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Paper

Optimal Switching Sequence Path for Distribution Network Reconfiguration Considering Different Types of Distributed Generation

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Minimizing power losses in a distribution system is commonly realized through optimal network reconfiguration. In the past, network reconfiguration research was focused on planning, where the final configuration with the lowest power losses was the main goal. However, power losses during switching operations from the initial state to the final state of the configuration were not considered. This paper presents the optimal switching sequence path to minimize power losses during the network switching operation. Apart from this contribution, the simultaneous optimal network reconfiguration for variable load network and distributed generation (DG) output is also proposed. The proposed methodology involves the (i) optimal network reconfiguration with variable load and DG output simultaneously, and (ii) the optimal sequence of switching operations required to convert the network from the original configuration to the optimal configuration obtained from (i). The selected optimization technique in this work is the firefly algorithm. To assess the capabilities of the proposed method, simulations using MATLAB are carried out on IEEE 33-bus radial distribution networks. The results demonstrate the effectiveness of the proposed strategy to determine the sequence path of switching operations, as well as the optimal network configuration and optimal output of DG units. © 2017 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: switching sequence; distribution network reconfiguration; distributed generation mode; firefly algorithm; load profile; voltage profile

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1. Introduction

One of the important issues for distribution companies is power losses from their systems. These losses could cost them revenue and, in the long run, environmental issues, since more power is needed to compensate for these losses. The network reconfiguration approach is a common technique that can be used to minimize power losses [1]. The reduction of power losses can also be realized by installing local generation, referred to as distributed generation (DG). DG comprises small generating units installed at strategic points in the distribution system, and most of the time they are based on renewable energy sources, such as mini-hydro, wind, solar, and biofuels [2]. By having a local supply, power can be delivered to the loads within short distances, which is then able to decrease the overall power losses. Furthermore, the integration of DGs would lead to improvement of the voltage profile. Therefore, it is essential to ensure that the DG output is at its optimum. An inappropriate value will cause power losses in the system to exceed that of the initial configuration. Therefore, proper output is critical to realize maximum benefits [3–5].

Several researchers have described the reconfiguration criteria. Baran and Wu [6], Su and Lee [7], and Hong and Ho [8] presented concepts and techniques that can be used to solve this problem. Network reconfiguration is a process of changing the switch states of the network. The switch can normally be open, where it is called tie switches, or normally closed, where it is called sectionalizing switches. The topological structure of the network can be altered by closing the open switches, and vice versa. This technique is able to reduce power losses and improve the overall voltage profile provided the optimum reconfiguration can be determined. By doing this, the load will be transferred to relatively less heavily loaded feeders from the heavily loaded feeders, leading to minimum power losses. Furthermore, in Ref. [9] a method that simultaneously solves both DG sizing and the reconfiguration problem was presented. The main objective was to reduce the total power losses and improve the voltage profile. Sensitivity analyses were conducted using the harmony search algorithm to solve the simultaneous process and compare the results with those of the genetic algorithm and the refined genetic algorithm. The results proved that the simultaneous process was more effective than the sequential process for minimizing power losses and improving the voltage profile.

There have been a few studies focusing on minimizing power losses via switching sequence operation. In Ref. [10], a new method was proposed for real-time configuration of distribution network incorporated with DG. This method used a heuristic algorithm to set the weights of the criteria. According to this method, only remote-controlled switches are used in network analysis. The best sequence of the switches was determined using the analytic hierarchy process of multi-criteria analysis. The presented method was tested in a real network of a power utility. The results showed the importance of integrating DGs to the network for reducing losses and increasing reliability during the automatic configuration of the system. Moreover, automatic reconfiguration in real time will help promote the efficient use of DG resources and improve network performance.

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Studies on network reconfiguration have also taken into account load variations and the operation mode of DGs. Yang *et al.* [11] considered the load profile in order to minimize power losses without taking into account the DGs, while in Ref. [12], the author integrated mixed renewable resources of biomass, photovoltaic, and wind power to the system in order to minimize the annual power losses, considering all load demand conditions. It should be pointed out that DGs can be operated in two modes, namely PV and PQ, which are based on the generator or interface between the grid and DGs [13]. These modes were considered in Ref. [14] for photovoltaic, wind, and fuel cell DGs in order to solve the network reconfiguration issue. Meanwhile, in Ref. [15], the effects of different DG operating modes were analyzed when simultaneous network reconfiguration was conducted with DG generation and tap changer setting to obtain the optimal configuration using the imperialist competitive algorithm (ICA). The results proved that the total daily power losses are affected by the DG operation modes.

