# Voltage Stability Maximization by Distribution Network Reconfiguration Using a Hybrid Algorithm

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**Abstract.** Voltage stability maximization by Distribution Network Reconfiguration (DNR) is the process of finding a network configuration offering the least voltage deviation at the buses. Through the use of an Improved Voltage Deviation Index (IVDI) the stability of the entire distribution network has been studied. Using a hybrid algorithm, the DNR problem was tested on 6 standard test systems: 16, 33, 70, 118, 135 and 880 bus systems. The results showed that DNR using the IVDI can indeed lead to the improvement of the entire system stability.

**Keywords:** Distribution network reconfiguration · Hybrid flower pollination algorithm · Hybrid genetic algorithm · Power distribution systems · Voltage stability maximization · Improved voltage deviation index · Radial networks

## 1 Introduction

Nowadays, the need to save our finite energy resources has led to a greater emphasis on energy efficiency and hence power loss reduction. But, this should not be at the expense of the reliability of our power systems. Indeed, voltage instability often translates into voltage collapse, which in turn leads to blackout or abnormally low voltage levels at the buses of our distribution networks [1]. Thus, the maximization of voltage stability is mandatory.

Throughout the years, various techniques have been formulated to determine the stability of the buses: the use of P-V and Q-V curves, L-index, FVSI, LQP, VCPI, modal analysis, amongst others [2]. In this way, the determination of the weakest bus was possible and from that appropriate measures, such as the installation of capacitors, tap-changing transformers and other related switching equipment could be done. However, through these techniques, only the stability of the weakest bus was improved and also additional costly resources were required.

This research therefore proposes a cost-free approach to the problem. Through the use of Distribution Network Reconfiguration (DNR), the mere opening of sectionalizing switches and the closing of tie switches finds a radial network configuration with improved stability [3]. But the complexity of DNR lies with its associated algorithm. In [4] the efficiency of a hybrid algorithm is shown through increasingly difficult problems


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using DNR for power loss reduction. Hence, this paper uses the same hybrid algorithm for the maximization of voltage stability (Sect. 5). Moreover, an improved voltage deviation index (IVDI) is presented which enables the analysis of the entire network's stability, rather than just the weakest bus of the system (Sect. 3). This paper hence demonstrates:

(i) The ability of DNR to improve the stability of the entire distribution network through the use of the IVDI (Sect. 7.1).
(ii) The effectiveness of the IVDI in the analysis of the network stability (Sect. 7.2).
(iii) The efficiency of the hybrid algorithm irrespective of the optimization case (Sect. 7.3).

## 2 Problem Definition

The main aim of this paper is the voltage stability maximization in radial distribution networks, by DNR using the hybrid algorithm presented in [4], while ensuring that the analysis is close to real life conditions. Therefore, the objective function can be presented as follows.

Minimise f = Total Voltage Deviation

Subject to the following constraints:

1. Radial Network

   Only the radial network configurations are considered while the non-radial one are penalized.

$$\varphi(x) = 0$$

2. Kirchhoff's Current Law

$$g_i(I, k) = 0$$

3. Kirchhoff's Voltage Law

$$g_i(V, k) = 0$$

## 3 The Improved Voltage Deviation Index (IVDI)

For the analysis of the stability of a network, this section shows an improvement to the Voltage Deviation Index (VDI) in [5]. The principle of the VDI basically implies that the closer the voltage level of a particular load bus is to the generator bus, the lesser the voltage deviation of the load bus and therefore the greater its stability. While being able to provide a direct and easy method to stability analysis, the only limitation of the method is that the voltage stability of a particular network configuration was determined by the stability of the weakest bus only. Thus, an extension is made to the method to enable the analysis of the entire system's stability.

The stability analysis begins with a load flow implementation, which determines the voltage level at each bus. In [6], a fast and efficient technique is proposed. Through the construction of a bus-injection to branch-current (BIBC) and a branch-current to bus-voltage (BCBV) a DLF matrix is formed, which can then be used to solve Eqs. (1–3) iteratively.

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{1}$$

$$\left[\Delta V^{k+1}\right] = [DLF]\left[I^k\right] \tag{2}$$

$$\left[V^{k+1}\right] = \left[V^0\right] + \left[\Delta V^{k+1}\right] \tag{3}$$

where $V_i^k$ and $I_i^k$ are the bus voltage and equivalent current injection of the bus $i$ at the $k^{th}$ iteration. $P_i$ and $Q_i$ represent the real and reactive power of the bus respectively.

