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Minimum switching losses for solving distribution NR problem with distributed generation

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Abstract: Power losses in a distribution system are commonly minimised via optimal network reconfiguration (NR). Previously, research on NR was focused on planning, where the final configuration reporting the lowest power losses being the main goal. However, power losses during switching operations from the original state to the optimal state of configuration were not considered. This study discusses the optimal switching path for minimising power losses when reconfiguring a network. The simultaneous optimal NR and distributed generation (DG) output was also proposed. The proposed methodology involves: (i) optimal NR and DG output simultaneously and (ii) optimal switching path to convert the network from the initial configuration to the final configuration obtained from (i). The selected optimisation technique in this study is the firefly algorithm. The proposed method was tested using IEEE 33-bus, 69-bus, and 118-bus radial distribution networks, while also accounting for static and dynamic loads. The results confirmed the effectiveness of the proposed method in determining the optimal path of switching operations, as well as the optimal network configuration and optimal output of DG units.

1 Introduction

A common problem encountered by electrical distribution companies is power losses from their respective networks. These losses increased their operating cost, and subsequently decreased their profit. In the long run, it will also lead to environmental problems due to the increased power generated grid site to compensate for the aforementioned power losses. An established technique for minimising power losses is network reconfiguration (NR) [1], where it changes the switches' states in the network, which would reduce power losses and improve the overall voltage profile, provided that the optimum reconfiguration could be determined. In doing this, the load will be transferred to relatively less heavily loaded feeders, which subsequently decreases power losses.

The importance of NR is evident due to the continuous development in this area. Gupta *et al.* in [2] presented a multi-objective method to solve the reconfiguration problem for radial systems by combining adaptive genetic algorithm (GA) and fuzzy logic approaches. The objective function combines minimising power losses, the number of node voltage violating the constraints, and the number of branch current violating the constraints. The results showed that the method is promising and efficient for the multi-objective reconfiguration of radial systems, and require less computational time compared with the ones reported in the literature. Meanwhile, Andervazh *et al.* [1] proposed a Pareto-based multi-objective distribution NR (DNRC) method using a discrete particle swarm optimisation (PSO) algorithm that concurrently optimises multiple objectives such as minimising power losses and buses' voltage deviation. The results confirmed the effectiveness of the proposed method for solving the multi-objective problem for DNRC by obtaining a Pareto front with high quality, great diversity, and proper distribution of non-dominated solutions for the objective space. In [3], a runner-root algorithm (RRA) was used on an electric DNRC problem, with the intention of minimising real power loss, balance the load among the feeders and branches, deviate the node voltage, and determine the number of switching operations using max–min method for the selection of the final compromised solution. The results were shown that an RRA is effective for single- and multi-objective NR problems.

There are very few works involving minimising power losses during switching changing operation. To the best of our best knowledge, there is only one work discussing minimising power losses during the switching process [4]. In this work, a new method was proposed for real-time configuration of distribution network incorporated with distributed generation (DG). This method used a heuristic algorithm to set the weights of the criteria. The best sequence of the switches was determined using the analytic hierarchy process multi-criteria analysis. The results confirmed the importance of the integrated DG to the network toward reducing losses and increase reliability during the automatic configuration of the system. Since this method was based on heuristic technique for selecting configurations and it assumes that only remote-controlled switches are considered in the analysis, the proposed method skips many probabilities of switching sequence paths, because it searches for one solution within an acceptable time. This differs from [4], where the proposed method in our work finds the optimal switching sequence based on all possible sequences using the optimisation technique, intending to realise minimum power loss and the best voltage profile. Both approaches use static or dynamic loads and store the optimal solution in order to change the form of the network whenever needed.

The works in minimising power losses via optimal DG output also have been conducted previously by a few researchers. In [5], optimal sizing and siting problem of DG was solved using a new optimisation method called ant lion optimiser (ALO). The objectives were to a reduce DGs' losses, DGs' application cost, buses' voltage deviation, energy cost from the upstream network, and improve its reliability. The optimisation problem was solved as a single-objective optimisation and a multi-objective optimisation. The result proved that ALO is better than PSO and GA in extracting the solution of the optimal sizing and siting problem of the DGs.

Many works have been conducted involving the optimal reconfiguration method and optimal DGs output. In [6], a simultaneous DNRC and DG allocation were reported. Prior to the NR, the uncertainties of load fluctuation were considered. The objectives were to minimise the expected energy not supplied, line loss cost, and switch operation cost. The weighting factors were used. The proposed method consists of two periods: the first creates a feasible topology network using the binary PSO, whereas the second solves the DG allocation using the harmony search algorithm (HSA). The results proved that the proposed NR algorithm is indeed feasible. Our work reports an optimal solution that guarantees power loss at levels lower than that reported previously.

The main contribution of this work is a method that can determine the optimal switching path for the optimal DNRC in the presence of an optimal DG output. The proposed method consists of two steps. Step 1 is to determine optimal network configuration and DGs output simultaneously and step 2 determines the optimal switching path from an initial configuration to the optimal configuration. In both steps, the objective function is to minimise power losses and improve the voltage profile index. Both static and dynamic loads can be considered in the proposed method. The results were subsequently compared with the values reported by other methods in the literature.

2 Mathematical formulation and constraints

NR is defined as the process of changing the topology of the network for a certain objective. This can be done by changing the states of the switches. Switching the changing path can be used to change the network from its original form to an optimal form. This work intends to minimise total system active power loss and voltage deviation index.

The following describes the objective function and constraints of the optimisation.

The objective function F can be presented in the following form [7]:

$$\text{minimise}\, F = \left(P_{\text{loss}}^{R} + \text{IVD}\right) \tag{1}$$

Since the total fitness has different objective units, the net power loss P_{loss}^{R} is taken as the ratio between the system total active power loss after $P_{\text{loss}}^{\text{rec}}$ and before reconfiguration P_{loss}^{0}, as follows:

$$P_{\text{loss}}^{R} = \frac{P_{\text{loss}}^{\text{rec}}}{P_{\text{loss}}^{0}} \tag{2}$$

The total power loss of the network is determined by the summation of losses in all lines

$$P_{\text{loss}} = \sum_{N=1}^{M} \left(R_N \times |I_N|^2\right) \tag{3}$$

where P_{loss} is the total active power losses in the network; M is the branch number; R_N is the resistance in the branch N; and I_N is the current in the branch N.

Voltage profile index (IVD) is defined as follows:

$$\text{IVD} = \max_{i=2}^{n} \frac{(|V_1| - |V_i|)}{|V_1|} \tag{4}$$

where V_i is the voltage at bus i; $i = 2, 3, \ldots, n$; n is the number of the network buses; and V_1 is the nominal voltage. The proposed method will try to minimise the IVD to almost zero, thereby improving both voltage profile and network performance.

