Optimal Configuration of Distribution System for Voltage Profile Improvement in Bulk Power Consumption Zones

K.K.S.V.V. Prakasa Rao, V. C. Veera Reddy

Abstract - This paper addresses the problem of optimal reconfiguration of distribution networks for improvement of voltage profile. The networks have a radial topology and proposed procedure finds a reconfiguration where the voltage magnitudes at the nodes are improved. This paper presents the developed methodology, which is based on genetic algorithms; furthermore, the electric distribution system is represented as a graph, and the evaluation of the network configuration is based on providing the mesh information of the system. Case studies are presented for 3-Feeder test system, a 33-bus IEEE test network and a launch complex test model, demonstrating the effectiveness of the implemented methodology.

Keywords - Distribution system, Fitness function, genetic algorithms, power quality, reconfiguration, sensitive loads, voltage profile.

I. Introduction

Distribution systems are operated radially and have the tendency of constantly changing because of the increasing energy demand. Under normal operating conditions, distribution feeders will be periodically reconfigured by opening and closing of sectionalizing switches in order to improve the voltages at nodes, increase the reliability and reduce line losses. The electrical distribution systems must be reliable, ensuring the supply of all the energy demand with the requirements of quality requested by energy users and the most sophisticated rocket launch related ground supporting systems. A typical rocket launch station consists of very critical equipment like High capacity DC power supplies to power the Radars, UPS systems, VVVF drives, Compressors, and Cranes/Elevators which demand a reliable power supply within acceptable voltage limits. Any sort of disturbance or reduction in voltage to all the above equipment will have direct impact on the operations/schedules of the rocket integration activities and real time activities.

Under this context, the power quality becomes more important since it is a crucial problem of great interest because of the integration of instrumentation devices and sensitive loads. This sensitive equipment is becoming more common in rocket launch complexes given that it demands a reliable power supply of good quality. As a consequence, problems related to power quality impact the schedules of the flight component testing, launch vehicle integration, satellite preparation and countdown activities resulting in significant delays.

Among these problems, low voltages are one of the most common and, also, difficult problems associated with power quality [1], [2]. Because of this, there is a need to characterize this phenomenon and also a need for novel techniques that can mitigate the effect related to this problem.

Low voltages are caused due to sudden variation of loads under specific conditions. Several methodologies have been proposed to tackle the problem of low voltages and voltage sags [3], [4], [5] in the electrical system.

Many authors have been using the system reconfiguration in order to improve the bus voltages and to reduce power losses [6], [7], [8]. Different optimization techniques, both traditional and non-traditional, such as simulated annealing and genetic algorithms (GA) are being practiced to solve reconfiguration problems [9], [10], [11], [12], [13], [14].

In this paper, it is proposed to solve the reconfiguration of radial distribution systems using GA. The proposed methodology uses a novel idea of checking radiality during the evaluation of fitness of the individual configurations. In order to test the proposed method, studies on 3-Feeder test system, IEEE 33-bus distribution test system and a practical distribution system at Spaceport of India at SDSC SHAR are presented.

II. FORMULATION OF THE PROBLEM

In this paper, the network reconfiguration problem is to determine the state (on/off) of the switches of the electrical system leading to radial topology that improves the voltage magnitudes with respect to specified values of voltage limits at system buses. These specified voltages limits are set based on standard values of voltage tolerances on these buses.

The problem is to find the configuration of a distribution network which yields acceptable voltage profile at all the nodes, satisfies the current limits in all the branches, minimum loss, supplies all the loads connected in the initial configuration and maintains the radial topology of the network.

Objective function for minimizing the least squares of voltage magnitude of load buses is shown by equation (1).

The above problem can mathematically be expressed as:

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$$\text{Minimize } Z = \sum_{i=1}^{N} P_{Vi}[V_i - V_{lmt}]^2 \quad (1)$$

Where:

N : the number of load buses

V_i : voltage magnitude of i'th load buse

V_{lmt}: desired voltage magnitude of i'th load bus

The V_{lmt} that is the desired voltage value is considered to be 0.9 per unit for all of the load buses in this work.