In this paper, we propose a method to determine the optimal sequence path of switching operations based on the optimal distribution network reconfiguration, taking into account the variable load in the presence of an optimal DG output using the firefly algorithm (FA). The main objective of this work is to minimize the daily power losses and improve the voltage profile. Simultaneously, important system constraints are taken into account. The method is tested on a 33-bus system, and the results are compared with those of other methods in the literature. The rest of this paper is arranged as follows: Section 2 describes the formulation and constraints of the problem. Section 3 presents the proposed strategy to obtain the optimal switching sequence and network configuration with optimal DG output. Section 4 details the simulation results and their discussion, and Section 5 concludes the work.

2. Mathematical Formulation and Constraints

The best switching sequence path to obtain the optimal network configuration and DG output is determined based on the lowest daily power loss that improves the overall voltage profile for the network system. The following describes the objective function and constraints of the optimization.

The fitness function F can be presented in the following form:

$$\text{Minimize } F = \sum_{h}^{T} (w_1 \times P_{\text{loss}}^{\text{R}} + w_2 \times si) \tag{1}$$

where h is the current time considered; T is the total number of hours considered in the time frame; and w_1 and w_2 are the weighting factors ($w_1 = w_2 = 0.5$). Since the total fitness has different objective units, the net power loss P_{loss}^{R} is taken as the ratio between the system's total active power loss after $P_{\text{loss}}^{\text{rec}}$ and before P_{loss}^{0} reconfiguration, as follows:

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

The power loss equation for a distribution system is given by

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

where P_{loss} is the total active power losses in the distribution 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.

The voltage stability index (SI) is considered to be maximized. SI is used to find the weakest voltage bus in the system that can lead to voltage instability when the load increases. The formulation of SI is as follows [16]:

$$\begin{aligned} SI = {} & |V_{\text{s}}|^4 - 4 \times \{P_r X_{ij} - Q_r r_{ij}\}^2 \\ & - 4 \times \{P_r r_{ij} - Q_r X_{ij}\}^2 \times |V_{\text{s}}|^2 \geq 0 \end{aligned} \tag{4}$$

where SI is the voltage stability index; V_{s} is the sending bus voltage in pu; P_r and Q_r are the active and reactive load at the receiving end in pu, respectively; and r_{ij} and X_{ij} are the resistance and reactance of the line $i - j$ in pu.

Under stable operation, the value of SI should be greater than 0 for all buses. When the value of SI becomes close to 1, all buses become more stable. In the proposed algorithm, the value of SI is calculated for each bus in the network, and they are sorted from the lowest to the highest value. The bus having the lowest value of SI will be considered in the fitness function. Since the fitness (1) has two terms (one to minimize power losses and the other one to maximize si) the equation should have the same form, so in order to change si to be minimum, the difference between the rated value of si (1) and the weakest bus is taken to be minimized as follows:

$$si = \frac{1 - \min(SI)}{\max(SI)} \tag{5}$$

where $\min(SI)$ and $\max(SI)$ are the buses having the lowest and highest values of SI, respectively. So the second term of (1) becomes unitless. In this case, (1) is consistent and could be minimized to obtain the objective of minimizing power losses and improving the voltage profile.

The main constraints the optimization needs to fulfill to get the best switching sequence for network reconfiguration with DGs are as follows:

1. Distributed generator capacity

$$P_i^{\min} \leq P_{\text{DG},i} \leq P_i^{\max} \tag{6}$$

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

2. Power injection

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

where k is the number of the DG; P_{load} is the total load of the active power of the network; and P_{loss} is the total active power losses of the network. This constraint is to ensure that there is no power flowing from DGs to the grid, which may cause protection issues.

3. Power balance

$$\sum_{i=1}^{k} P_{\text{DG},i} + P_{\text{substation}} = P_{\text{load}} + P_{\text{loss}} \tag{8}$$

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

4. Voltage magnitude

$$V_{\min} \leq V_{\text{bus}} \leq V_{\max} \tag{9}$$

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

5. Radial configuration

All the time, the distribution network should be in a radial form. For this purpose, a graph theory function in MATLAB (Kuala Lumpur, Malaysia) is used:

$$TF = graphisspa\_ntree(G) \tag{10}$$

$$TF = \begin{Bmatrix} 1 & radial \\ 0 & not\_radial \end{Bmatrix} \tag{11}$$

where G is the distribution network.

6. No load isolation

All nodes must be energized to ensure they receive the power sources.

3. Proposed Strategy

In this work, FA is suggested to find the optimal switching sequence path within network reconfiguration technique in the presence of DGs. The optimal switching sequence represents the best path to transfer the network configuration from the original form to the optimal configuration form, with the aims of minimizing the daily power losses and improving the overall voltage profile during the switching sequence process.

