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Full paper

An Optimal Load Shedding Methodology for Radial Power Distribution Systems to Improve Static Voltage Stability Margin using Gravity Search Algorithm

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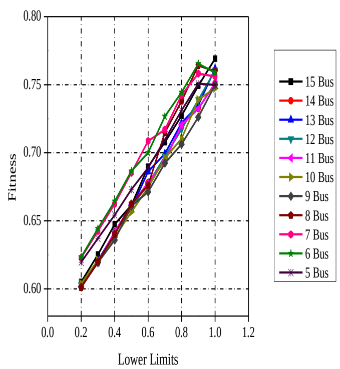
Graphical abstract



Abstract

Voltage stability is one of the major concerns in operational and planning of modern power system. Many strategies have been implemented to avoid voltage collapse, which the load shedding considered as the last option. However, optimization is needed to estimate the minimum amount to shed so as to prevent voltage instability. In this paper, an effective method is presented for estimating the optimal amount of load to be shed in a distribution system based on the gravitational search algorithm (GSA). The voltage stability margin (VSM) of the system has been considered in the objective function. The optimization problem is formulated to maximize the VSM of the system and at the same time satisfying the operation and security constraints. The optimum solution depends on the predefined constraints such as the number of load buses available to shed and the maximum amount of load permitted to shed. Simulation result conducted on the IEEE 33 bus radial distribution system shows that the system voltage stability can be improved by optimally shedding the loads at critical system buses. The results also indicate that the numbers of load buses available for load shedding does not have a significant impact on voltage stability margin, but it is highly dependent on the maximum amount of load permitted to shed.

Keywords: Voltage stability margin (VSM); gravity search algorithm (GSA); linear static index; Radial Distribution system (RDS)

1.0 INTRODUCTION

The main function of power system is to supply electricity to all consumers. However, when the system is in an unstable condition, only a certain amount of electricity can be supplied. Thus, in many cases part of the system load needs to be shed in order to make sure the system is stable and able to provide power to critical loads.

Various methods have been used to determine the amount of load to be shed. For instance, traditional load shedding has been applied in where it sheds a fixed amount load with decreasing frequency [1, 2]. Aoki *et al.* proposed a load curtailment procedure where it considers violation vector with current capacity and also voltage drops [3]. Deb C. and Bhujanga B.C presented a control method to prevent voltage instability using a dynamic model of load shedding [4]. The load shedding scheme by Shilling, S.R. showed that the high speed under frequency relays can be utilized to maintain the power supply to important loads during the disturbance [5]. Bansilal *et al.* introduced a nonlinear least squares optimization algorithm for voltage stability enhancement by utilizing the L-index proposed in [6, 7]. In an improvement voltage instability proximity index (VIPI) has been developed by utilizing the successive quadratic programming method and controlling the specific sensitivity value of VIPI with respect to control variable [8]. In the work of Hamada *et al.* [9], a new static voltage stability index for radial distribution system was introduced where the effectiveness of the index has been tested with two relatively large distributed systems. These new indexes could be utilized for load shedding considering voltage stability as the main criteria for load shedding.

Recently, some heuristic optimization approaches has been applied to solve the load shedding problem where the goal is to determine the optimal amount of load shed. These techniques include the application genetic algorithm (GA) [10-12], particle swarm optimization (PSO) [13-17]and linear optimization (LP) based on optimal power flow [18-20]. Generally, most of the optimum load shedding scheme utilized the L-index in the objective function. However, none of previous research works applied the linear static voltage stability margin (VSM) index in the objective function for solving the optimal load shedding problem. The advantages of using the VSM index in optimal load curtailment are its adaptability to distribution system, linear relationship between loading level and voltage stability and its simple calculation steps. Therefore, in this paper, the VSM is suggested as the main criterion for optimal load shedding problem formulation. The GSA is applied to solve the optimal load shedding problem. The proposed method is applied to IEEE 33 radial distribution system (RDS) network to validate the effectiveness of GSA in determining the numbers of load buses available to shed and maximum amount of load permitted to shed.

2.0 VOLTAGE STABILITY MARGIN AS LOADING LEVEL

The voltage stability margin index was first proposed by M. H. Haque[21], where it is based on a typical radial feeder of a distribution system as illustrated in Figure 1.