Subject to

(i) Power flow balance expressed as

$$F(x,d) = 0 \quad (2)$$

(ii) Limit on bus voltage magnitude expressed as

$$V_{max} \geq V_i \geq V_{min} \quad \text{for } i = 1 \text{ to } N \quad (3)$$

(iii) Limit on branch current magnitude expressed as

$$I_j \leq I_{max} \quad \text{for } j = 1 \text{ to } M \quad (4)$$

(iv) All the loads are served.

(v) Radial topology of the network is maintained

Where,

P_{loss} = active power loss in the network

Z = objective function value

x = Power flow variables (complex voltages at buses)

d = Demand (complex load) at different buses

V_{max} = 1.0 p.u, maximum voltage magnitude,.

V_{min} = minimum acceptable voltage magnitude

V_{lmt} = acceptable Voltage magnitude at Bus i

V_i = voltage magnitude at bus i

I_{max} = maximum branch current magnitude limit

I_j = current magnitude of branch j

N = number of buses in the network

M = number of branches in the network

P_{Vi} = penalty factor for violation of voltage limit of bus i

P_{Ij} = penalty factor for violation of current limit of branch j

P_c = penalty factor for having common switch, for non-radial topology or not supplying load.

Each solution in the search process satisfies the power flow equations (2). However, the constraints on bus voltages and branch currents expressed by equations (3) and (4) are imposed by addition of appropriate penalty terms in objective function so as to decrease the fitness function. Thus the problem is reduced to,

$$\text{Min. } Z = \sum_{i=1}^{N} P_{Vi}[V_i - V_{lmt}]^2 + \sum_{j=1}^{M} P_{Ij}[I_j - I_{lmt}]^2 + [\,P_{loss}\,] \quad (5)$$

Where,

$V_{lmt} = V_i$ if $[\,V_{max} \geq V_i \geq V_{min}\,]$

$V_{lmt} = V_{min}$ if $[\,V_i < V_{min}\,]$

$V_{lmt} = V_{max}$ if $[\,V_i > V_{max}\,]$

$I_{lmt} = I_j$ if $[I_j \leq I_{max}]$

$I_{lmt} = I_{max}$ if $[I_j \geq I_{max}]$

The other constraints of supply to all the loads and maintenance of radial structure are enforced by non acceptance of those solutions (strings) which violate these constraints.

III. Network Reconfiguration using GA

The proposed Genetic Algorithm (GA) uses the crossover and mutation operators, designed to generate individuals. This approach involves encoding of initial solution, fitness assignment, and selection of mating population, cross over and mutation. The crossover and mutation probabilities are suitably selected. A particular configuration of the network is represented in form of a binary string. The radiality of the network is checked during the fitness calculation of the configuration and the configuration which is not satisfying the radiality conditions will be heavily penalized such that it will have no fitness to get selected in further generations. Furthermore, this ensures that only feasible individuals will be evaluated on the fitness function. In order to explain the proposed methodology, the basic distribution system shown in Fig. 1 is used.

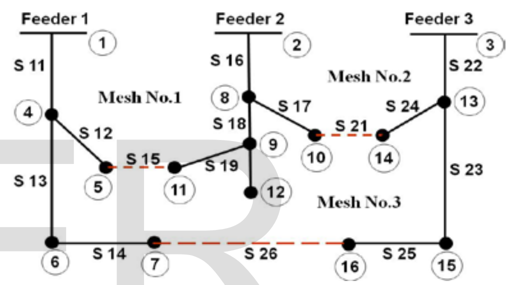

Fig 1. Distribution system.

I. Encoding of Solution Point

The two important aspects to be considered for encoding the solution are every legal solution shall have unique representation and also the search shall cover the entire solution space. The initial, intermediate and final solutions in the population must be legal points. A solution consisting of all the nodes in the network and maintaining radial topology is called legal solution. Encoding of chromosome is very key factor in solving the problem using GA.