Based on the radiality method, a distribution network should always have a number of tie switches which are normally open (e.g., the IEEE 33-bus network has five switches). Furthermore, the network after reconfiguration should also have the same number of open switches. In this work, the original five switches (related to the original network from) and the new five switches (related to the optimal network form after simultaneous network reconfiguration with the DG output process is completed) will be used to find the optimal switching sequence path. This path appears at the opening and closing operation sequence of these switches. Therefore, there are many possibilities (paths) of changing the state of these ten switches to obtain the new form of the network. Generally, if the number of the tie switches in any network is t, then the number of the sequence possibilities can be calculated by

$$\Pr_{\text{size}} = t! \times t! \times 2 \tag{12}$$

This equation shows the large number of possibilities that could be generated. Thus, it is crucial that the optimization technique be applied to determine the optimal switching sequence path of the network during the reconfiguration technique.

Therefore, the proposed strategy is divided into two stages:

Stage 1 aims at determining the DGs output real power and network reconfiguration with variable load simultaneously.

Stage 2 aims at determining the optimal switching sequence path to change the network configuration from the original form to the optimal form, based on stage 1.

3.1. Simultaneous network reconfiguration and DG output using FA

FA is a recent nature-inspired metaheuristic optimization method. It is based on the behavior of social insects (fireflies). Each individual in social insect colonies seems to have its own agenda, yet the group as a whole appears to be highly organized [17,18].

The steps for this stage are as follows:

1. Determine the input data, such as the bus load and voltage, DG location, lines resistance and reactance values, DG mode, PV generation output, and load profile.
2. Generate random initial populations of firefly (x), which in this case represents the switches' number and the DG output, taking into consideration all the limitations and constraints. The variable used in this work for tie switches is represented by S and the DG output is represented by P_{DG}. For the simultaneous case, both the number of switches and the DG output should be determined simultaneously, as follows:

$$x = \begin{bmatrix} S_{11}, S_{12}, & \cdots & S_{1\text{n}}, & P_{\text{DG11}}, & P_{\text{DG12}}, & \cdots & P_{\text{DG1K}} \\ S_{21}, S_{22}, & \cdots & S_{2n}, & P_{\text{DG21}}, & P_{\text{DG22}}, & \cdots & P_{\text{DG2K}} \\ \vdots \;\; \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{m1}, S_{m2}, & \cdots & S_{mn}, & P_{\text{DGm1}}, & P_{\text{DGm2}}, & \cdots & P_{\text{DGmK}} \end{bmatrix} \tag{13}$$

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

3. Start the iteration by solving load flow analysis to obtain power flow through all network lines. From the results, the power losses and minimum value of the voltage for the entire system can be determined.
4. Evaluate the fitness for each of the population $(1-m)$ using (1). With the mean, evaluate the summation of the power losses and the minimum value of the stability index for each hour of a day.
5. Rank the populations according to the light intensity (low to high fitness) and save the best value, which is the minimum:

$$[\ \text{Light,Index} = \text{sort(x)}\ ]$$
$$\text{Light}_{\text{best}} = \text{Light}(1) \tag{14}$$

6. Update all fireflies on matrix x (switches number and DG output) and rank the movement taking into consideration all the limitations and constraints using the following equations:

The firefly attractiveness β is presented as the following form:

$$\beta(r) = \beta_0 \mathrm{e}^{-\gamma r^2} \tag{15}$$

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 follows:

$$r_{lj} = \|x_l - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{l,k} - x_{j,k})^2} \tag{16}$$

where $x_{l,k}$ and $x_{j,k}$ represent the kth component of the Cartesian coordinate x_l and x_j of fireflies l and j, respectively; d is the number of the parameters that are needed to be optimized. The movement of fireflies, where firefly l is attracted to a brighter firefly j, is determined by

$$x_{l,k} = x_{l,k} + \beta_0 \mathrm{e}^{-\gamma r_{lj}^2} (x_{j,k} - x_{l,k}) + \alpha(rand - 0.5) \tag{17}$$

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

7. Repeat the steps from step 3 until the max iteration number is completed.

Stop the process and print the best solution that represents the switch number that forms the optimal network configuration, the output of the DGs, the daily power losses, the voltage at each bus for the optimal configuration, and the total fitness plots during all iterations.

3.2. Optimal switching sequence path using FA

Once the first stage is completed, the DG output and the final configuration of the network are determined. These data will be used in stage 2 in order to determine the best path for changing the network from the original form to the optimal form at any hour. The steps for this stage are as follows:

1. Identify the initial and final configuration of the network. The variable '*SC*' represents the switches, where it should be closed during the switching sequence process, while the variable '*SO*' represent the switches that should be open during the switching sequence process. Set the size of the DGs (obtained in stage 1).
2. Remove the replica switch. This means that if one of the switches is still in the same state after reconfiguration, it should be removed, i.e. if any switch has the same state of normally open before and after reconfiguration, there is no need to use it in the sequencing process.
3. Generate random initial populations of firefly (x), where in this case x represents the switching sequence paths as mentioned in (18), taking into the account the constraint of voltage limitation.