Using the bus voltage levels obtained, the absolute values are taken and converted into per unit. Substituting these values in Eq. (4), the voltage deviation at each bus is calculated [5].

$$\Delta V_{D_i} = \frac{V_G - V_i}{V_G} \tag{4}$$

where
$V_G$ : Voltage at the Generator node (1 pu)
$V_i$ : Absolute Voltage at the Load Bus
$\Delta V_{D_i}$ : Voltage deviation Index at a bus

The total stability of a particular network configuration was finally found through the addition of the total voltage deviation of all the buses in the system using Eq. (5).

$$V_D = \sum_i^N \Delta V_{D_i} \tag{5}$$

where
$V_D$ : Total voltage deviation of the system
$N$ : Total number of load buses

Therefore, the smaller the value of $V_D$ the greater the voltage stability of the distribution network.

# 4 Mathematical Modelling of DNR

In this paper, the maximization of the voltage stability of radial distribution networks is being considered. Thus, to ensure radiality, there is a predefined number of sectionalized switches and tie switches for any distribution network. In this paper, tie switch numbers in an array are used to represent a particular network configuration. The tie switch can be any branch number of the system.

## 4.1 The Repair Algorithm

Repetition in tie switch number is not allowed for any configuration. A repair algorithm [4] was immediately applied if such a configuration was detected such that a unique copy of the switch numbers were retained and new switch numbers were generated to fill in the array.

# 5 The Hybrid Algorithm

In [4], a hybrid algorithm is presented which combines deterministic refinements to any heuristic algorithm. This paper considers the hybridization of 2 heuristic algorithms: Genetic Algorithm (GA) and Flower Pollination Algorithm (FPA). GA consists of a selection, crossover and mutation parameter while FPA makes use of the concept of local and global pollination. However due to this greedy search, obtaining the true global solution becomes difficult. Hence, the following refinements are included in the algorithms.

1. Use of a 'warm start'
   This is achieved through the inclusion of the initial configuration in the initial search.
2. Elitism
   This involves the retention of good solutions after each computation process of the algorithm to prevent loss of solutions.
3. Hill Climbing Strategy
   This is a local search which enables the finding of better solutions by opening 'n' sectionalized switches and simultaneously closing 'n' tie switches.

# 6 DNR Using HGA and HFPA

The same technique as in [4] is used for the application of the hybrid algorithm to the DNR problem, with the only difference in the objective function. Figures 1 and 2 give a description of the steps for the implementation of the hybrid GA (HGA) and the hybrid FPA (HFPA), respectively.

Regardless of the algorithm, the fitness of any individual can be evaluated using Eq. 6.