The solution methodology is explained with the help of a sample network shown in Fig. 1 above. The network has 15 branches. It is assumed that every branch has a switch. The normally open branches with tie switches are shown by dotted lines (s15, s21 and s26). Closure of any tie switch would result in formation of a mesh. Thus this network can form three meshes corresponding to tie switches s15, s21 and s26 called mesh 1, mesh 2 and mesh 3 respectively. Binary encoding is employed for the network considered. The positions of the switches in each mesh are encoded in a binary number and the resulting chromosome represents which switches are open in three meshes. The mesh 1 has six branches/switches (s11, s12, s15, s16, s18, & s19), mesh 2 has five branches/switches (s16, s17 s21, s22 & s24) and mesh 3 has seven branches/switches (s11, s13 s14, s26, s25, s23 & s22). This would require 3, 3 and 4 binary bits respectively for their representation. Thus the

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length of the chromosome to represent the entire network would be seven (3+3+4) bits. The branches are renumbered sequentially mesh wise for convenience while maintaining same numbers for branches common to other meshes. The renumbered network is shown in Fig. 1 (b). Encoding of the network for two configurations of open switches s5, s1 and s9 and s4, s2 and s9 in meshes 1, 2 and 3 respectively are shown in Fig. 2.

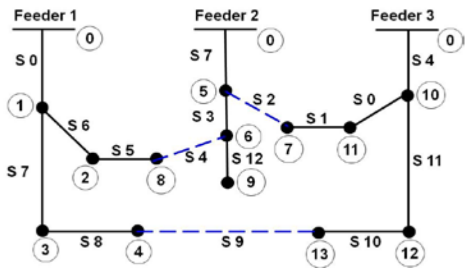

Fig. 1 (b)

Configuration	Encoding
5 1 9	101 001 1001
4 2 9	100 010 1001

Fig.2

II. Initial population

The initial population required to solve the problem using GA approach is generated randomly. According to encoding of the open tie/sectionalizing switches; combination of '0' and '1' are generated for specified chromosome length. After initial population evaluation, genetic operators generate successive populations using the GA.

III. Crossover operation

Single point cross over is employed in this proposed work. The crossover operation used is a uniform crossover. One pair of chromosome will be considered at a time and a random number is generated between 1 and (L-1) of the chromosome, where, 'L' is the length the string. The two chromosomes will be swapped at the crossover point checking the crossover probability. The crossover operation is shown in Fig.3.

Parent 1	0	1	0	0	1	0	1
Parent 2	0	1	1	1	1	1	1

Child 1	0	1	0	1	1	1	1
Child 2	0	1	1	0	1	0	1

Fig. 3. Crossover of individuals.

IV. Mutation operator

Mutation occurs with a small probability after cross over. Mutation prevents premature convergence to local optimum value. It randomly jumps to new solution points that might be in the promising range of the search space. In mutation all the bits in the chromosome are evaluated by generating a random number to check for necessity of mutation. Some of the bits are changed in this process. A binary encoding is used here, and selected bit '1' will be changed to '0' and '0' will be changed to '1'. Fig. 4 shows the individual obtained by the mutation operation.

Child	0	1	0	1	1	1	1
Mutation Child	0	1	1	0	1	0	1

Fig. 4. Mutation of individuals.

V. Fitness function evaluation

An appropriate fitness is assigned to a chromosome according to the objective function. Since the objective, in present case, is to have minimum least squares of voltage magnitude of load buses, its reciprocal is taken as fitness function governed by the relation expressed by equation (6).

$$\text{Fitness} = 1/(1+Z)^2 \qquad (6)$$

The fitness of the chromosome will be maximum if the objective function value is minimum thereby giving the configuration of the network with improved voltage magnitudes at the buses.

The above fitness governed by equation (6) is valid for feasible strings only. However, for infeasible strings generated for common switches, not maintaining radial topology and not supplying all the loads, the fitness is evaluated using equation (7). This relation uses a high value penalty term, 'P_c', such that the infeasible solution arising due to above mentioned reasons are regretted because of their low value of fitness.

$$\text{Fitness} = 1/(1+P_c) \qquad (7)$$

The procedure for application of the proposed reconfiguration method is described as follows:

1)Read the electrical system's parameter data and data of voltage limits imposed at system buses, this is, *Vlmt*.
2) Identify the base system and provide it as an individual in the initial population.
3) Generate the population as described in subsection II.
4)Carry out the genetic operations, described above, to generate new individuals.
6)Evaluate the voltage magnitudes by power flow analysis to obtain fitness of configuration of the system.
7)If results not meet the criteria of stop, return to step 4 and re-evaluate possible solutions.