$$x = \begin{bmatrix} SC_{11}, SO_{12}, & SC_{13}, & \mathrm{SO}_{14}, & \cdots & \mathrm{SC}_{1q-1}, & SO_{1q} \\ SC_{21}, SO_{22}, & SC_{23}, & SO_{24}, & \cdots & SC_{2q-1}, & SO_{2q}, \\ \vdots \quad \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ SC_{m1}, SO_{m2}, & SC_{m3}, & SO_{m4}, & \cdots & SC_{mq-1}, & SO_{mq}, \end{bmatrix} \tag{18}$$

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

The first row of matrix x represent the first switching sequence path, SC_{11} is the first switch that should be closed (in the first row and first column of the first population), then SO_{12} is the second switch that should be open (in the first row and second column of the first population), after that SC_{13} is the third switch that should be closed (in the first row and third column of the first population), then SO_{14} is the fourth switch that should be open (in the first row and fourth column of the first population), and so on, until SC_{1q-1}, SO_{1q} where SC_{1q-1} represents the switch number $q-1$ that should be closed (in the first row and column number $q-1$ of the first population), then SO_{2q} is the final switch that should be open (in the first row and final column of the first population).

The second row of matrix x represents the second switching sequence path, where SC_{21} is the first switch that should be closed (in the second row and first column of the second population), then SO_{22} is the second switch that should be open (in the second row and second column of the second population), after that SC_{23} is the third switch that should be closed (in the second row and third column of the second population), then SO_{24} is the fourth switch that should be open (in the second row and fourth column of the second population), and so on, until SC_{2q-1}, SO_{2q}, where SC_{2q-1} represents the switch number $q-1$ that should be closed (in the second row and column number $q-1$ of the second population), then SO_{2q} is the final switch that should be open (in the second row and final column of the second population); and continue until population number m.

4. At 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, then open to closed. 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).

For example, for the 33-bus network, the initial configuration of the network (33, 34, 35, 36, and 37) is normally open. Suppose the final configuration of the network (8, 9, 12, 26, and 33) is normally closed. The matrix x for example will be as follows:

$$x = \begin{bmatrix} 36{,}8, & 37, & 26, & \cdots & 34, & 9 \\ 37{,}9, & 35, & 8, & \cdots & 36, & 26 \\ \vdots \quad \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 36\ 9 & 37 & 26 & \cdots & 34 & 8 \end{bmatrix} \tag{19}$$

That means that the first row represents the first switching sequence path. Switch 36 should be closed first, then switch 8 should be open, after that switch 37 should be closed, then switch 26 should be open, and so on, until the final switch number 9 is open.

5. Compute the power losses and voltage profile for each step (in each closed or open of the switch operation) during the sequence path for each population. This means that each population should have the number of steps, as follows:

$$N_{\text{steps}} = 2 \times t \tag{20}$$

where t is the number of tie switches as we mentioned before.

In other words, the normally open switches will be closed, and another t number of the normally closed switch 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 to avoid being disconnected from any bus.

6. The light intensity (fitness) of each firefly (sequence path) in (18) is calculated for all hours (considering the time frame of the system loading) as follows:

$$F_z = \sum_{h=1}^{T} \sum_{r=1}^{N_{\text{steps}}} (w_1 \times P^R_{\text{loss}_r} + w_2 \times si_r) \tag{21}$$

where r is the step number; z is the firefly $(1, \ldots, m)$; and T is the total hour considered in the time frame and is the current time. In this study, the time frame is considered for 24 h. This means that the proposed method will find one optimal switching sequence when applied in any hour of a day (24 h) producing minimum power losses and best voltage index.

7. Rank the fireflies (sequence path) based on the light intensity (fitness) to find the best firefly with the minimum light intensity.
8. Update and rank the fireflies, taking into consideration the same constraints in point 4 based on (15)–((17).
9. Repeat the process from step 5.
10. Save the best solution after the maximum iteration is completed.