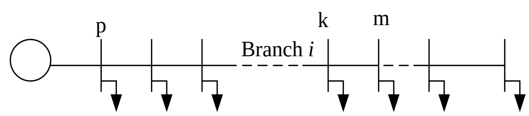


Figure 1 Typical radial feeder of distribution system[7]

$$L_i = \left(2\frac{V_m}{V_k}\cos\partial_{km} - 1\right)^2 \tag{1}$$

As stated in M. H. Haque the *Li* index shown in Equation (1) provides a better estimation of maximum load level of a single line section and can be used any loading levels due to its linear relationship with voltage stability [21]. Due to its linear relationship, it can be utilized to represents the voltage stability at any loading level of any line section in the system. Like others voltage stability indexes, the *Li* also varies between unity (at no load) and zero (at voltage collapse point). For a multiple feeder system, the VSM of a feeder can be evaluated as the product of loading indices for all branches of the feeder as shown in Equation (2).

$$VSM = \prod_{i\in\Omega} L_i \tag{2}$$

Where, Ω is a set of branches constituting the feeder (from source bus *p* to end bus *q*). Practically, the distribution system may consist of more than one feeder. Thus, the voltage stability of the system (VSM_{sys}) for multiple feeders can be considered as

$$VSM_{sys} = \min(VSM_1, VSM_2, ...VSM_k) \tag{3}$$

Where, *k* is the number of feeders in the system.

3.0 PROBLEM FORMULATION

The optimization objective associated with the load shedding process in distribution network considers voltage stability criterion. Therefore, in the proposed method the optimization problem is carefully formulated to maximize the VSM as follows.

$$f = \max(VSMsys) \tag{4}$$

And it is subjected to the following system constraints:

(i) Power flow balance: During the optimization process, the total power generation should be equal to the total consumption by the load and losses as shown in the following equations.

$$\sum P_{gi} - \sum P_{di} - P_{loss} = 0 \tag{5}$$

$$\sum Q_{gi} - \sum Q_{di} - Q_{loss} = 0 \tag{6}$$

(ii) Power flow limit: The apparent power, S_l that is transmitted through the branch l must not exceed the maximum thermal limit $S_{l\text{-}max}$ in steady state operation.

$$S_l \le S_{l-\max} \tag{7}$$

(iii) To prevent voltage instability of the system, the bus voltage at each bus *i* must be maintained around its normal value V_i within a permissible voltage band, specified as [$V_{i\text{-}min}$, $V_{i\text{-}max}$], where $V_{i\text{-}min}$ is the minimum permissible value of the voltage at bus *i*, and $V_{i\text{-}max}$ is the maximum permissible voltage at bus *i*. These limits can be expressed in terms of an inequality function as:

$$V_{i-\min} \le V_i \le V_{i-\max} \tag{8}$$

(iv) The chosen load to be shed during the optimization process should be maintained within a permissible band, specified as [$S_{i\text{-}min}$,,S_i], where $S_{i\text{-}min}$ is the minimum permissible value and S_i is the load at bus *i* before load shedding. These limits can be expressed in term of inequality function as

$$S_{i-\min} \le S_i \tag{9}$$

The constraints illustrated in Equation (5)-(9) are determined by performing load flow solution at the objective function evaluation stage in the optimization process.

4.0 IMPLEMENTATION OF GSA TO SOLVE LOAD SHEDDING PROBLEM

GSA algorithm has been developed for solving the real-value numerical optimization problems. GSA algorithm has been inspired by the universal gravitational laws [22]. Random solution of the respective problem desired to be solved in GSA have been modeled as fictitious objects that apply gravitational force to each other. The mass of fictitious objects is related to the quality of the solution that a fictitious object provides for the respective problem. The higher the quality of the solution, slower the speed that a fictitious body abandons that position due to the gravitation force applied to it by other fictitious objects. The speed of the fictitious objects with inferior quality of solution is higher in the search-space. This phenomenon allows GSA to search the search space very efficiently to find a solution for a problem. The following describes the GSA implementation to solve optimum load shedding problem.

Step 1: Input system data: This includes bus data and branch data. Also the number of load busses available to shed (X_{bus}) and maximum amount of load permitted to shed (L_{factor}).
Step 2: Initialization: Randomly generate the population of 50 agents that contains the bus number (X_{bus}) and amount of load permitted to shed (L_{factor}).Generated agent is uniformly distributed in the range of [$S_{i\text{-}min}$, S_i] with no repeated elements in each of X_{bus}.
Step 3: Run the power flow program and evaluate the fitness of each agent using Equation (4).
Step 4: Set iteration number to 1.
Step 5: Calculate mass and acceleration and update the position and velocity of the agents.
Step 6: Run the load flow and re-evaluate the fitness of each agents.
Step 7: If the iteration count is less than 1000 repeats from **step 3**. Otherwise stop and print the results.

Figure 2 shows the flow chart of the GSA implementation procedure in load shedding.