IV. IMPLEMENTATION AND TEST RESULTS

In order to demonstrate the performance of the proposed methodology, several case studies are presented. A 3-feeder test system, a 33-bus IEEE test system and a typical launch complex practical distribution test system have been used. The voltage magnitudes at all the buses during the initial conditions and the final voltages at buses after reconfiguration were studied and presented.

A. 3-Feeder test system

The 3-feeder test system is a radial distribution system (Fig. 5) consisting of three feeders, 14 buses interconnected by 16 lines, of which 3 are for tie line or normally open circuits,

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and 13 are lines with normally closed switches. The data of this system is provided by [6].

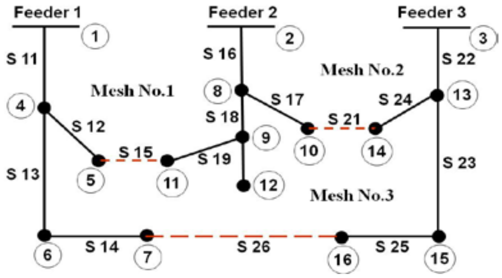

Fig. 5. 3-Feeder radial distribution system

The analysis on initial configuration shows that the minimum voltage is 0.81840 p.u observed at bus 6 with tie switches 16, 22 & 13 kept open.

After the evaluation with the initial configuration (actual) at 10 of the 14 buses of the electrical system, the voltage magnitude is observed to be between 0.8 to 0.9 p.u, at 2 buses the voltages are between 0.9 to 0.95 p.u and at 2 buses it is >0.95 p.u. (See Table I).

TABLE I. ACTUAL STATUS OF THE 3-FEEDER RADIAL SYSTEM (BEFORE RECONFIGURATION)

Voltage Magnitudes	**0.8 - 0.9 p.u**	**0.9 -0.95 p.u.**	**>0.95 p.u.**
Buses	6,7,8,9,10,12,13, 14,15,16 (10 Buses)	5, 11 (2 Buses)	3, 4 (2 Buses)
Open lines	16, 22, & 13		

In order to find a new topology that improves the voltage magnitudes at buses, the proposed methodology of reconfiguration is applied. The obtained results after reconfiguration are shown in Table II. The minimum voltage magnitude observed is 0.97159 p.u at bus 10 after the reconfiguration of the network with tie switches 19, 17 & 26 kept open. The voltage magnitudes of all the buses after reconfiguration are >0.95 p.u.

TABLE II. RESULTS FOR THE 3-FEEDER RADIAL SYSTEM (AFTER RECONFIGURATION)

Voltage Magnitudes	**0.8 - 0.9 p.u**	**0.9 -0.95 p.u.**	**>0.95 p.u.**
Buses	Nil	Nil	For all buses
Open lines	19, 17 & 26		

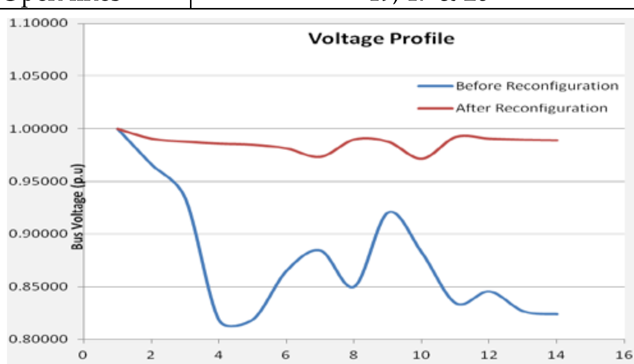

Fig. 6. Voltage Profile of 3-Feeder system

The above test results indicate that there is an increase in voltage magnitude of 15.7% at the buses from an initial operating configuration to a final reconfigured system using proposed methodology.

B. IEEE 33-bus test system

The IEEE 33-bus test system which is a radial distribution system (Fig. 7) consisting of one substation is considered. In this system there are 33 buses interconnected by 37 lines, of which five are for tie line or normally open circuits, and 32 are lines with normally closed switches. The total of the active load is 3715 kW and reactive load is 2300 kVA. The data system is provided in [3].