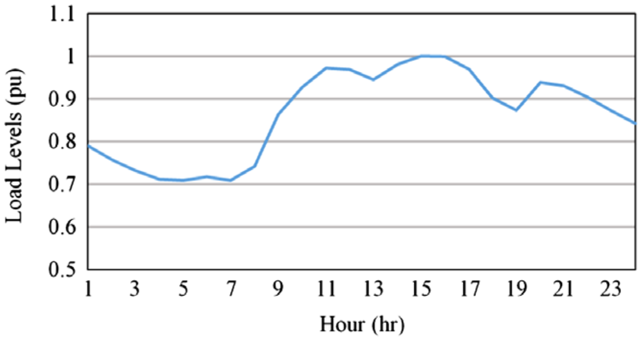

Fig. 1. Hourly load profile for individual loads

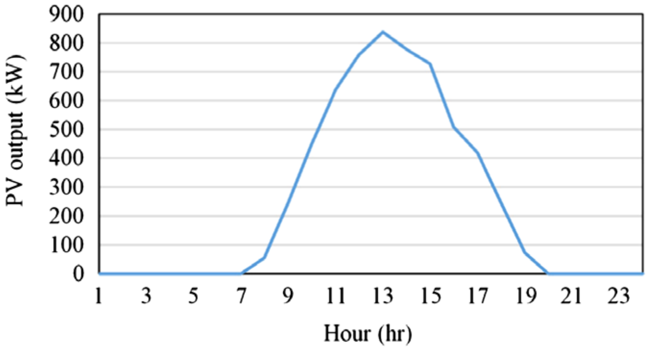

Fig. 2. Hourly PV power production

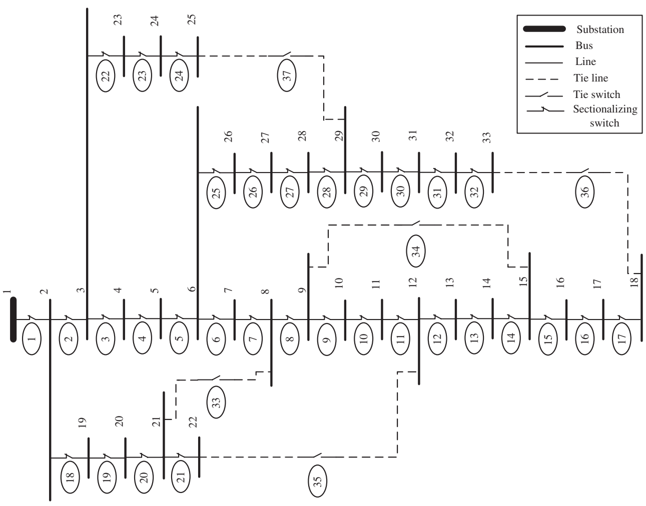

Fig. 3. IEEE 33-bus distribution network before reconfiguration process

The best solution represents the following:

1. The optimal switching sequence path that changes the network from the original form to the optimal form during the time work of the system.
2. The voltage profile for all buses during all steps operation of the optimal switching sequence path. The main fitness value and power loss during the optimal switching sequence path at any hour.

4. Simulation Result and Discussion

This work focuses on the reduction of daily power loss and voltage profile improvement by finding the optimal switching sequence

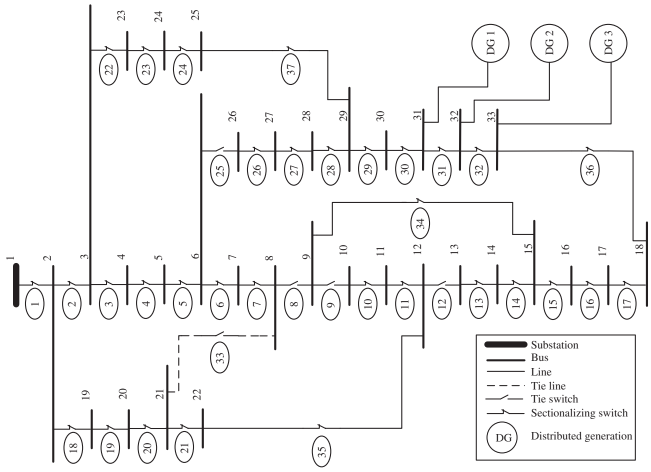

Fig. 4. IEEE 33-bus distribution network after reconfiguration process

Table I. DG operating mode

DG type	Mode	Location	Size
DG 1 (biomass)	PV	31	0.832
DG 2 (photovoltaic)	PQ	32	Based on solar radiation
DG 3 (mini-hydro)	PV	33	0.47

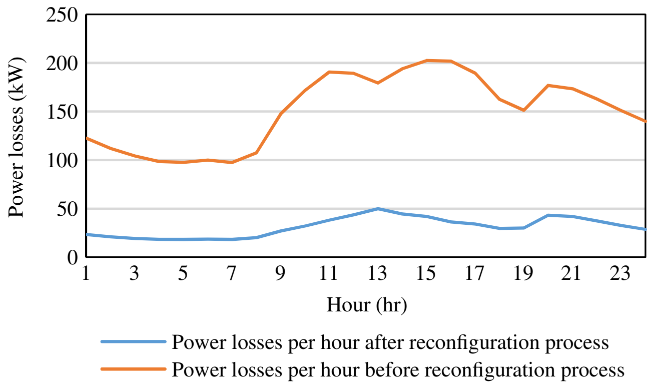

Fig. 5. Power losses per hour before and after reconfiguration process

path to get the optimal form of the network within simultaneous network reconfiguration and DG output. All programs were carried out in MATLAB on a PC with 3.07 GHz CPU and 8-GB RAM. For the application of the FA algorithm, the population size is set to 100, while the number of iteration is set to 300.

