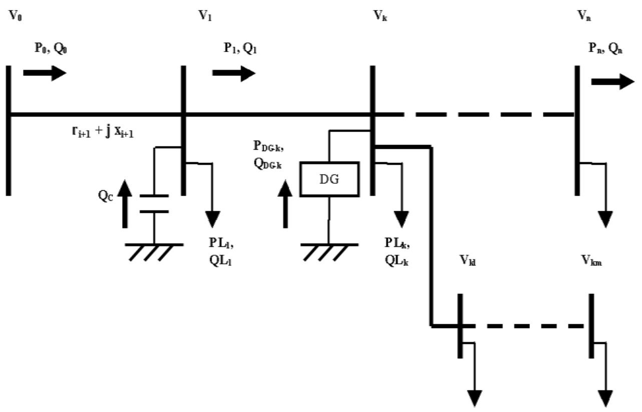


Fig. 1: Single line diagram of a Radial distribution system

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} \cdot \left(\frac{P_i^2 + Q_i^2}{|V_i|^2} \right) \tag{1}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} \cdot \left(\frac{P_i^2 + Q_i^2}{|V_i|^2} \right) \tag{2}$$

Where P_i is the real power flow into the sending end of branch $i+1$connecting bus i and bus $i+1$; $P_{Li+1}$is real component of load at bus $i+1$; $R_{i,i+1}$ is the resistance of line section between buses i and $i+1$and V_i is the bus voltage magnitude at bus $_i$. Q_i is the reactive power flow into the sending end of branch $i+1$connecting bus i and bus $i+1$; $Q_{Li+1}$is reactive component of load at bus $i+1$; $X_{i,i+1}$is the reactance of line section between buses i and$i+1$.

The problem of capacitor allotment with their proper capacities is of great importance. The installation of shunt capacitors at non-optimal places can result in an increase in system losses, voltage deviations and costs. Therefore, a power system planning engineer requires an efficient and fast optimization method capable of indicating the best solution for a given distribution network. The selection of the best places for installation and the preferable sizes of the shunt capacitor banks in large distribution systems is a complex discrete optimization problem. In order to incorporate the proposed method recursive equations (1) and (2) are modified as follows:

2.1 Real Power Flow with Installation of Shunt Capacitor

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} \cdot \left(\frac{P_i^2 + Q_i^2}{|V_i|^2} \right) + AP_{i+1} \cdot \mu P \tag{3}$$

Where$AP_{i+1}$is shunt capacitor active power magnitude injected at bus$i+1$; $\mu P$is shunt capacitor power multiplier, set to zero when there is no shunt capacitor power source or set to 1 when there is active power source.

2.2 Reactive Power Flow with Shunt Capacitor Placement

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} \cdot \left(\frac{P_i^2 + Q_i^2}{|V_i|^2} \right) + RP_{i+1} \cdot \mu Q \tag{4}$$

Where$RP_{i+1}$is shunt capacitor reactive power magnitude injected at bus $i+1$;$\mu Q$is Shunt capacitor power multiplier, set to zero when there is no capacitor power source or set to 1 when there is a capacitor power source.

2.3 Computation of Bus Voltages

$$V_{i+1}^{\ 2} = V_i^2 - 2(R_{i,i+1}.P_i + X_{i,i+1}.Q_i) + (R_{i,i+1}^{\ \ 2} + X_{i,i+1}^{\ \ 2}). \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{5}$$

3. PROBLEM FORMULATION

The following sections describe the details of the proposed problem formulation.

3.1 The Objective Functions

The main advantages of Shunt capacitors in the distribution system are loss minimization in the feeders and the improvement in the voltage profile, i.e. maintaining the voltages at customer terminals with reactive power compensation. The following functions are computed using the proposed algorithm: Total Line Loss (TLL), Total Voltage Deviation (TVD).

3.2 Total Line Loss (TLL)

The installation capacitor banks should not result in an increase in the system losses. The power loss of the line section connecting buses i and $i+1$ is computed as:

$$P_{loss}(i, i+1) = R_{i,i+1} * \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{6}$$

$$TLL = \sum_{i}^{n-1} P_{loss}(i, i+1) \tag{7}$$

3.3. Total Voltage Deviation (TVD)

Voltage deviation can also be minimized with integration of Shunt capacitors. The total voltage deviation (TVD) in the system, which is to be minimized, is expressed as:

$$TVD = \sum_{i1}^{n-1} |1 - V_i| \tag{8}$$

Where i=1, 2, 3……..n and V_i is the voltage of ith bus in per unit for the system buses; the ideal magnitude of each bus voltage is unity.

3.4 Constraints

The following constraints are considered [20].

i) Total Power Conservation:
The algebraic summation of all incoming and outgoing powers over the feeders, taking into consideration the feeders' losses and the powers supplied by Shunt capacitors should be equal to the total demand at that bus.

ii) Distribution Feeder's Thermal Capacity:
Power flows in feeders must be within their capacities.

iii) Distribution Substation's Capacity:
The summation of total powers delivered to the network by the substation's transformers must be within the substation's capacity limit.

iv) Shunt capacitor Operation Limits:
The Shunt capacitor's generated power must be within the Shunt capacitor's capacity.

v) Voltage Drop Limits:
The voltage levels at different buses must be within predetermined values.