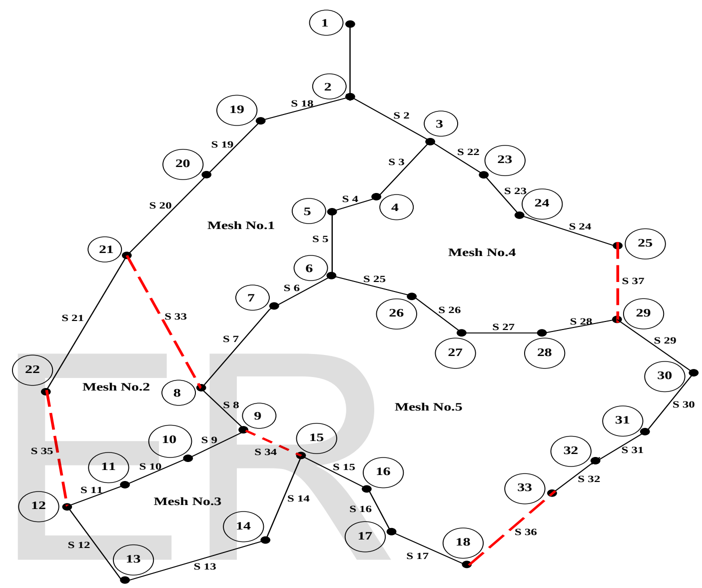

Fig. 7. IEEE 33-bus radial distribution system.

The evaluation of initial configuration shows that the minimum voltage is 0.67736 p.u observed at bus 15 with tie switches 2, 21,13, 3 & 15 kept open.

After the analysis with the initial configuration (actual) at 28 of the 33 buses of the electrical system, the voltage magnitude is observed to be between 0.65 to 0.85 p.u, at 2 buses the voltages are between 0.85 to 0.95 p.u and at 3 buses it is >0.95 p.u. (See Table III).

TABLE III. ACTUAL STATUS OF IEEE 33- BUS RADIAL SYSTEM (BEFORE RECONFIGURATION)

Voltage Magnitudes	**0.65 - 0.80 p.u**	**0.85 - 0.95 p.u.**	**>0.95 p.u.**
Buses	2 to 17 & 21 to 32 (28 buses)	19, 20 (2 Buses)	0, 1, 18 (3 Buses)
Open lines	2, 21, 13, 3, 15		

In order to find a new topology that improves the voltage magnitudes at buses, the proposed methodology of reconfiguration is applied. The obtained results after reconfiguration are shown in Table IV. The minimum voltage magnitude observed is 0.93782 p.u at bus 32 after the reconfiguration of the network with tie switches 7, 9, 14, 37 & 32 kept open. The voltage magnitudes of all the buses after reconfiguration are >0.90 p.u. The voltages of all the 28 buses having <0.80 p.u voltage were improved to >0.9 p.u after reconfiguration. The proposed methodology using GA approach has yielded very good results (minimum bus voltage of 0.93782 p.u) similar to that of the earlier authors (with minimum bus voltage of 0.93764 p.u) using conventional methods [8] which require switch exchange and loop power/current flow solution.

TABLE IV. RESULTS FOR IEEE 33- BUS RADIAL SYSTEM
(AFTER RECONFIGURATION)

Voltage Magnitudes	**0.65 - 0.80 p.u**	**0.9 - 0.95 p.u.**	**>0.95 p.u.**
Buses	Nil	16, 17, 28 to 32 (7 Buses)	0 to 15 & 18 to 27 (26 Buses)
Open lines	7, 9, 14, 37, 32		

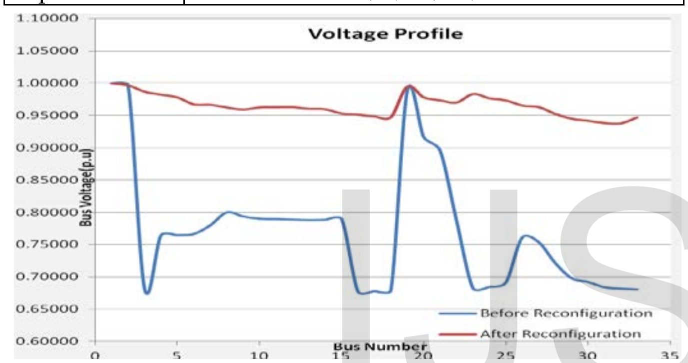

Fig. 8. Voltage Profile of IEEE 33-bus system

C. Typical Launch complex test system

A typical launch complex distribution system which is a radial distribution system (Fig. 9) consisting of a Main Receiving Station and other 31 substations is considered. In this system there are 32 buses interconnected by 42 lines, of which 11 are for tie line or normally open circuits, and 31 are lines with normally closed switches. Two cases with different loading of distribution system were considered. Firstly active load of 3880 kW & reactive load of 1880 kVA and secondly active load of 7700 kW & reactive load of 3356 kVA were studied.