The DGs in this test system are assumed to be mini-hydro, biomass, and PV generation. The capacity of each DG is 2 MW. In this work, the optimal locations for the DGs are at buses 31, 32, and 33. This location is based on Ref. [9]. The biomass and mini-hydro DGs are operated in PQ mode (that means, the DG generates constant real and reactive power). The active power is obtained by optimization, while it assumes no reactive power is injected into the grid, while the photovoltaic unit operates on PV mode (that means that the DG generates specific active power and bus voltage). This DG model is based on Ref. [15]. In this work, the bus voltage is fixed to be 1 pu. The PV generation output based on the solar irradiance is taken from Kuantan site in 2008 from the Malaysian Meteorological Department. The peak load per unit of 24 h is shown in Fig. 1, as in Ref. [19]. The values of PV generation output of a day are shown in Fig. 2 [20].

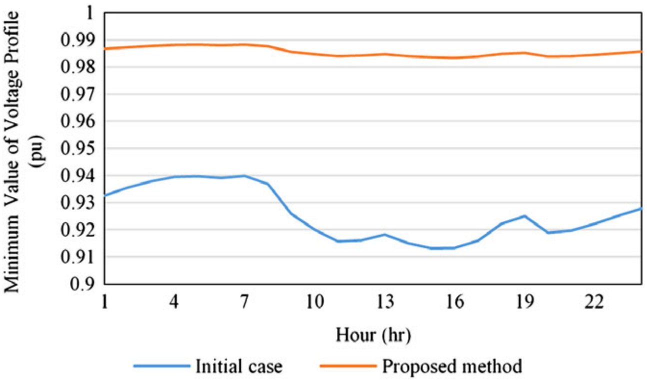

Fig. 6. Daily minimum value of voltage profile (pu) for radial distribution network

Table II. Comparison of simulation result of 33-bus system considering variable loads

Method	Open switches	Total daily power losses (kWh)	Total daily power loss reduction (%)
GSA [15]	32, 7, 33, 13, 26	915.91	74.717
ICA [15]	33, 21, 13, 25, 32	915.65	74.725
Proposed method	8, 9, 12, 26, 33	747.8	79.360

An IEEE 33-bus distribution network system is used to test the proposed method. The network consists of 37 switches, 32 sectionalizing switches, and 5 tie switches. Switch numbers 33–37 are normally open for the original network, while the other switches are normally closed, as shown in Fig. 3. The total real load demand is 3715 kW, while the system voltage is 12.66 kV. The base value of the apparent power is 100 MVA. The power loss of the network at the initial configuration is 202.677 kW, with 0.913 pu as the lowest bus voltage. The complete bus and line data are given in Ref. [6]. The optimal solution is obtained for tie switch, DG output (real power), and switching sequences. Both DG output and the tie switches are determined simultaneously. Since the IEEE 33-bus network had five tie switches and referred to as '(12)', there are $5! \times 5! \times 2$ different possibilities, which is equal to 28 800 possibilities representing the switching sequence paths that could be used to transfer the network from the original form to the expected optimal form.

4.1. Simultaneous network reconfiguration and DG output In this work, the proposed method looks for the best configuration that realizes the lowest daily power losses and best voltage profile at any hour of the day. From the simulation results, the daily power loss after network reconfiguration within the DG is 747.8 kWh, while before reconfiguration it is 3622.7 kWh, which means that power losses are reduced by 2874.9 kWh, i.e. 79.36% reduction compared to the initial state. The normally open switches after reconfiguration are 8, 9, 12, 26, and 33, as shown in Fig. 4, while before reconfiguration, they are 33–37. This configuration is optimal at any hour of the day, which means that the proposed method calculated the main fitness F refer to '1', which is equal to 2.4491 after reconfiguration, while before reconfiguration it is 12.039. The DG1 output is 0.832 MW; DG2 is related to Fig. 2, and that of DG3 is 0.47 MW. Table I shows the DG mode. Additionally, it can be observed that the power losses at any hour after reconfiguration are less than those before reconfiguration, as shown in Fig. 5.

Figure 6 shows the minimum values of voltage profile (pu) for the radial distribution network at any hour of the day. It can be observed that all minimum values of the bus voltage magnitude at any time are larger than the initial state.