4. PROPOSED BINARY GRAVITATIONAL SEARCH ALGORITHM

The conventional GSA was originally designed to solve problems in continuous valued space [6]. The search algorithm is based on the metaphor of gravitational interaction between masses in the Newton theory. A jth bit of the ith agent (x_{ij}) in a system is represented as a bit 0 or 1 where a combination of bits gives the ith agent position.

The next agent's velocity $(v_{ij})$is calculated based on its current velocity and its acceleration as expressed in (9). Then, a new agent's position (x_{ij}) is updated using a condition as shown in (11). However, the velocity is limited in interval [-6, 6] so as to achieve a good convergence rate.

$$v_{ij}(t+1) = r^* v_{ij}(t) + a_{ij}(t) \qquad (9)$$

$$Sigmoid\left(v_i^{\,d}\right) = \frac{1}{1+e^{-v_i^{\,d}}} \qquad (10)$$

$$x_i^{\,d} = \begin{cases} 0, \text{if } r >= sigmoid\left(v_i^{\,d}\right) \\ 1, otherwise \end{cases} \qquad (11)$$

5. SIMULATION RESULTS AND DISCUSSION

To demonstrate the performance of the proposed BGSA in solving the optimal shunt capacitor placement problem, the IEEE 12-bus distribution system is used in this study. In this paper, for this test system, TLL and TVD were minimized and compared to the conventional BPSO as to illustrate its performance in solving the same problem. All the optimization parameters are standardized where population size and maximum population are set to 60 and 100, respectively. In the BPSO, two positive coefficients are set to 2 ($c1 = c2 = 2$) and inertia weight, (w) monotonously decreases from 0.9 ($w_{\max}$) to 0.4 ($w_{\min}$). In the BGSA, the initial gravity constant, G0 is set to 100 and the best applying force, (K_{best}) is monotonously decreased from 100% (K_{bestmax}) to 2.5% (K_{bestmin}). The proposed BGSA algorithm has been implemented on IEEE 12-bus radial distribution network.

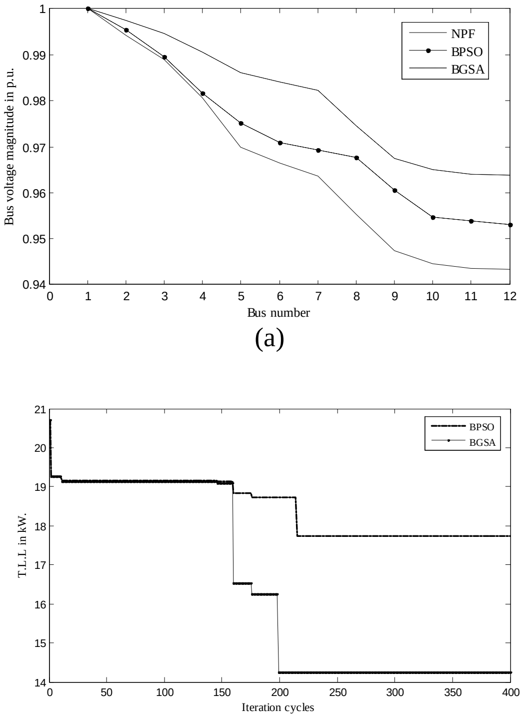
IEEE 12-Bus [21] has single line main feeder (Base Voltage = 11 KV, Base MVA = 0.1 MVA) without laterals and sublaterals and having total active and reactive powers of 435 kW and 81 kVAR, respectively. Without any injection of shunt capacitors' reactive powers, the normal power flow (NPF) yields Total Line Loss (TLL) and total voltage deviation (TVD) as 20.7138 kW and 0.4020 p.u. respectively.

5.1 Total Line Loss (TLL) Minimization

With no constraints on the total capacities of Shunt capacitors, convergence characteristics of lossminimization and voltageprofile obtained by different algorithms are depicted in Fig. 2(a) and 2(b) respectively. It is observed from Table 3, voltage profile is improved as that of BPSO, and lowest bus voltage increased 1.02% by BPSO whereas in Binary GSA, it is improved by 2.17 %. In TLL minimization, TLL is reduced from 20.7138 kW to 12.2455 kW in case of BGSA, where as in BPSO it reduces to 17.7354 kW only and TVD is minimized from 0.4020 p.u. to 0.1993 p.u. and 0.2353 p.u. by BGSA and BPSO, respectively with injection of optimal placement of Shunt capacitors, as indicated in Table 1. From Table 4, it is observed three Shunt capacitors, each of 25 kVAR capacity, equivalent to total 75 kVAR, are optimally placed for TLL minimization in BGSA approach but, in BPSO, total capacities of shunt capacitors is seems to be more.