The main constraints that the optimisation is subjected results in the best switching changing for NR with DGs:

i. Distributed generator capacity

$$P_i^{\min} \le P_{\text{DG},\,i} \le P_i^{\max} \tag{5}$$

where $P_{\text{DG},\,i}$ is the DG output at bus i; $P_i^{\max}$ and $P_i^{\min}$ are the upper and lower bounds of the DG output, respectively.

ii. Power injection

$$\sum_{i=1}^{k} P_{\text{DG},\,i} < \sum_{n}^{n\,\text{bus}} (P_{\text{load}\,n}) + P_{\text{loss}} \tag{6}$$

where k is the number of the DGs; P_{load} is the load (active power) at bus n; $n$bus is the bus number; and P_{loss} is the total active power losses in the network. The constraint is to ensure that there is no power from DGs flowing to the grid, which may cause protection issues.

iii. Power balance

$$\sum_{i=1}^{k} P_{\text{DG},\,i} + P_{\text{substation}} = P_{\text{load}} + P_{\text{loss}} \tag{7}$$

Depending on the principle of equilibrium, the supply of power must be equal to its demand. That means, the summation of power losses and power load should be equal to the total power generated from DG units and substation. The summation of power losses and power load should be equal to the total power generated from DG units and substation.

iv. Voltage magnitude

$$V_{\min} \le V_{\text{bus}} \le V_{\max} \tag{8}$$

Each bus should have an acceptable voltage value within the limits of 0.95 and 1.05 (±5% of rated value).

v. Radial configuration

The network configuration must be in radial after the reconfiguration process. For this purpose, a graph theory function in MATLAB is used to determine the radiality of the network, as follows:

$$\text{TF} = \text{graphisspa\_}n\,\text{tree}(G) \tag{9}$$

$$\text{TF} = \begin{Bmatrix} 1 & \text{radial} \\ 0 & \text{not\_radial} \end{Bmatrix} \tag{10}$$

where G is the distribution network. If the network is radial, TF equals to 1 (true), or else it is 0 (false).

To ensure that a radial network is maintained, some rules are proposed. Rule 1: all switches that do not belong to any loop are to be closed. Rule 2: all switches connected to the sources are to be closed. Rule 3: all switches contributing to a meshed network needs to be opened. For example, Fig. 1 shows an IEEE 16-bus distribution network. Switch no. 9 is closed, which conforms to rule 1, whereas switch nos. 2, 6, and 11 are closed because they are connected to the sources according to rule no. 2. The rest of the switches will be adjusted closed/opened automatically using algorithms during simulations to create radial (tree) form linked to rule 3. Implementing these rules in the proposed methods will decrease central processing unit time and quicken convergence during the simulation.

vi. No load isolation

All nodes must be energised to ensure they all receive power.

3 Proposed strategy

In this work, firefly algorithm (FA) is proposed for finding the optimal switching changing path within the NR technique in the presence of the DGs. The optimal switching changing represents the best path to transfer network configuration from its original form to its optimal configuration form, with the aim of minimising power losses and improving the overall voltage profile during the switching changing process.

On the basis of the radiality method, the distribution network should always have a number of tie switches – normally open switch – (for example, IEEE 33-bus network have five switches). Furthermore, the network after reconfiguration should also possess five different open switches. In this work, the original five switches and the new five switches (related to the optimal network form

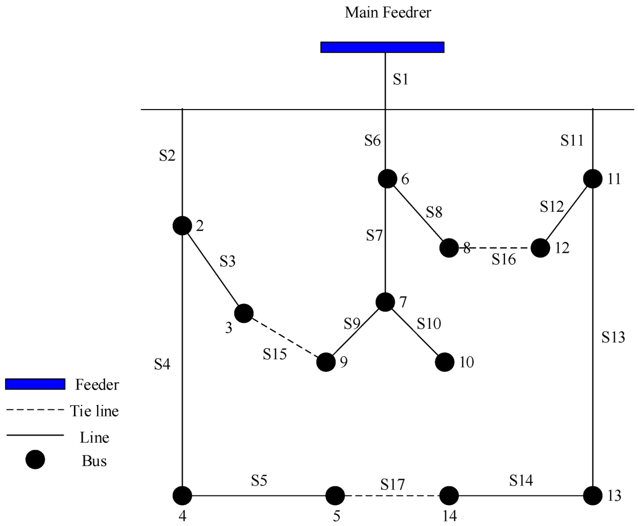

Fig. 1 *IEEE 16-bus distribution network*

after simultaneous NR with the DG output process is completed) will be used to determine the optimal switching changing path. This path appears at the opening and closing operation sequences of these switches. Therefore, there are many probabilities (paths) of changing the state of these ten switches to obtain a new form of the network. Generally, if the number of the tie switches in the original network is T and the number of the open switches that should be changed is t, then the number of the sequence (changing) probability can be calculated by

$$\underset{\text{size}}{\text{Pr}} = t! \times t! \times 2 \tag{11}$$

This equation confirms a large number of possibilities that could be generated. Thus, it is crucial that the optimisation technique is applied to determine the optimal switching changing path of the network during the reconfiguration technique.

3.1 Simultaneously NR and DG output using FA

FA is a recent nature-inspired metaheuristic optimisation method. It is based on the behaviour of social insects (fireflies). Each individual in social insect colonies seems to have their respective agendas, yet the group, as a whole, appears to be highly organised [8]. The FA method is used in this work because it is easy to code and understand and could obtain an optimal or near optimal solution. It can also find the local and global optimum solutions. The simple block diagram of basic FA is shown in Fig. 2*a*, which summarises the function of the FA.

The steps for this stage are as follows:

i. The input data such as the bus load and voltage, DG location, and lines' resistance and reactance values are determined.
ii. Generate random initial populations of firefly (x), where it represents the switches' number and DGs' output, accounting for both limitations and constraints. The variable used in this work for tie switches is represented by S, whereas DG output is represented by P_{DG}. In the simultaneous case, both switches' number and DG output should be determined simultaneously, as follows:

$$x = \begin{bmatrix} S_{11}, S_{12}, \cdots S_{1n}, P_{\text{DG}11}, P_{\text{DG}12}, \cdots P_{\text{DG}1K} \\ S_{21}, S_{22}, \cdots S_{2n}, P_{\text{DG}21}, P_{\text{DG}22}, \cdots P_{\text{DG}2K} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ S_{m1}, S_{m2}, \cdots S_{mn}, P_{\text{DG}m1}, P_{\text{DG}m2}, \cdots P_{\text{DG}mK} \end{bmatrix} \tag{12}$$

where m indicates the population size; n is the number of the switches; $K$is the number of DGs.

iii. Start the iteration by solving the load flow analysis to obtain power losses and the minimum value of the voltage for the entire system.
iv. Evaluate the fitness for each of the population.
v. Rank the populations according to the light intensity and save the best value

$$\begin{gathered} [\text{Light, Index} = \text{sort}(x)] \\ \text{Light}_{\text{best}} = \text{Light}(1) \end{gathered} \tag{13}$$

vi. Update all fireflies on the matrix x and rank the movement.