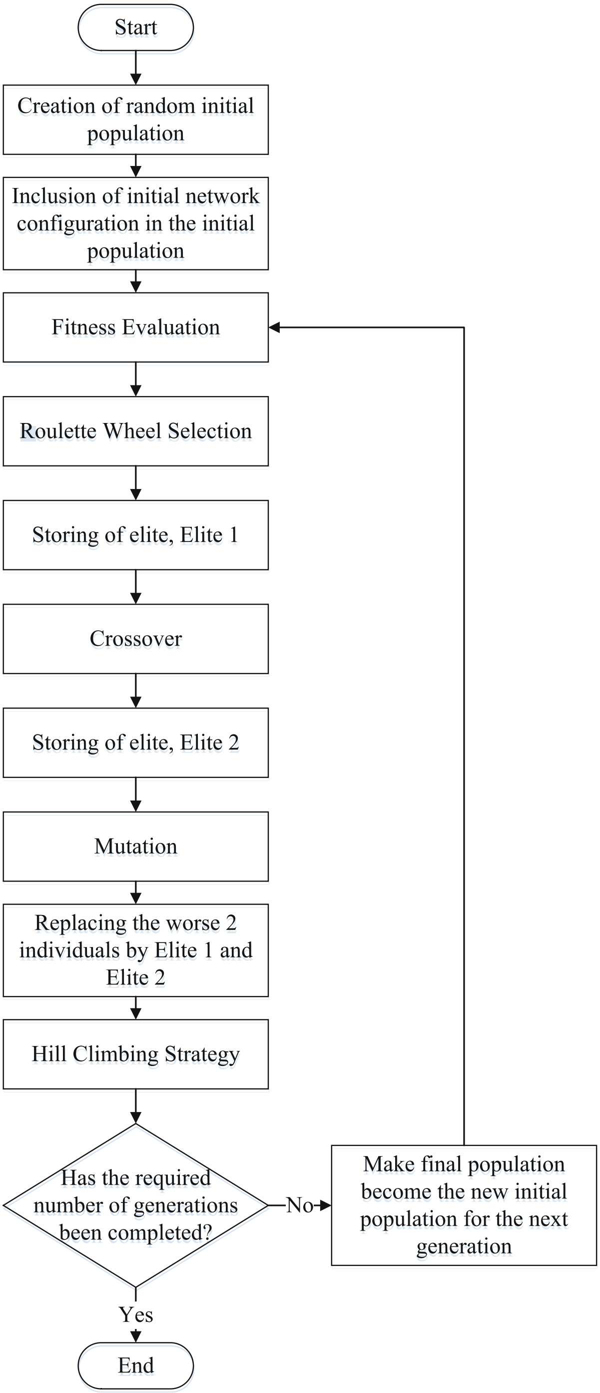


**Fig. 1.** Flowchart of HGA

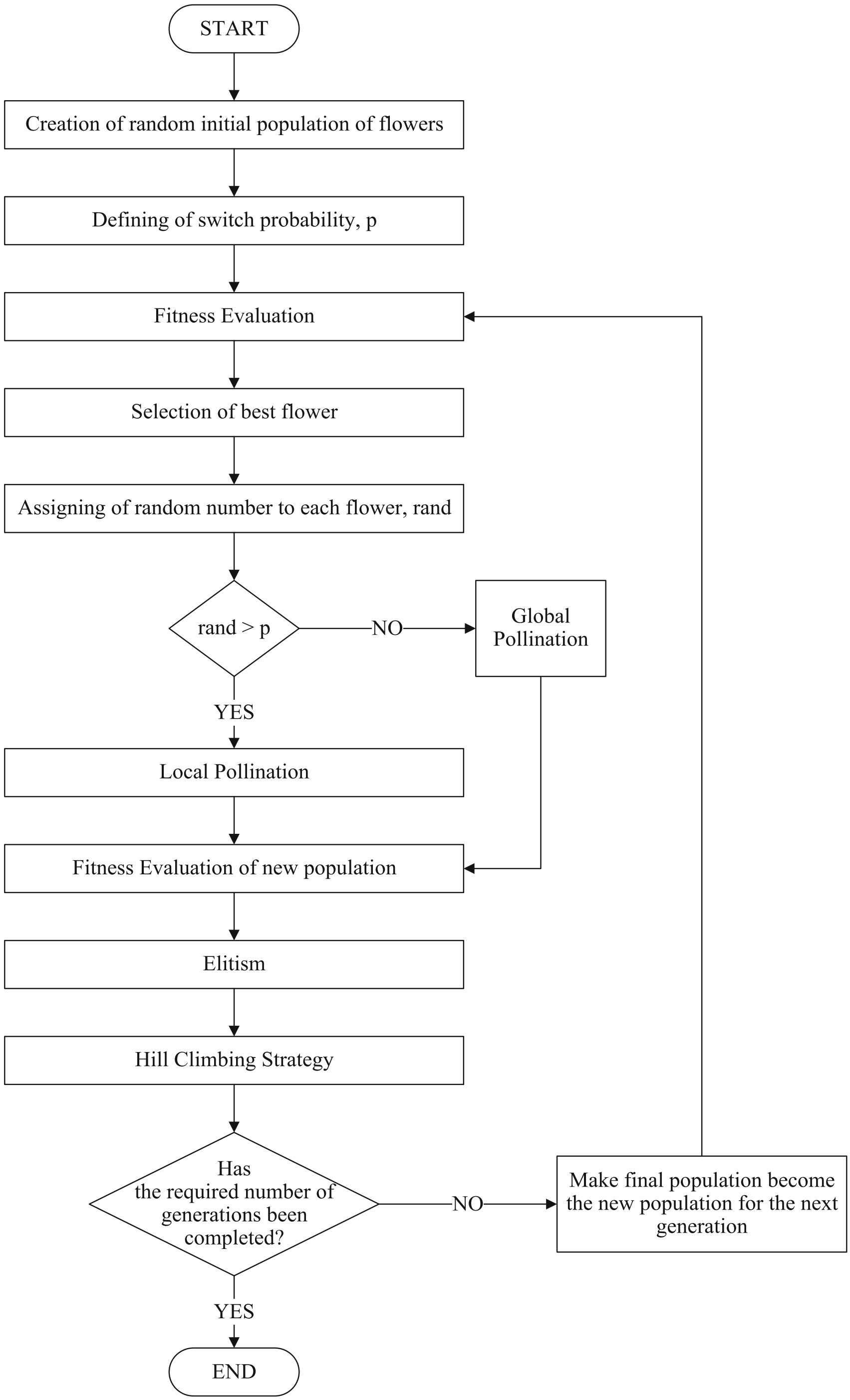


**Fig. 2.** Flowchart of HFPA

$$f'(x) = \frac{1}{f(x) + \varphi(x)} \tag{6}$$

where

$x$ : Individual under test

$f'(x)$ : Fitness function

$f(x)$ : Objective function (Total Voltage Deviation)

$\varphi(x)$ : Constraint

## 7 Results

For this research, all programming was done using the MATLAB R2013a software. The simulations were performed using an Intel core i5 1.80 GHz processor with 4.00 GB of RAM. Also, the random number generator was initialized using the function rng(seed) so that results could be reproduced.

To test the efficiency of the developed algorithms, simulations were performed on systems of increasing sizes with greater computational difficulty as shown in Table 1.

**Table 1.** Details of system data

| Test system | 16 [7] | 33 [7] | 70 [8] | 118 [9] | 135 [10] | 880 [11] |
|---|---|---|---|---|---|---|
| No. of branches | 16 | 37 | 79 | 133 | 156 | 900 |
| No. of nodes | 16 | 33 | 70 | 123 | 223 | 880 |
| No. of generator nodes | 3 | 1 | 2 | 1 | 1 | 7 |
| Generator node | 1–3 | 1 | 1, 70 | 1 | 0 | 1–6, 880 |
| No. of sectionalising branch | 11 | 32 | 68 | 118 | 135 | 873 |
| No. of tie branch | 3 | 5 | 11 | 15 | 21 | 27 |
| Base power, $S_{base}$/MVA | 10 | 10 | 10 | 10 | 100 | 50.68 |
| Base voltage, $V_{base}$/kV | 10 | 12.66 | 11 | 11 | 13.8 | 130.8 |
| Search space of system | 364 | $4.35 \times 10^5$ | $7.78 \times 10^{12}$ | $2.43 \times 10^{19}$ | $5.44 \times 10^{25}$ | $3.00 \times 10^{51}$ |