5.2 Total Voltage Deviation (TVD) Minimization

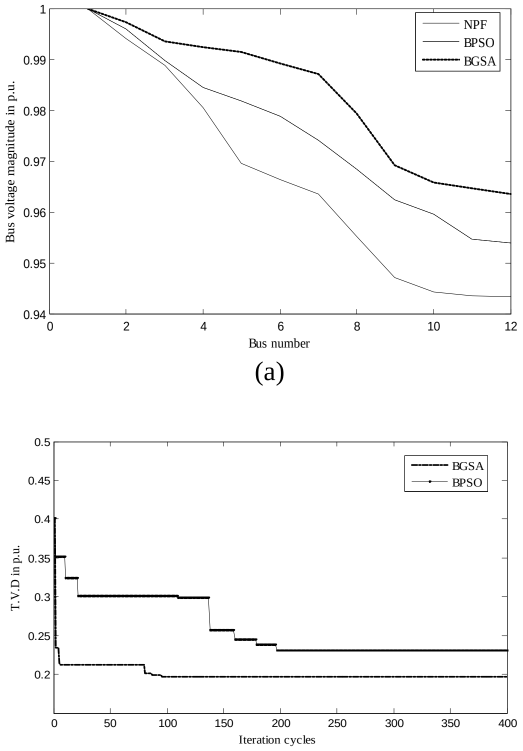
Fig. 2(a) represents voltage profile of IEEE 12-bus radial distribution system obtained by optimization techniques (BPSO, BGSA) and normal power flow (NPF). It can be seen that voltage profile is improved as that of BPSO, lowest bus voltage increased 1.13% by BPSO whereas in Binary GSA, it is improved by 2.15%, as seen from Table 3. Convergence characteristic of TVD minimization is shown in Fig. 3(b). It can be found from Table 5, three Shunt Capacitors (at 2nd, 3rd and 8th bus position), each of 25 kVAR capacity, are equivalent to total 75 KVAR optimally placed in BGSA. Some more capacity of Shunt capacitors is used in BPSO technique for TVD minimization.



(a)

(b)

Fig. 2: TLL Minimization Characteristics of IEEE 12 Bus Radial Distribution System; (a) Voltage profile obtained by different algorithms, (b) Convergence characteristics



(a)

(b)

Fig. 3: TVD Minimization Characteristics of IEEE 12 Bus Radial Distribution System; (a) Voltage profile obtained by different algorithms, (b) Convergence characteristics.

6. CONCLUSION

This paper presented a BGSA and a comparative performance of BGSA and BPSO in solving the two separate single-objective optimization problem for optimal Shunt capacitor placement in IEEE radial distribution test system. The optimization techniques have been tested on this distribution test system for determining the best optimal Shunt capacitor placements for TLL and TVD minimization. The comparative results showed that the proposed BGSA is the most effective and precise among the aforementioned optimization techniques. In conclusion, the authors' contribution in this work is successful application of a binary GSA algorithm for simultaneous solution of optimal number and placements of Shunt capacitors in a balanced distribution system.

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Table 1: Comparative Study Of TLL Minimization Ieee 12-Bus Test System

Test System	NPF (kW)	BPSO (kW)	% Improvement in BPSO over NPF	BGSA (kW)	% Improvement in BGSA over NPF
EEE 12-Bus	20.7138	17.7354	14.37	14.2455	31.22

Table 2: Comparative Study Of TVD Minimization Ieee 12-Bus Test System

Test System	NPF (p.u.)	BPSO (p.u.)	% Improvement in BPSO over NPF	BGSA (p.u.)	% Improvement in BCAB over NPF
IEEE 12-Bus	0.4020	0.2312	42.48	0.1963	51.16

Table 3: Comparative Study Of Lowest Bus Voltage Improvement in Tll and TvdMinimization Ieee 12-Bus Test System

Test System	TLL Minimization					TVD Minimization			
	NPF (p.u.)	BPSO (p.u.)	% Improvement in BPSO over NPF	BGSA (p.u.)	% Improvement in BGSA over NPF	BPSO (p.u.)	% Improvement in BPSO over NPF	BGSA (p.u.)	% Improvement in BGSA over NPF
IEEE 12-Bus	.9434	.9531	1.02	.9639	2.17	.9541	1.13	.9637	2.15

Table 4: Optimal Locations Of Shunt capacitors for TLL Minimization Ieee 12-Bus Test System

Test System	BPSO		BGSA	
	Shunt Capacitors (kVAR)	Optimal locations of shunt capacitors	Shunt Capacitors (kVAR)	Optimal locations of shunt capacitors
IEEE 12-Bus	100	[2,4,5,7], each capacitor of 25kVAR	75	[2,3,5], each capacitor of 25kVAR

Table 5: Optimal Locations Of Shunt capacitors for Tvd Minimization Ieee 12-Bus Test System

Test System	BPSO		BGSA	
	Shunt Capacitors (kVAR)	Optimal locations of shunt capacitors	Shunt Capacitors (kVAR)	Optimal locations of shunt capacitors
IEEE 12-Bus	100	[2,4,5,7], each capacitor of 25kVAR	75	[2,3,5], each capacitor of 25kVAR