The firefly attractiveness β is presented in the following form:

$$\beta(r) = \beta_0 e^{-\gamma r^2} \tag{14}$$

where β_0 is the attractiveness at $r = 0$; γ is the coefficient of the light absorption; and r is the distance between any two fireflies. The Cartesian distance between any two fireflies l and j (which is represented by a row of the x matrix), can be expressed as

$$r_{lj} = \| x_l - x_j \| = \sqrt{\sum_{k=1}^{d} \left(x_{l,k} - x_{j,k}\right)^2} \tag{15}$$

where $x_{l,k}$ and $x_{j,k}$ represents the kth component of the Cartesian coordinates x_l and x_j of fireflies l and j, respectively; d is the number of the parameters that need to be optimised. The movement of fireflies, where firefly l is attracted to brighter firefly j, is determined by

$$x_{l,k} = x_{l,k} + \beta_0 e^{-\gamma r_{lj}^2}(x_{j,k} - x_{l,k}) + \alpha(\text{rand} - 0.5) \tag{16}$$

where the second term is caused by the attraction (with $\gamma = 1$), whereas the third term represents the randomised parameter (α being a randomisation parameter). The random number rand (1) is usually a uniformly distributed random number in [0, 1].

vii. Repeat the steps from step 3 until the maximum iteration.
viii. Stop the process and print the best solution.

3.2 Optimal switching changing path

Once the first stage is completed, the DGs output and final configuration of the network can be determined. This data will be used in stage two to determine the best path for changing the network from its original form to its optimal form. The steps for this stage are as follows:

i. Identify the initial and final configurations of the network. The variable sc represents the switches, where it should be closed during the switching changing process, whereas the variable so represents the switches that should be open during the switching sequence process.
ii. Set the size of the DGs (obtained in stage 1).
iii. Remove the replica switch. This means that if one of the switches is still in the same state after reconfiguration, it should be removed. That is, if any switch has the same state of normally being open before/after reconfiguration, there is no need to use it in the changing process.
iv. Generate random initial populations x_{seq} to represent the switching changing paths, as mentioned in (17), taking into the account the constraints of voltage limitation

$$x = \begin{bmatrix} SC_{11}, SO_{12}, SC_{13}, SO_{14}, \cdots SC_{1q-1}, SO_{1q} \\ SC_{21}, SO_{22}, SC_{23}, SO_{24}, \cdots SC_{2q-1}, SO_{2q}, \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ SC_{m1}, SO_{m2}, SC_{m3}, SO_{m4}, \cdots SC_{mq-1}, SO_{mq}, \end{bmatrix} \tag{17}$$

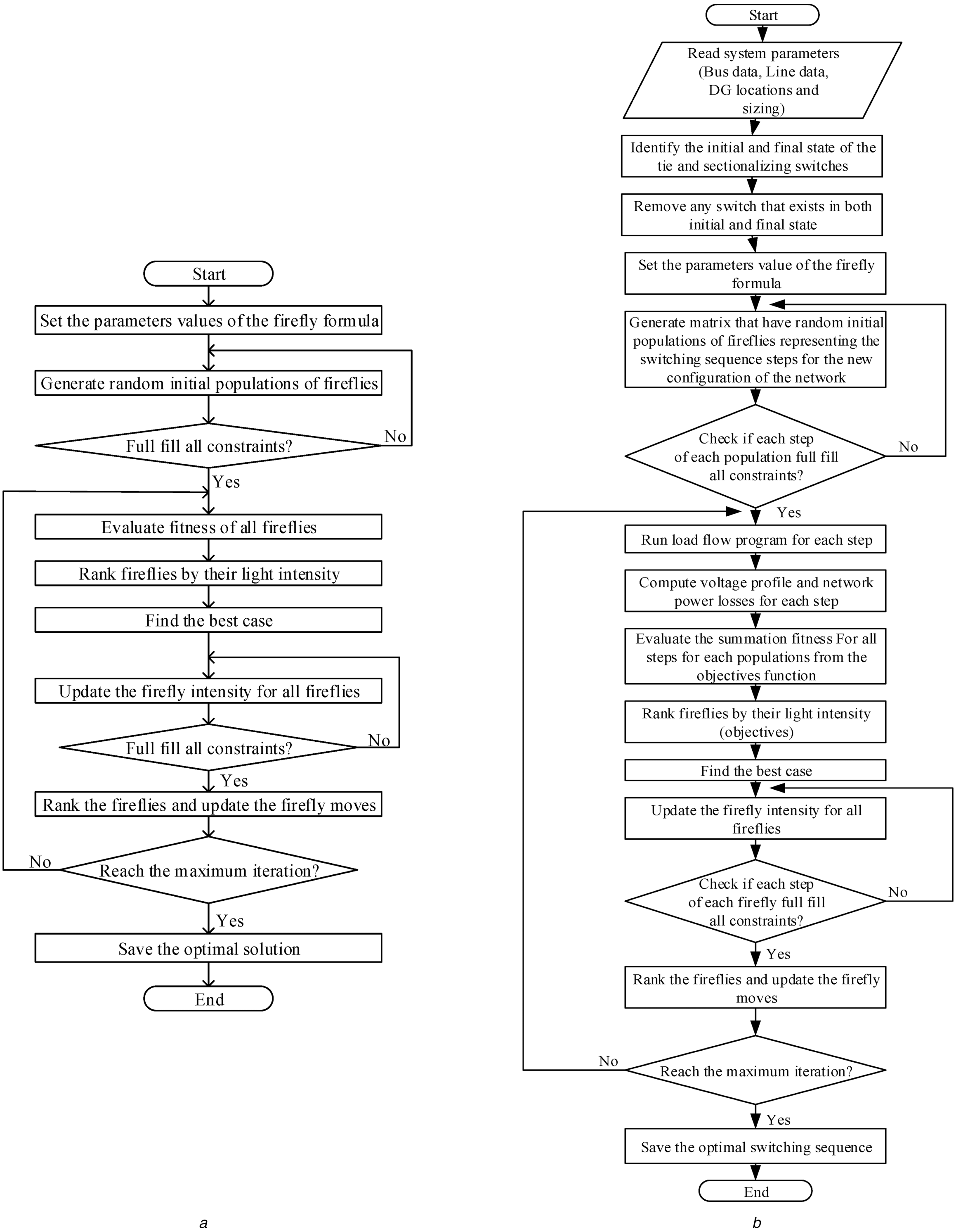

Fig. 2 *Simultaneously NR and DG output using FA*
(a) Flowchart of FA, ***(b)*** Flowchart for switching changing path process

where q is the number of the steps (number of switching changing steps in each path) and m indicates the population size.

In this stage, another constraint should be taken into account, which is the equality switches. This means that the same switch should not be changed from closed to open, and vice versa. Furthermore, the same switch should not be closed or open more than once in the same path. Each path consists of a number of steps (switches opening and closing operation).

v. Compute the power losses and voltage profile for each step during the changing path for each population. This means that each population should have the number of steps

$$N_{\text{steps}} = 2 \times t \tag{18}$$

where t is the number of tie switch.