### 7.1 Effect of DNR on the Voltage Stability of Distribution Networks

This section demonstrates the effect of DNR on the voltage stability of the network. From Table 2, it can be seen that the optimization of the distribution networks by DNR indeed leads to a decrease in the total voltage deviation of the system and thus causes an improvement in stability.

### 7.2 Voltage Profile Analysis of the Distribution Networks

The effect of DNR on the stability of the weakest and strongest buses of the examined systems is analysed here. As shown in Table 3, DNR for minimisation of total voltage

**Table 2.** Analysis of total voltage deviation after DNR

| Test system | Total voltage deviation (pu) | | |
|---|---|---|---|
| | Initial configuration | HGA | HFPA |
| 16 | 0.211045 | 0.184465 | 0.184465 |
| 33 | 1.701121 | 1.051281 | 1.051281 |
| 70 | 3.415624 | 3.158206 | 3.158206 |
| 118 | 5.240284 | 3.755860 | 3.755860 |
| 135 | 3.407807 | 3.015136 | 3.015136 |
| 880 | 11.389184 | 3.971487 | 3.971080 |

deviation did not always improve the voltage profile at the weakest and strongest bus. Rather it aimed at improving the stability of the entire system.

In Table 4, the voltage at the weakest bus was seen to approach close to that of the generator bus after DNR, except for the 135 bus system. Even though there was no improvement in the stability of its weakest or strongest bus, the stability of the other buses were in turn improved, thereby leading to an overall improvement in system stability.