Table III. 33-Bus network switching sequence results

Proposed method	Switching sequence path	Objective function	Switching sequence energy losses (kWh): Load levels	h	P	E
First step	36 close	21.444	Minimum value	7	157.9	315.8
Second step	9 open		Average value	9	232.83	465.66
Third step	37 close		Maximum value	15	355.74	711.48
Fourth step	26 open					
Fifth step	35 close					
Sixth step	12 open					
Seventh step	34 close					
Eighth step	8 open					
	33 NC					

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

Switching sequence steps	Minimum value of load profile: Min. value of voltage profile ($h=7$)	Max. value of voltage profile ($h=7$)	Average value of load profile: Min. value of voltage profile ($h=9$)	Max. value of voltage profile ($h=9$)	Maximum value of load profile: Min. value of voltage profile ($h=15$)	Max. value of voltage profile ($h=15$)
1	0.98505	1	0.981701	1	0.978992	1.0004
2	0.98512	1	0.981778	1	0.978973	1.0004
3	0.98518	1	0.981899	1	0.978973	1.0004
4	0.98518	1	0.981899	1	0.978973	1.0004
5	0.98693	1	0.984006	1	0.981644	1.0004
6	0.98697	1	0.984042	1	0.981749	1.0004
7	0.9891	1	0.986633	1	0.984875	1.0004
8	0.98827	1	0.985634	1	0.983606	1.0004

Table V. Comparison of simulation result between the proposed method and random cases

Case	Step	Switching sequence path	Switching sequence energy losses (kWh)			
			Load levels	h	P	E
Random case no. 1	First step	36 close	Minimum value	7	179.83	359.66
	Second step	9 open	Average value	9	259.08	518.16
	Third step	35 close	Maximum value	15	433.36	866.72
	Fourth step	26 open				
	Fifth step	37 close				
	Sixth step	12 open				
	Seventh step	34 close				
	Eighth step	8 open				
		33 NC				
Random case no. 2	First step	34 close	Minimum value	7	307.34	614.68
	Second step	9 open	Average value	9	441.74	883.48
	Third step	37 close	Maximum value	15	743.94	1487.88
	Fourth step	26 open				
	Fifth step	35 close				
	Sixth step	12 open				
	Seventh step	36 close				
	Eighth step	8 open				
		33 NC				
Random case no. 3	First step	37 close	Minimum value	7	199.5	399
	Second step	26 open	Average value	9	293.23	586.46
	Third step	36 close	Maximum value	15	452.83	905.66
	Fourth step	9 open				
	Fifth step	35 close				
	Sixth step	12 open				
	Seventh step	34 close				
	Eighth step	8 open				
		33 NC				
Proposed method	First step	36 close	Minimum value	7	157.9	315.8
	Second step	9 open	Average value	9	232.83	465.66
	Third step	37 close	Maximum value	15	355.74	711.48
	Fourth step	26 open				
	Fifth step	35 close				
	Sixth step	12 open				
	Seventh step	34 close				
	Eighth step	8 open				
		33 NC				

The performance of the proposed method is compared with published results, where they have the same DG unit's locations, as shown in Table II. It is clear that the proposed method, which is based on FA, is better than Gravitational Search Algorithm (GSA) and ICA.

It is essential to effect the reconfiguration hourly, which means that the optimal configuration is suitable at any hour instead of finding the configuration for a fixed network. It should be pointed out that the proposed method looks for the optimal configuration for the network at any hour (i.e., one configuration suitable at any hour for a day).

The reason of having one reconfiguration for a day is based on implementation issue and also prevention of switches (circuit breaker) from damage if continuously 'on' and 'off'. In terms of practical implementation, the time to complete the switching procedure will depend whether it is manual switching or automatic switching (automation). For manual switching, the time taken depends on the switching time at a particular substation and the time taken to travel from one substation to another. For example, let us assume that to complete switching procedure at one substation it takes 15 min, and time to travel from that substation to the next substation is 10 min. If the switching sequence consists of eight steps, the total time take will be 15 min $\times$ 8 steps, which is equal to 120 min (2 h). During this process, power loss occurs. Therefore, the optimal sequence of switching will help reduce the power losses while the switching takes place. In other words, since most of the power systems still change the switches manually, it is hard to change the sequence hourly. It should have one configuration and one switching sequence for 24 h.

4.2. Optimal switching sequence path

The optimal solution of network reconfiguration and DG output obtained from the first section is used to find the best switching sequence path to transfer the network from the initial states (33, 34, 35, 36, 37) to the final states (8, 9, 12, 26, 33) at any time. The obtained best switching sequence path is as follows:

Sequence 1: Sw36 (close) $\rightarrow$ Sequence 2: Sw9 (open) $\rightarrow$ Sequence 3: Sw357 (close) $\rightarrow$ Sequence 4: Sw26 (open) $\rightarrow$ Sequence 5: Sw35 (close) $\rightarrow$ Sequence 6: Sw12 (open) $\rightarrow$ Sequence 7: Sw34 (close) $\rightarrow$ Sequence 8: Sw8 (open) $\rightarrow$ Sw33 (NC).

As shown in Table III, the optimal fitness for the switching sequence path is 21.444. The summation of the power losses during all the steps of the optimal path at any time is also presented. That means that the optimal switching sequence path minimizes the total power losses during all steps at any time. In a practical case, there is a technician who changes the state of the switches manually. In this case, the technician needs time to transfer from the switch to another, which could be 15 min. In this case, energy losses are possible during the switching sequence, as pointed out in Table III.