In other words, the normally open switches will be closed, and another t number of the normally closed switches will be open during $2 \times t$ steps in order to change the network topography. Another constraint that is accounted for here is the closed step that should come before the open step in order to avoid being disconnected by any bus.

vi. Apply the fitness detailed in (1) for each step of each path (firefly), then calculate the total fitness for all of the steps of each path, as follows:

$$\text{total fitness} = \sum_{r=1}^{N_{\text{steps}}} \text{fitness}_{\text{step}_r} = \sum_{r=1}^{N_{\text{steps}}} \left(P_{\text{loss}_r}^{R} + \text{IVD}_r\right) \tag{19}$$

Table 1 33-Bus NR and DG output results

Case	Open switch	DG optimal output in MW (bus number)	Minimum and maximum values of the voltage profile, pu		Objective function F minimise $F = (P^R_{\text{loss}} + \text{IVD})$	Power losses, kW	Percentage of the power reduction, %
			Minimum	Maximum			
initial	33, 34, 35, 36, 37	no DG	0.91310	1	1.11350	202.60	—
proposed method	8, 9, 28, 32, 33	DG1 = 0.8414 (31)DG2 = 0.3408 (32)DG3 = 0.5916 (33)	0.97352	1	0.41982	73.048	63.95

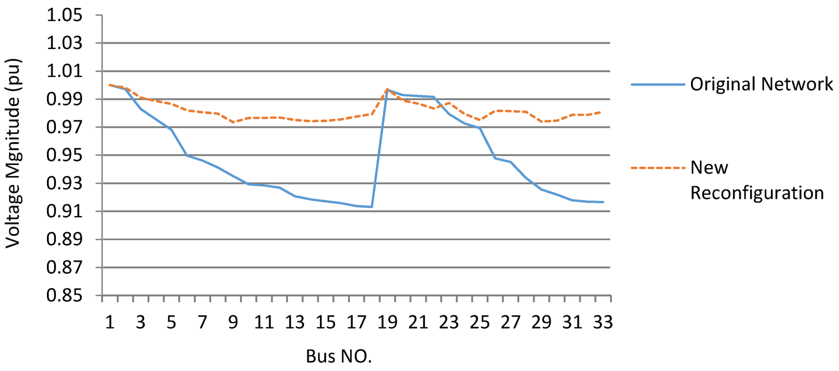

Fig. 3 *Voltage profile of IEEE 33-bus radial distribution network*

Table 2 Comparison of simulation result of 33-bus system

Method	Open switches	Total DG output, MW	Minimum value of voltage profile, pu	Power losses, kW	Percentage of the power reduction, %
GA [10]	7, 10, 28, 32, 34	1.9633	0.9766	75.13	62.92
RGA [10]	7, 9, 12, 27, 32	1.774	0.9691	74.32	63.33
HAS [10]	7, 14, 10, 32, 28	1.6684	0.9700	73.05	63.95
proposed method	8, 9, 28, 32, 33	1.7738	0.97352	73.048	63.95

vii Rank the light intensity and find the best solution.
.
vii Update and rank the fireflies.
i.
ix. Repeat the process from step 5.
x. Save the best solution after the maximum iteration is completed.

Fig. 2*b* introduces the FA algorithm based on switch changing path optimisation.

4 Simulation result and discussion

This work focuses on power loss reduction and voltage profile improvement by determining the optimal switching changing path to obtain the optimal form of the network from simultaneous NR and DG output. To demonstrate the effectiveness of the proposed method, three test systems were used.

4.1 IEEE 33-bus

An IEEE 33-bus distribution network system was used to test the proposed method. The network consists of 37 switches, 32 sectionalising switches, and 5 tie switches. Switch numbers 33, 34, 35, 36, and 37 are normally open for the original network, while the other switches are normally closed. The total real load demand was 3715 kW, while the system's voltage was 12.66 kV. The base value of the apparent power was 100 MVA. The power losses of the network at the initial configuration were 202.677 kW, with 0.913 pu being the lowest bus voltage. The complete bus and line data are given in [9]. The DG in this test system was assumed to be a mini-hydro generation. The capacity for each DG is 2 MW. In this work, the optimal locations for the DGs were located at buses 31, 32, and 33, as in [10]. Optimal solutions were obtained for the tie switch, DG output (real power), and switching sequences. Both DG output and the tie switches were determined simultaneously. Since the IEEE 33-bus network had five tie switches and was referred to as '(11)', there are $5! \times 5! \times 2$ probabilities, which are equal to 28,800 probabilities, representing the switching changing paths that could be used to transfer the network from its original form to an expected optimal form.

4.1.1 Simultaneously NR and DG output for static loads: Table 1 shows the comparison between the initial case and final state after reconfiguration, taking into account DGs' optimal output. The power loss after NR within the DG was 73.048 kW, whereas before reconfiguration it was 202.6 kW. It can also be seen from Fig. 3 that all buses voltage magnitude is larger than its initial state. The performance of the proposed method was compared with published work, as in Table 2.

It is clear that the proposed method better than GA, refined genetic algorithm (RGA), and HSA.

4.1.2 Optimal switching changing path process: The optimal solution of NR and DG output obtained from Table 1 was used to determine the best switching sequence path to transfer the network from its initial states to the final states. The obtained best switching sequence path is:

Sequence 1: Sw36 (close) → Sequence 2: Sw32 (open) → Sequence 3: Sw35 (close) → Sequence 4: Sw8 (open) → Sequence 5: Sw37 (close) → Sequence 6: Sw28 (open) → Sequence 7: Sw34 (close) → Sequence 8: Sw9 (open) → Sw33 (NC).

The optimal fitness for switching changing path is 3.6188. The summation of the power losses during all of the steps of the optimal path is 642.22 kW.

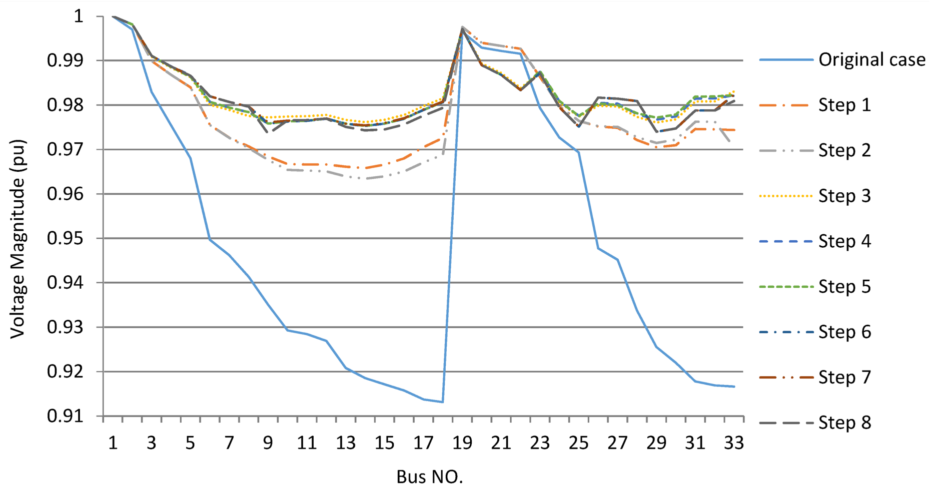

Fig. 4 *Voltage profile of 33-bus radial distribution network for all switching changing steps*