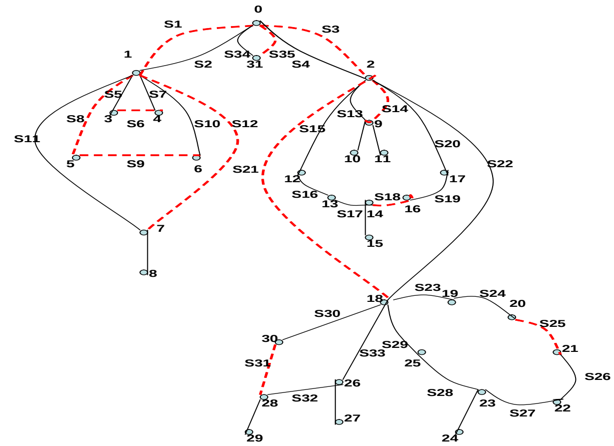

Fig. 9. Launch complex Power distribution system

With Nominal Load

Launch complex power distribution system with **nominal load** on the network has been considered and evaluation of initial configuration shows that the minimum voltage is 0.90294 p.u observed at bus 19 with tie switches 2, 3, 5, 8, 11, 13, 15, 21, 21, 23, 33, 35 kept open.

After the analysis with the initial configuration (actual) at 19 of the 32 buses of the electrical system, the voltage magnitude is observed to be between 0.90 to 0.95 p.u, and at 13 buses it is >0.95 p.u. (See Table V).

TABLE V. ACTUAL STATUS OF LAUNCH COMPLEX RADIAL SYSTEM
(BEFORE RECONFIGURATION)

Voltage Magnitudes	**0.90 - 0.95 p.u.**	**>0.95 p.u.**
Buses	12 to 30 (19 buses)	0 to 11 & 31 (13 buses)
Open lines	2, 3, 5, 8, 11, 13, 15, 21, 23, 33, 35	

To find a new topology that improves the voltage magnitudes at buses, the proposed methodology of reconfiguration is applied. The obtained results after reconfiguration are shown in Table VI. The voltage magnitude observed is 0.9315 p.u at bus 19 after the reconfiguration of the network with tie switches 2, 3, 6, 9, 12, 14, 18, 22, 26, 32 & 35 kept open. The voltage magnitudes of 6 buses improved >0.95 p.u. After reconfiguration 13 buses are showing voltages between 0.90 to 0.95 p.u and all other buses are having >0.95 p.u.

TABLE VI. RESULTS FOR LAUNCH COMPLEX RADIAL SYSTEM
(AFTER RECONFIGURATION)

Voltage Magnitudes	**0.90 - 0.95 p.u.**	**>0.95 p.u.**
Buses	18 to 30 (13 buses)	0 to 17 & 31 (19 buses)
Open lines	2, 3, 6, 9, 12, 14, 18, 22, 26, 32, 35	

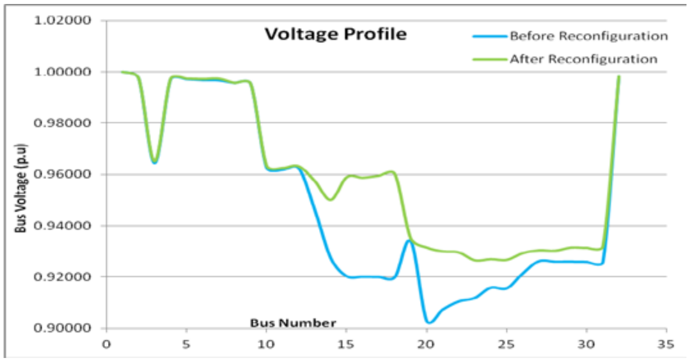

Fig. 10. Voltage Profile of Launch complex distribution system

With Peak Load

Launch complex power distribution system with **Peak load** on the network has been considered and evaluation of initial configuration shows that the minimum voltage is 0.91285 p.u observed at bus 17 with tie switches 2, 3, 5, 8, 11, 13, 15, 21, 21, 23, 33, 35 kept open.