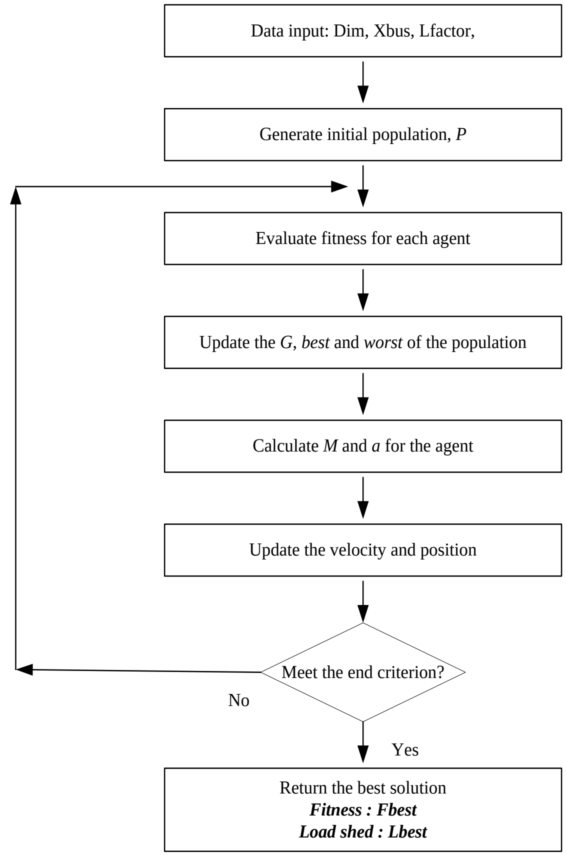


Figure 2 Optimum load shedding procedure using GSA

5.0 RESULTS AND DISCUSSION

To evaluate the performance of the proposed GSA, the IEEE 33 bus system is studied. It is a balance three-phase system that consists of 33 buses and 32 branches, operating at 11 kV voltage level. It is assumed that the bus is fed from the main substation connected at bus 1. The system contains 32 loads totaling 3.72 MW and 2.29 MVar, real and reactive power loads respectively. The initial base load of the system studied is taken from M. Hamada *et al*. [9]. The conventional GSA is implemented in order to evaluate its performance in solving the optimal load shed problems [22].

Figure 3 shows the single line diagram of the IEEE 33 RDS with one main feeder and three sub-feeder. The set of branches between any two busses in each feeder is given as follows:-

Feeder 1: Ω_1= [1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17]
Feeder 2: Ω_2= [18-19-20-21]
Feeder 3: Ω_3= [22-23-24]
Feeder 4: Ω_4= [25-26-27-28-29-30-31-32]

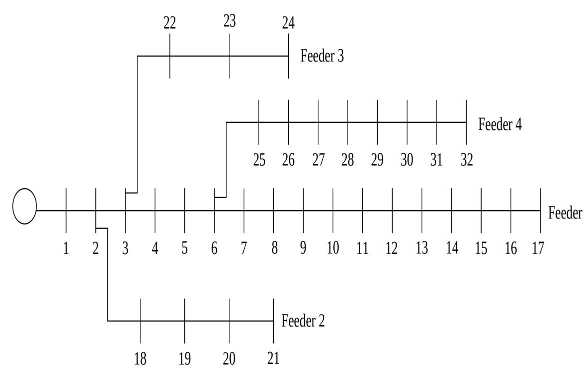


Figure 3 Single line diagrams of the IEEE 33-bus system

CASE STUDY 1: When only five buses are available to shed with 0.6 as their lower limits

In this case it is assumed that only 5 out of 33 buses are allowed to be considered for load shedding. It is further constrained by imposing the lowest limit as 60% of base case apparent power. The purposed of this case study is to improve system voltage stability margin, VSM_{sys}, as much as possible and identify the five optimum location (buses) and optimum load to be shed at those buses. Figure 4 illustrated the convergence characteristics of the GSA in obtaining the best optimal solution for the cases, where the maximum VSM_{sys} is found to be 0.67359 compared with the VSM_{sys} before the optimization, which is 0.56534. Figure 5 shows the corresponding voltage profile before and after the load is curtained from the system. From Figure 5, it can be noted that before load shed the voltage profile of the system is unacceptable where some of the system bus voltage are below 0.9 p.u. However, after the optimum load curtailment, the voltage profile of the system is improved with minimum bus voltage 0.91 p.u at bus 17. In this case, the total load curtailment is 0.4 MW, which is 10.76% of the total base case load. Figure 6 exhibits the loading level of the system buses before and after optimum load shedding. From Figure 6, it can be seen that only 5 bus loads namely buses 8, 14, 17, 18 and 30 are curtailed. These buses are signified as optimum location to shed the load when the number of available buses to shed is constrained to 5.