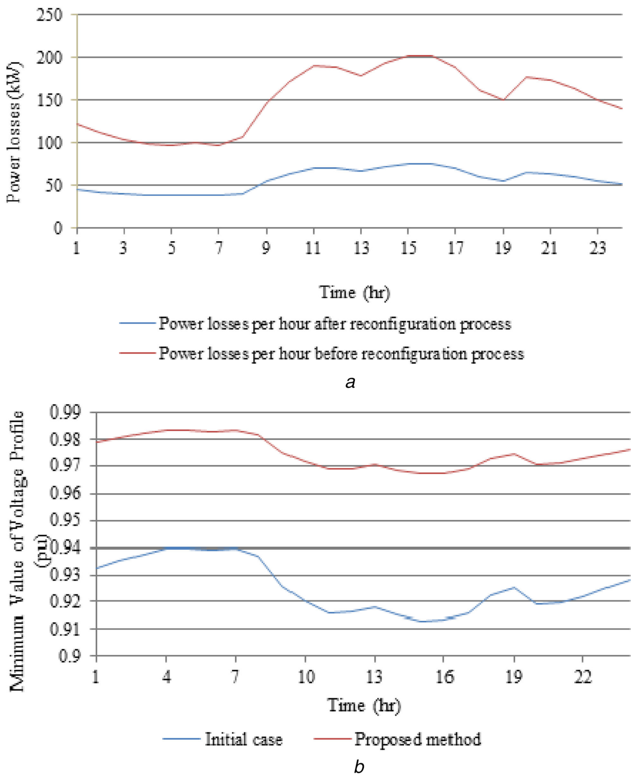

Fig. 5 *Power losses and voltage profile*

(a) Power losses per hour before and after reconfiguration processes for 33-bus network, ***(b)*** Daily minimum value of voltage profile (pu) for 33-bus radial distribution network

Fig. 4 shows the voltage profile during the optimal path sequence of switching. It is clear that the best switching changing path does not cause the voltage profile to exceed the allowable limit.

4.1.3 Simultaneously NR and DG output for dynamic loads: This section focuses on the reduction of daily power loss and voltage profile improvement by finding the optimal NR and DG output within load variation. The peak load per unit of 24 h is similar to the ones reported in [11].

The proposed method looks for the best configuration that realises the lowest daily power losses and best voltage profile at any hour of the day. From the simulation results, the daily power losses after NR within DG was 1356.7 kWh, whereas before reconfiguration it was 3622.7 kWh. The normally open switches after reconfiguration are 12, 32, 10, 7, and 26, whereas before reconfiguration they are 33, 34, 35, 36, and 37. The DG1 output is 0.602 MW; DG2 output is 0.419 MW; and DG3 is 0.554 MW. The proposed method looks for one solution that is optimal for any hour of the day. Since a day is made up of 24 h, instead of finding different configurations at each hour, the proposed method looks for one solution that best represents any hour of the day. On the basis of that, the main fitness F refers to '1', is evaluated during 24 h, which is equal to 7.3024 after reconfiguration, whereas before reconfiguration it was 19.664. Additionally, it can be observed that the power losses at any hour after the reconfiguration process is less than the power losses before the reconfiguration process, as shown in Fig. 5*a*.

Fig. 5*b* shows the minimum values of voltage profile (pu) for radial distribution network at any hours of the day. It can be observed that all minimum values of the voltage profile at any time is larger than the initial state.

Table 3 33-Bus network switching changing results

Proposed method	Switching changing path	Objective function	Switching changing power losses, kW		
		total fitness $= \sum_{hr=1}^{24} \sum_{r=1}^{N_{\text{steps}}} \left(P_{\text{loss}_r}^{R} + \text{IVD}_r\right)$			
first step	36 close	85.917	Load levels	*hr*	*P*
second step	32 open				
third step	37 close		minimum value	7	413.33
fourth step	26 open				
fifth step	33 close		average value	9	592.53
sixth step	7 open				
seventh step	34 close		maximum value	15	820.28
eighth step	12 open				
—	35 close				
—	10 open				

Table 4 Minimum and maximum values of voltage profile for each step per hour (pu) for 33-bus radial network

Switching changing steps	Minimum value of load profile		Average value of load profile		Maximum value of load profile	
	Minimum value of voltage profile (*hr* = 7)	Maximum value of voltage profile (*hr* = 7)	Minimum value of voltage profile (*hr* = 9)	Maximum value of voltage profile (*hr* = 9)	Minimum value of voltage profile (*hr* = 15)	Maximum value of voltage profile (*hr* = 15)
1	0.982818	1	0.971941	1	0.961218	1
2	0.982601	1	0.970813	1	0.959427	1
3	0.981861	1	0.97147	1	0.961385	1
4	0.982437	1	0.973221	1	0.963903	1
5	0.98298	1	0.97425	1	0.966381	1
6	0.982591	1	0.972863	1	0.963371	1
7	0.982308	1	0.973687	1	0.965789	1
8	0.982007	1	0.972908	1	0.964328	1
9	0.98334	1	0.974872	1	0.967244	1
10	0.98334	1	0.974871	1	0.967243	1

Table 5 69-Bus NR and DG output results

Case	Open owitch	DG optimal output in MW (bus number)	Minimum and maximum values of the voltage profile, pu		Objective function *F* minimise$F = (P_{\text{loss}}^{R} + \text{IVD})$	Power losses, kW	Percentage of the power reduction, %
			Minimum	Maximum			
initial	69, 70, 71, 72, 73	no DG	0.90929	1	1.1172	224.56	—
proposed method	12, 19, 57, 61, 69	DG1 = 0.25177 (60)DG2 = 1.23280 (61)DG3 = 0.45254 (62)	0.9816	1	0.22662	40.30	82.08

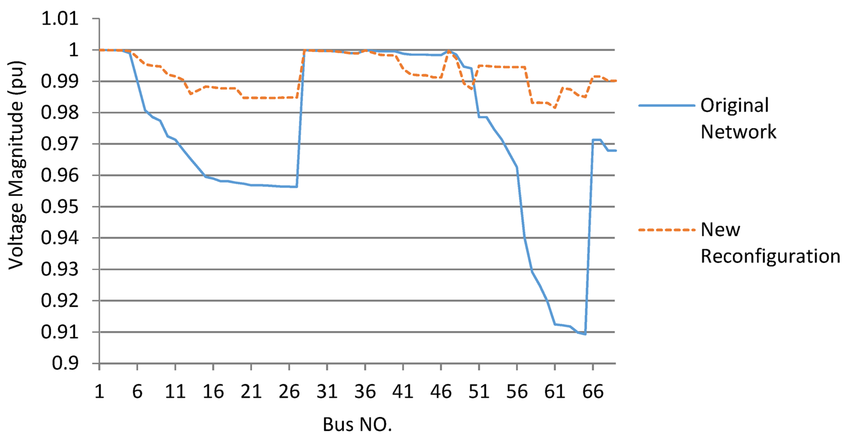

Fig. 6 *Voltage profile of IEEE 69-bus radial distribution network*

Table 3 shows the fitness for optimal switching sequence path. The summation of power losses during the steps of the optimal path at any time is also tabulated, which means that the optimal switching changing path minimises the total power losses during all of the steps at any time.