Moreover, it was seen for the 880 bus system that a decrease of 0.0002 pu occurred at the strongest bus of the network after DNR. That did not imply a decrease in the stability of the system. Rather, this small decrease in stability at the strongest bus led to the enhancement of the voltage of the other buses of the system (as seen for the weakest bus).

### 7.3 Efficiency of the Hybrid Algorithm

In [4], the superiority in the converging ability of the hybrid algorithms for power loss reduction by DNR was analyzed. This section is thus used to demonstrate whether the hybrid algorithm operates with the same level of efficiency when applied to another optimization case (the minimization of the total voltage deviation).

From Table 5, it can be seen that:

(i) Application of the hybrid algorithm for the minimization of the total voltage deviation by DNR can indeed be done.
(ii) HFPA was able to find the true global optimum solution for all test systems while HGA was unable to do the same, thereby implying greater reliability of HFPA.
(iii) In terms of the time and number of iterations required to convergence, HFPA was again better than HGA.

**Table 3.** Identification of weakest and strongest bus

| Test system | Weakest bus number | | | Strongest bus number | | |
|---|---|---|---|---|---|---|
| | Initial conf. | HGA | HFPA | Initial conf. | HGA | HFPA |
| 16 | 12 | 12 | 12 | 14 | 13 | 13 |
| 33 | 18 | 33 | 33 | 2 | 2 | 2 |
| 70 | 67 | 29 | 29 | 51 | 51 | 51 |
| 118 | 77 | 77 | 77 | 100 | 100 | 100 |
| 135 | 116 | 106 | 106 | 63 | 63 | 63 |
| 880 | 769 | 396 | 396 | 825 | 604 | 604 |

**Table 4.** Voltage deviation at weakest and strongest bus

| Test system | Voltage at weakest bus | | | Voltage at strongest bus | | |
|---|---|---|---|---|---|---|
| | Initial conf. | HGA | HFPA | Initial conf. | HGA | HFPA |
| 16 | 0.9693 | 0.9716 | 0.9716 | 0.9948 | 0.9923 | 0.9923 |
| 33 | 0.9131 | 0.9356 | 0.9356 | 0.9970 | 0.9971 | 0.9971 |
| 70 | 0.9059 | 0.9247 | 0.9247 | 0.9931 | 0.9946 | 0.9946 |
| 118 | 0.8688 | 0.8688 | 0.8688 | 0.9963 | 0.9963 | 0.9963 |
| 135 | 0.9307 | 0.9596 | 0.9596 | 0.9999 | 0.9999 | 0.9999 |
| 880 | 0.9561 | 0.9916 | 0.9916 | 0.9999 | 0.9997 | 0.9997 |

**Table 5.** Performance analysis of HGA and HFPA

| Test system | Method | No. of times global solution reached in 100 runs | No. of iterations to convergence | Time for 1 run (s) |
|---|---|---|---|---|
| 16 | HGA | 100 | 2 | 83.660 |
| | HFPA | 100 | 2 | 4.498 |
| 33 | HGA | 100 | 5 | 122.745 |
| | HFPA | 100 | 5 | 29.868 |
| 70 | HGA | 99 | 103 | 235.468 |
| | HFPA | 100 | 15 | 98.734 |
| 118 | HGA | 94 | 195 | 418.723 |
| | HFPA | 98 | 46 | 176.410 |
| 135 | HGA | 86 | 279 | 627.119 |
| | HFPA | 100 | 96 | 243.971 |
| 880 | HGA | 0 | 817 | 1294.317 |
| | HFPA | 94 | 249 | 628.349 |

## 8 Conclusion

Distribution Network Reconfiguration can no doubt be used as an optimization technique for the maximization of the stability of a given network. In this paper, the proposed Improved Voltage Deviation Index (IVDI) enables the fast and easy analysis of the entire system stability. Through consideration of the voltage deviation of the entire system, rather than just the weakest bus, greater improvement in system stability was achieved. Thus, using DNR as an optimization tool, network stability was achieved without requiring any additional cost. Also, the hybrid algorithm in [4] works with the same level of efficiency, irrespective of the optimization case, thereby confirming its effectiveness.

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