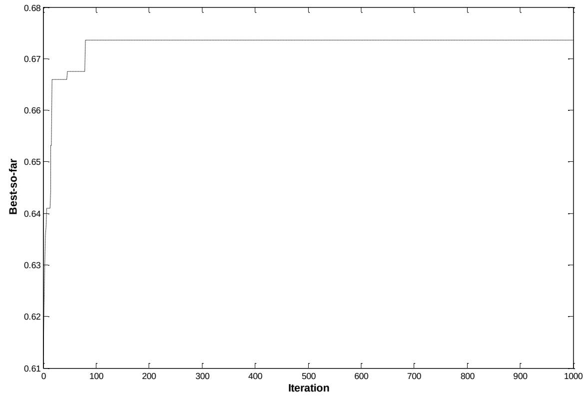


Figure 4 The convergence characteristic of GSA for case study 1

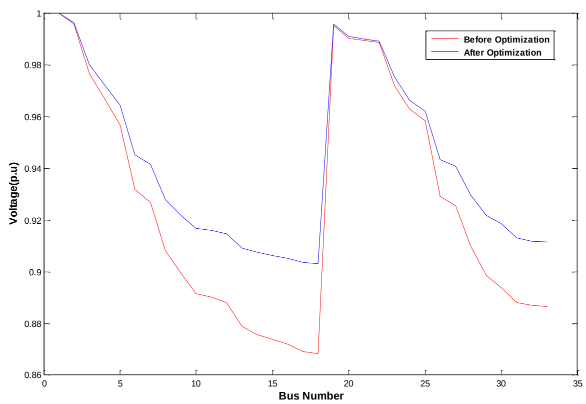


Figure 5 Voltage profile before and after load shedding for study case 1

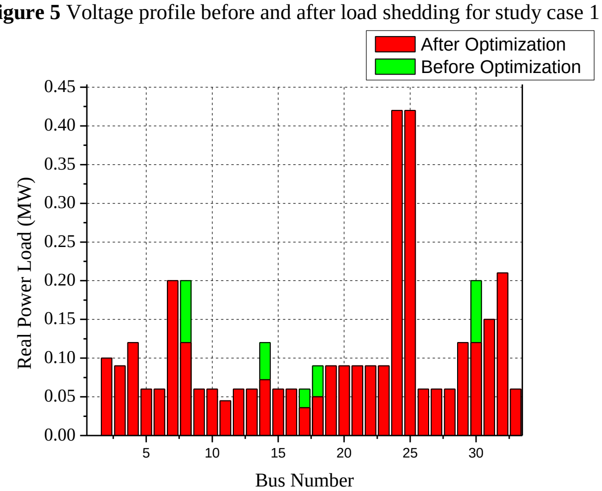


Figure 6 Optimal load curtailments for study case 1

CASE STUDY 2: When 10 buses are available to shed with 0.6 as their lower limit

The aim of this study case is to investigate the effect of increasing the number of available buses to shed the load while improving the voltage stability margin of the system as much as possible. In this case it is assumed that only 10 out of 33 buses are allowed to use for load shedding with 60% as the allowable lower limit to cut. Similar to the previous case, Figure 7 shows the convergence characteristics of the GSA in obtaining the best optimal solution. The best fitness value, VSM_{sys} in this case is found to be 0.6786. This is 20.05% improvement in terms of voltage stability margin from the base case cases. While this is just a 0.88% improvement from the case studies 1. Thus, it shows that there is no much improvement in voltage stability if it is allowed to curtail load in more locations. To illustrate further the improvement for this case, the voltage profile of the system is plotted in Figure 8. This figure also shows similar trend in voltage profile improvement as in the case study one. However, the voltage at bus 17 (worst bus voltage) is 0.89 p.u which is lower than in case study one (0.91 p.u). Optimum amount of load to be curtailed is found to be 0.60365 MW as illustrated in Figure 9. In this case 16.13% of total load is removed from the system to achieve similar voltage stability margin of the system. The optimum locations to shed are from buses 8, 12, 13, 14, 17, 18, 24, 29 and 30. By comparing both case study one and two, it can be noted that although the number of variable buses to be shed increases, it may not improve the voltage stability of the system.