Table 4 shows the minimum/maximum values of the voltage profile during the steps of the optimal path sequence of switching at different hours. The proposed method finds for the optimal path sequence at any hour of the day, which means that instead of looking for a different solution at each hour, the proposed method looks for an optimal solution that best fits any hour of the day. It should be pointed out that at any time (*hr* of the day) when the network changes its configuration from its initial form to its optimal form, the process takes ten steps, because only five switches will change from closed to open, and vice versa, simultaneously. At each step, the minimum/maximum values of the bus voltage will be evaluated. It is clear that the best switching changing path does not cause the voltage profile to exceed the allowable limits.

4.2 IEEE 69-bus

An IEEE 69-bus network system was used to test the proposed method. The network consists of 73 switches, 68 sectionalising switches, and 5 tie switches. Switch numbers 69, 70, 71, 72, and 73 are normally open for the original network, whereas the others are normally closed. The total real load demand was 3801.89 kW. The system's voltage was 12.66 kV. The base value of the apparent power was 100 MVA. The power loss of the network at its initial configuration was 224.56 kW, with 0.90929 pu as its lowest bus voltage. The complete bus and line data are given as per [12]. The optimal locations for the DGs were located at buses 60, 61, and 62. This location is based on [10].

4.2.1 Simultaneously NR and DG output for static loads: Table 5 shows the comparison between the initial case and final state. Power loss after NR within DG was 40.30 kW, whereas before reconfiguration it was 224.56 kW. The minimum voltage for all of the buses after reconfiguration was improved to 0.9816 pu, whereas before reconfiguration it was 0.90929 pu, as shown in Fig. 6. The performance of the proposed method was compared

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Table 6 Comparison of simulation result of 69-bus system

Method	Open switches	Total DG output, MW	Minimum value of voltage profile, pu	Power losses, kW	Percentage of the power reduction, %
GA [10]	10, 15, 45, 55, 62	2.0292	0.9727	46.50	73.38
RGA [10]	10, 16, 14, 55, 62	2.0654	0.9742	44.23	80.32
HAS [10]	69, 17, 13, 58, 61	1.8718	0.9736	40.30	82.08
proposed method	12, 19, 57, 61, 69	1.93711	0.9816	40.30	82.08

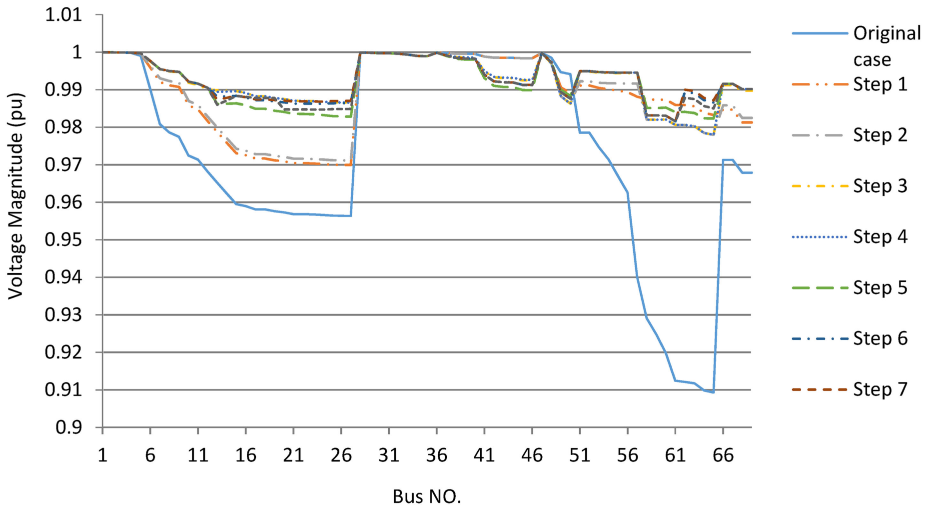

Fig. 7 *Voltage profile of 69-bus radial distribution network for all switching changing steps*

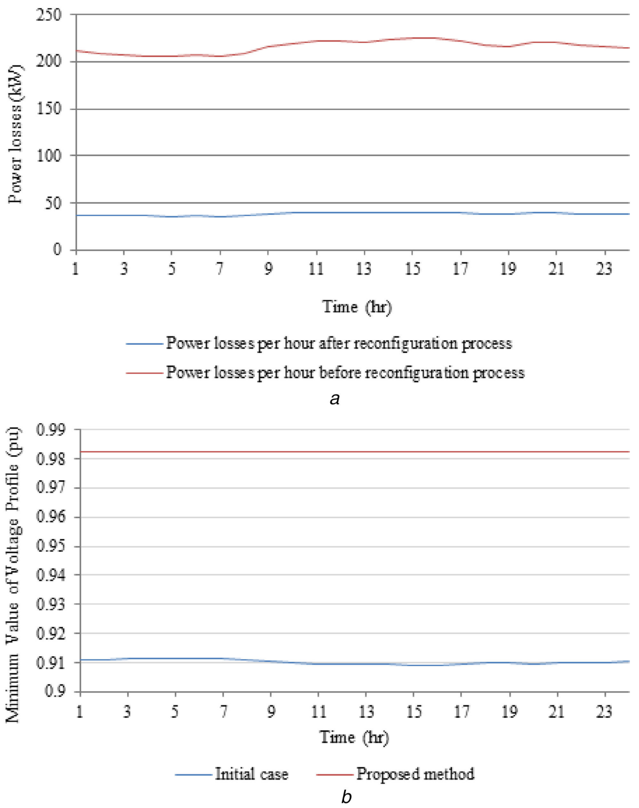

Fig. 8 *NR and DG output for dynamic loads*
(a) Power losses per hour before and after reconfiguration processes for 69-bus network, ***(b)*** Daily minimum value of voltage profile (pu) for 69-bus radial distribution network

with other published work, and shown in Table 6. It is clear that the proposed method is better than GA, RGA, and similar to HSA.

4.2.2 Optimal switching changing path process: The obtained best switching changing path is:

Sequence 1: Sw72 (close) → Sequence 2: Sw57 (open) → Sequence 3: Sw71 (close) → Sequence 4: Sw12 (open) → Sequence 5: Sw73 (close) → Sequence 6: Sw61 (open) → Sequence 7: Sw70 (close) → Sequence 8: Sw19 (open) → Sw69 (NC).

The optimal fitness for switching sequence path is 2.023747. The summation of power losses during all of the steps of the optimal path is 363.809 kW.

Fig. 7 shows the voltage profile during the optimal path sequence of switching. It is clear that the best switching sequence path does not cause the voltage profile to exceed the allowable limit.

4.2.3 Simultaneously NR and DG output for dynamic loads: From the simulation results, the daily power loss after NR within DG is 917.92 kWh, whereas before reconfiguration it is 5180.2 kWh. The normally open switches after reconfiguration were 12, 20, 57, 61, and 69, whereas before reconfiguration they were 69, 70, 71, 72, and 73. The main fitness *F* was equal to 4.5084 after reconfiguration, whereas before reconfiguration it was 25.222. The DG1 output was 0.2543 MW, DG2 output was 1.2716 MW, and DG3 output was 0.4517MW. It can also be seen that the power losses at any hour after the reconfiguration process is less than power losses before the reconfiguration process, as shown in Fig. 8*a*.

Fig. 8*b*. shows the minimum values of voltage profile (pu) for radial distribution network at any hours of the day. It can be observed that all minimum values of the voltage profile at any time is larger than the initial state.