Table IV shows the minimum and maximum values of the voltage profile during the steps of the optimal path sequence of switching at different hours. At each hour, there are eight lines that present the minimum values of the bus voltages during the

Table VI. Minimum and maximum values of voltage profile for each step per hour (pu) for 33-bus radial network for proposed method and random cases

Case	Switching sequence steps	Minimum value of load profile: Min. value of voltage profile ($h=7$)	Minimum value of load profile: Max. value of voltage profile ($h=7$)	Average value of load profile: Min. value of voltage profile ($h=9$)	Average value of load profile: Max. value of voltage profile ($h=9$)	Maximum value of load profile: Min. value of voltage profile ($h=15$)	Maximum value of load profile: Max. value of voltage profile ($h=15$)
Random case no. 1	36 close	0.98505	1	0.9817	1	0.97899	1.0004
	9 open	0.98512	1	0.98178	1	0.97897	1.0004
	35 close	0.98509	1	0.98176	1	0.97899	1.0004
	26 open	0.98448	1	0.98103	1	0.97801	1.0004
	37 close	0.98693	1	0.98401	1	0.98164	1.0004
	12 open	0.98697	1	0.98404	1	0.98175	1.0004
	34 close	0.9891	1	0.98663	1	0.98488	1.0004
	8 open	0.98827	1	0.98563	1	0.98361	1.0004
Random case no. 2	34 close	0.96889	1	0.96181	1.0001	0.95573	1.0006
	9 open	0.96305	1	0.95461	1.0001	**0.94727**	1.0006
	37 close	0.96242	1	0.95387	1.0001	**0.94649**	1.0006
	26 open	0.95942	1	0.95015	1.0001	**0.94207**	1.0006
	35 close	0.97634	1	0.97104	1.0001	0.96644	1.0006
	12 open	0.96757	1	0.96022	1.0001	0.95389	1.0006
	36 close	0.9891	1	0.98663	1	0.98488	1.0004
	8 open	0.98827	1	0.98563	1	0.98361	1.0004
Random case no. 3	37 close	0.96012	1	0.95104	1.0001	**0.94318**	1.0006
	26 open	0.95711	1	**0.94731**	1.0001	**0.93875**	1.0006
	36 close	0.98614	1	0.98302	1	0.98068	1.0004
	9 open	0.98518	1	0.9819	1	0.97897	1.0004
	35 close	0.98693	1	0.98401	1	0.98164	1.0004
	12 open	0.98697	1	0.98404	1	0.98175	1.0004
	34 close	0.9891	1	0.98663	1	0.98488	1.0004
	8 open	0.98827	1	0.98563	1	0.98361	1.0004
Proposed method	36 close	0.98505	1	0.981701	1	0.978992	1.0004
	9 open	0.98512	1	0.981778	1	0.978973	1.0004
	37 close	0.98518	1	0.981899	1	0.978973	1.0004
	26 open	0.98518	1	0.981899	1	0.978973	1.0004
	35 close	0.98693	1	0.984006	1	0.981644	1.0004
	12 open	0.98697	1	0.984042	1	0.981749	1.0004
	34 close	0.9891	1	0.986633	1	0.984875	1.0004
	8 open	0.98827	1	0.985634	1	0.983606	1.0004

Numbers in bold font exceed the limitation value.

switching sequence. It is clear that the best switching sequence does not cause the voltage profile to exceed the allowable limit (less than 0.95 and larger than 1.05).

From the results, it can be concluded that in order to change the initial network to the optimal form, four switches should be changed, and referred to '(12)', there are $4! \times 4! \times 2$ different possibilities, which is equal to 1152 possibilities representing the switching sequences that could be used to transfer the network from the original form to the expected optimal form. Moreover, since there is no relevant literature, and to further validate the results, different random sequence cases are presented in Tables V and VI. These cases are selected randomly to show how much the power loss and voltage profile during switching sequence have been improved by the proposed method. From Table V, it can be observed that any random case could have larger power losses and larger energy compared to the proposed method at any time (at hours 7, 9, and 15). Furthermore, during switching sequence some random cases violate the limitation of the voltage bounded, as shown in Table VI.

5. Conclusion

This paper proposed a new strategy to determine the optimal switching sequence path based on the optimal simultaneous distribution network reconfiguration with variable load and DG output to change the network from the original form to the optimal form. The presented method achieved the minimum daily power losses and the best voltage profile for the network. The firefly algorithm, a heuristic method, was used to achieve the distribution minimum main fitness. The effectiveness of the presented method has been verified on a 33-bus distribution system. The presented approach is of high quality and is capable of realizing the optimal switching sequence path, optimal network configuration, and DG output. Computational results showed that the FA performs better than both GSA and ICA. The results indicate the possibility of implementing the proposed method in real systems with DGs.

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