To observe the effect of increasing the lower limit of load that can be shed, similar studies were conducted by decreasing the lower limits of available load buses that can be used to shed. Figure 10 illustrate the VSM_{sys} fitness versus the lower limit of the load. From the figure, it can be seen, lower limit of loads is more appropriate variable, rather than the number of available buses, that can be used to control the load shedding scheme.

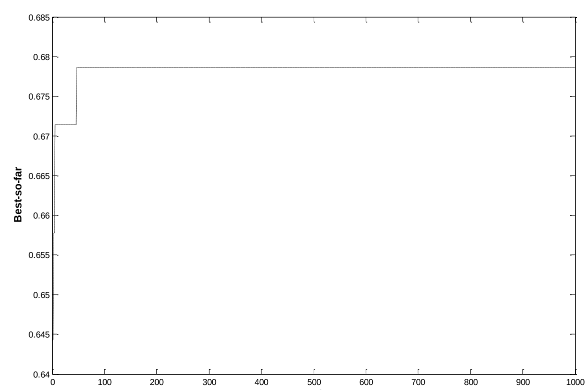


Figure 7 The convergence characteristic of GSA for case study 2

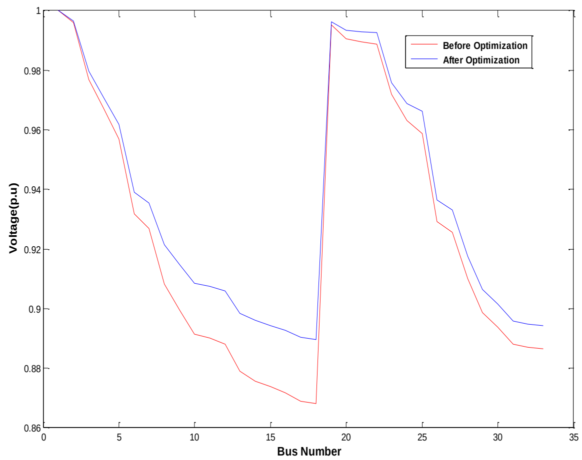


Figure 8 Voltage profile before and after load shedding for study case 2

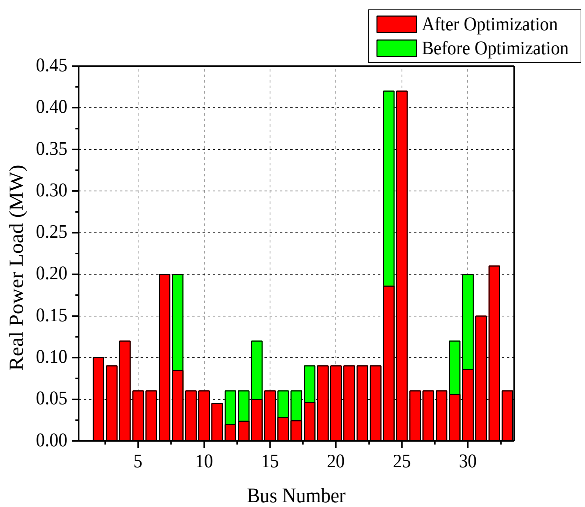


Figure 9 Optimal load curtailments for study case 2

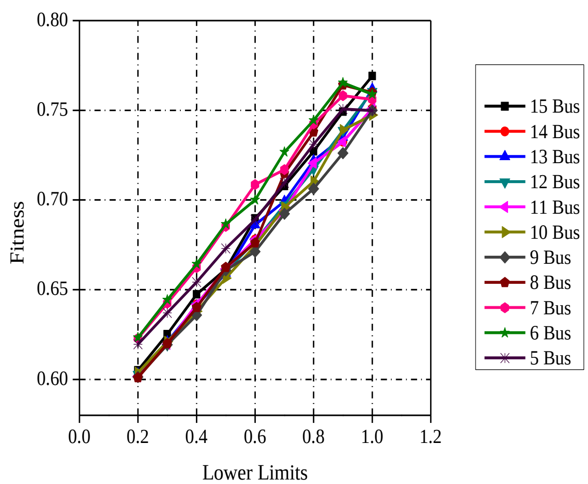


Figure 10 Effect of increasing the lower limit of load that can be shed

6.0 CONCLUSION

This paper proposed a method of optimal load shedding in radial distribution network using linear static VSM with GSA. The aim of the problem formulation is to maximize the system voltage stability margin by controlling the number of available load to be shed and also the amount load permitted to be shed. The simulation results on the IEEE 33 network show that the proposed GSA is effective in evaluating the optimum amount of load to be shed. In addition, the results indicated that by increasing the numbers of load buses to shed do not have significant impact on voltage stability margin, but it is highly dependent on the maximum amount of load to be shed.

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