4.2.4 Optimal switching changing path process: As shown in Table 7, the fitness for optimal switching sequence path is 46.052. The summation of the power losses during all the steps of the optimal path at any time is also presented, which means that the optimal switching changing path minimises the total power losses during all steps at any time.

Table 8 shows the minimum/maximum values of the voltage profile during the steps of the optimal path sequence of switching at different hours. It is clear that the best switching changing path does not cause the voltage profile to exceed the allowable limits.

Table 7 69-Bus network switching changing results

Proposed method	Switching changing path	Objective function total fitness $= \sum_{hr=1}^{24} \sum_{r=1}^{N_{steps}} \left(P_{loss_r}^{R} + \mathrm{IVD}_r\right)$	Switching changing power losses, kW		
first step	72 close	46.052	Load levels	*hr*	*P*
second step	57 open				
third step	71 close				
fourth step	12 open		minimum value	7	319.5545
fifth step	73 close				
sixth step	61 open		average value	9	341.9937
seventh step	70 close				
eighth step	20 open		maximum value	15	364.8414
—	69 NC				

Table 8 Minimum and maximum values of voltage profile for each step per hour (pu) for 69-bus radial network

Switching changing steps	Minimum value of load profile		Average value of load profile		Maximum value of load profile	
	Minimum value of voltage profile (*hr* = 7)	Maximum value of voltage profile (*hr* = 7)	Minimum value of voltage profile (*hr* = 9)	Maximum value of voltage profile (*hr* = 9)	Minimum value of voltage profile (*hr* = 15)	Maximum value of voltage profile (*hr* = 15)
1	0.977573	1	0.973598	1	0.970049	1
2	0.978839	1	0.974822	1	0.97116	1
3	0.97885	1	0.978845	1	0.97884	1
4	0.978849	1	0.978844	1	0.97884	1
5	0.984258	1	0.983564	1	0.982845	1
6	0.982478	1	0.982474	1	0.982469	1
7	0.982478	1	0.982474	1	0.98247	1
8	0.982478	1	0.982473	1	0.982469	1

Table 9 118-bus NR and DG output results

Case	Open switch	DG optimal output in MW (bus number)	Minimum and maximum values of the voltage profile, pu		Objective function *F* minimise$F = (P_{loss}^{R} + \mathrm{IVD})$	Power losses, kW	Percentage of the power reduction, %
			Minimum	Maximum			
initial	118, 119, 120, 121, 122, 132, 124, 124, 126, 127, 128, 129, 130, 131, 132	no DG	0.8688	1	1.1565	1297.8	—
proposed method	41, 25, 21, 121, 122, 58, 38, 125, 70, 127, 128, 81, 130, 131, 33	DG1 = 1.5075 (24)DG2 = 1.2489 (42)DG3 = 1.8218 (47)DG4 = 1.8248 (74)DG5 = 1.2820 (78)DG6 = 1.2642 (94)DG7 = 2.991 (108)	0.9502	1	0.51773	571.38	55.97

4.3 IEEE 118-bus

An IEEE 118-bus large distribution network system was used to test the proposed method. The network consists of 132 switches, 117 sectionalising switches, and 15 tie switches. Switch numbers 118, 119, 120, 121, 122, 132, 124, 124, 126, 127, 128, 129, 130, 131, and 132 are normally open in the case of the original network, while the other switches are normally closed. The total real load demand was 22,709 kW, whereas the system's voltage was 11 kV. The base value of the apparent power was 100 MVA. The power loss of the network at the initial configuration was 1297.8 kW, with 0.8688 pu as its lowest bus voltage. The complete bus and line data are given in [13]. The optimal locations for the DGs were located at buses 24, 42, 47, 74, 78, 94, and 108, as per [14].

4.3.1 Simultaneously NR and DG output for static loads: Table 9 tabulates the comparison between the initial case and final state. Power loss after NR within DG was 571.38 kW, whereas before reconfiguration it was 1297.8 kW. The minimum voltage for all the busses after reconfiguration improved to 0.9502 pu, whereas before reconfiguration it was 0.8688 pu The performance of the proposed method was compared with published works, and the comparison shown in Table 10. It is clear that the proposed method is better than GA, RGA, improve tabu search (ITS), and moving target search (MTS).

4.3.2 Optimal switching changing path process: The obtained best switching changing path is:

Sequence 1: Sw120 (close) → Sequence 2: Sw21 (open) → Sequence 3: Sw119 (close) → Sequence 4: Sw25 (open) → Sequence 5: Sw118 (close) → Sequence 6: Sw41 (open) → Sequence 7: Sw132 (close) → Sequence 8: Sw33 (open) → Sequence 9: Sw129 (close) → Sequence 10: Sw81 (open) → Sequence 11: Sw126 (close) → Sequence 12: Sw70 (open) → Sequence 13: Sw124 (close) → Sequence 14: Sw38 (open) → Sequence 15: Sw123 (close) → Sequence 16: Sw58 (open) → (Sw121, Sw122, Sw125, Sw127, Sw128, Sw130, Sw131 are NC).

Table 10 Comparison of simulation result of 118-bus system in case of reconfiguration

Method	Open switches	Minimum value of voltage profile, pu	Power losses, kW
initial	118, 119, 120, 121, 122, 132, 124, 124, 126, 127, 128, 129, 130, 131, 132	0.8688	1297.8
GA [15]	43, 120, 24, 51, 49, 62, 40, 126, 74, 73, 77, 83, 31, 110, 35	0.9321	885.56
MTS [16]	42, 26, 23, 51, 122, 58, 39, 95, 71, 74, 97, 129, 130, 109, 34	0.9323	867.4
ITS [13]	43, 27, 24, 52, 120, 59, 40, 96, 75, 72, 98, 130, 131, 110, 35	0.9323	865.86
RGA [17]	43, 27, 23, 52, 49, 62, 40, 126, 74, 73, 77, 83, 131, 110, 33	0.9321	883.13
proposed method	42, 23, 25, 121, 50, 58, 33, 95, 74, 71, 97, 130, 129, 109, 39	0.93231	859.38

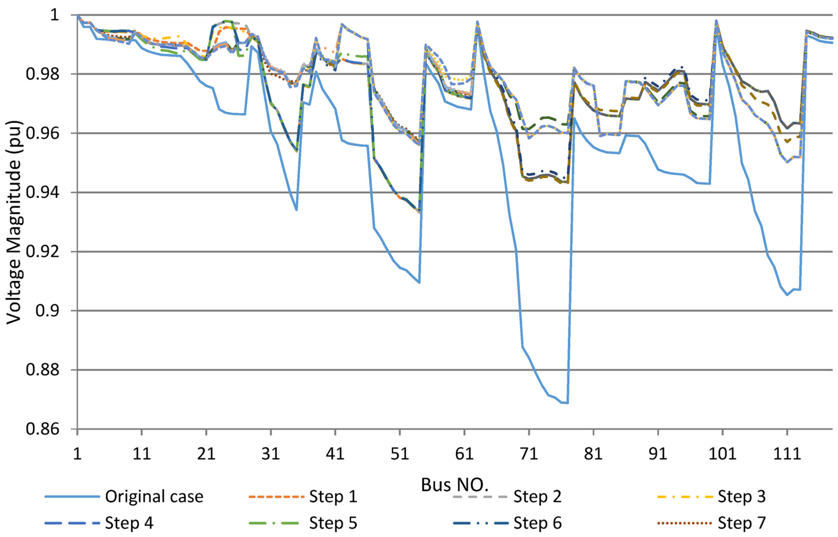

Fig. 9 *Voltage profile of 118-bus radial distribution network for all switching changing steps*