After the analysis with the initial configuration (actual) at 5 of the 32 buses of the electrical system, the voltage magnitude is observed to be between 0.85 to 0.90 p.u, at 19 buses it is 0.90 to 0.95 p.u. and at 8 buses it is >0.95 p.u. (See Table VII).

TABLE VII. ACTUAL STATUS OF LAUNCH COMPLEX RADIAL SYSTEM (BEFORE RECONFIGURATION)

Voltage Magnitudes	**0.85 - 0.90 p.u.**	**0.90 - 0.95 p.u.**	**>0.95 p.u.**
Buses	26 to 30 (5 buses)	2, 9 to 25, 31 (19 buses)	0, 1, 3 to 8 (8 buses)
Open lines	2, 3, 5, 8, 11, 13, 15, 21, 23, 33, 35		

To find a new topology that improves the voltage magnitudes at buses, the proposed methodology of reconfiguration is applied. The obtained results after reconfiguration are shown in Table VIII. The voltage magnitude observed is 0.94293 p.u at bus 17 after the reconfiguration of the network with tie switches 1, 3, 6, 8, 12, 14, 18, 21, 25, 31 & 35 kept open. The voltage magnitudes of 5 buses improved >0.90 p.u. After reconfiguration 24 buses are showing voltages between 0.90 to 0.95 p.u and all other buses are having >0.95 p.u.

TABLE VIII. RESULTS FOR LAUNCH COMPLEX RADIAL SYSTEM (AFTER RECONFIGURATION)

Voltage Magnitudes	**0.85 - 0.90 p.u.**	**0.90 - 0.95 p.u.**	**>0.95 p.u.**
Buses	Nil	2, 9 to 31 (24 buses)	0, 1, 3 to 8 (8 buses)
Open lines	1, 3, 6, 8, 12, 14, 18, 21, 25, 31, 35		

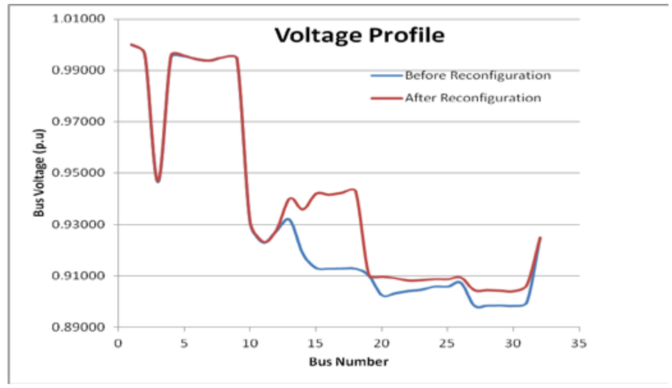

Fig. 11. Voltage Profile of Launch complex distribution system

Clearly the reconfiguration provides good results, decreasing the number of buses with voltage less than the specified limits and improving the voltage profile of the system as a whole.

V. CONCLUSIONS

The work in this paper presents a methodology for the reconfiguration of radial distribution systems in order to improve the voltage profile, using a genetic algorithm. This algorithm generates and reproduces individuals in the form of radial networks given that the initial population, crossover and mutation operators were designed for optimization purpose. This is reflected in the reduction of the search space for valid configurations. The results show the efficiency of the proposed method. The good voltage profile improvement has been obtained by only switch exchanges in the network and without incorporating additional components. The reconfiguration using Genetic Algorithm does not require any switch exchanges, loop power or loop current evaluation as in other methods for decision making. The radial topology of the distribution system is maintained throughout the search process. Test results of 5-feeder system by GA approach are similar to that of the result obtained by earlier authors which yields good results of bus voltages. Considerable voltage improvement is demonstrated after reconfiguration using proposed methodology in all the test systems. This methodology is very useful in the SCADA environment of sub-stations to reconfigure the distribution system based on the changes with the help of intelligent switchgear to improve the voltage profile.

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