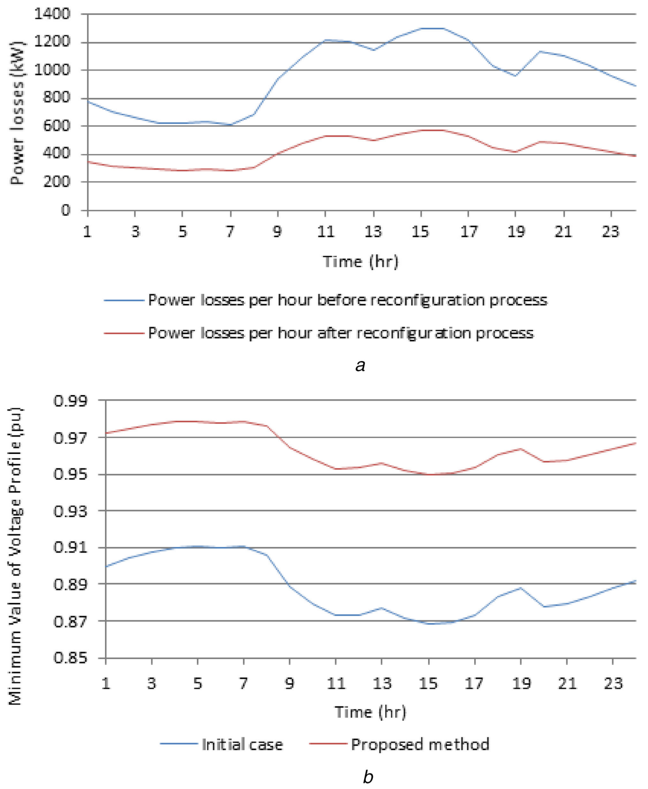

Fig. 10 *NR and DG output for dynamic load*
(a) Power losses per hour before and after reconfiguration processes for 118-bus network, ***(b)*** Daily minimum value of voltage profile (pu) for 118-bus radial distribution network

The optimal fitness for switching sequence path is 8.5017, while the summation of power losses during all steps of the optimal path is 9265.5 kW.

Fig. 9 shows the voltage profile during the optimal path sequence of switching. It is clear that the best switching sequence path resulted in minimum bus voltage larger than the initial case.

4.3.3 Simultaneously NR and DG output for dynamic loads: The daily power losses after NR within DG was 10,244 kWh, whereas before reconfiguration it was 23,125 kWh. The normally open switches after reconfiguration were 42, 25, 21, 121, 122, 58, 38, 125, 70, 127, 128, 81, 130, 131, and 33, whereas before reconfiguration they were 118, 119, 120, 121, 122, 132, 124, 124, 126, 127, 128, 129, 130, 131, and 132. The main fitness F was equal to 8.7611 after reconfiguration, whereas before reconfiguration it was 20.494. Additionally, it can be observed that the power loss at any hour after reconfiguration process is less than the power loss before the reconfiguration process, as shown in Fig. 10*a*.

Fig. 10*b* shows the minimum values of voltage profile (pu) for radial distribution network at any hours of the day. It can be seen that all minimum values of the voltage profile at any time is larger than its initial state.

4.3.4 Optimal switching changing path process: Table 11 shows the fitness for optimal switching sequence path. The summation of the power losses during the steps of the optimal path at any time is also presented. This means that the optimal switching changing path minimises the total power losses during all steps at any time.

Table 12 shows the minimum/maximum values of the voltage profile during the steps of the optimal path sequence of switching at different hours. It is clear that the best switching changing path results in better voltage profiles compared with its initial case.

5 Conclusion

This paper proposed a new strategy to locate optimal switching changing path based on the optimal simultaneously DNRC and DG output to change a network from its original form to its optimal form. The reported method realised the minimum power losses and

Table 11 118-bus network switching changing results

Proposed method	Switching changing path	Objective function total fitness $= \sum_{hr=1}^{24} \sum_{r=1}^{N_{\text{steps}}} \left(P_{\text{loss}_r}^{R} + \text{IVD}_r\right)$	Switching changing power losses, kW		
step 1	120 close	154.7	Load levels	*hr*	*P*
step 2	21 open				
step 3	119 close				
step 4	25 open		minimum value	7	4608.8
step 5	118 close				
step 6	42 open		average value	9	6634.2
step 7	132 close				
step 8	33 open		maximum value	15	9247.8
step 9	129 close				
step 10	81 open				
step 11	126 close				
step 12	70 open				
step 13	124 close				
step 14	38 open				
step 15	123 close				
step 16	58 open				
—	121, 122, 125, 127, 128, 130, 131 are NC				

Table 12 Minimum and maximum values of voltage profile for each step per hour (pu) for 118-bus radial network

Switching changing steps	Minimum value of load profile		Average value of load profile		Maximum value of load profile	
	Minimum value of voltage profile (*hr* = 7)	Maximum value of voltage profile (*hr* = 7)	Minimum value of voltage profile (*hr* = 9)	Maximum value of voltage profile (*hr* = 9)	Minimum value of voltage profile (*hr* = 15)	Maximum value of voltage profile (*hr* = 15)
1	0.9601	1	0.9461	1	0.9334	1
2	0.9603	1.001	0.9463	1	0.9335	1
3	0.9601	1	0.9461	1	0.9334	1
4	0.9603	1.001	0.9463	1	0.9336	1
5	0.9603	1.001	0.9463	1	0.9337	1
6	0.9604	1.002	0.9465	1	0.9338	1
7	0.9758	1.002	0.9594	1	0.9428	1
8	0.9761	1.002	0.9594	1	0.9428	1
9	0.9762	1.002	0.9592	1	0.9422	1
10	0.9771	1.002	0.9606	1	0.9442	1
11	0.9791	1.002	0.9645	1	0.9500	1
12	0.9788	1.002	0.9645	1	0.9500	1
13	0.9788	1.003	0.9645	1	0.9500	1
14	0.9785	1.002	0.9645	1	0.9500	1
15	0.9785	1.002	0.9645	1	0.9500	1
16	0.9785	1.002	0.9645	1	0.9500	1

best voltage profile for the network. The firefly is the heuristic method that was used to achieve the distribution minimum main fitness. The effectiveness of the presented method has been verified on 33-bus, 69-bus, and 118-bus distribution systems using static and dynamic loads. The presented approach is of high quality when it comes to achieving an optimal switching changing path and optimal network configuration and DG output. The results obtained using FA was compared with the results reporting using GA, RGA, HSA, ITS, and MTS. The computational results showed that the performance of FA exceeds that of GA, RGA, HSA, ITS, and MTS. The results confirmed that the proposed method could be adapted to other real systems with DGs.

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