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Distribution network reconfiguration utilizing the particle swarm optimization algorithm and exhaustive search methods

Yulianta Siregar, Tomi Saputra Jaya Tambun, Sihar Parlinggoman Panjaitan, Kasmir Tanjung, Syiska Yana
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia

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ABSTRACT

The load level for each period in the distribution network can be considered non-identical due to the increasing demand for loads and the bigger distribution network. The main problem in the transmission and distribution network system is power losses and voltage profiles, affecting the quality of service and operating costs. This study compares the reconfiguration of the network using exhaustive search techniques and particle swarm optimization (PSO) algorithms on the IEEE 33 bus distribution network system. The study's results compare the study of power flow before and after network reconfiguration, which is a decrease in the value of power losses from 202.7 kW to 139.6 kW. Then voltage profile improved from 91.309% to 93.782%. The simulation results also found that this reconfiguration can improve the system voltage profile, which initially contained 21 buses outside the standard limits of IEEE Std 1159-1995 to 7 buses.

Corresponding Author:

Yulianta Siregar
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara
20155 Medan City, North Sumatera Province, Indonesia
Email: julianta_srg@usu.ac.id

1. INTRODUCTION

The distribution load generally shows different characteristics according to the distribution network and the appropriate line section. Therefore, the load levels for each period can be considered non-identical. This is also due to the increasing electrical energy consumption, so the demand for loads is increasing and making the distribution network bigger [1]–[3].

The distribution system with some overloads is caused by electrical equipment from consumers of electrical energy. If this situation is allowed to continue, it will cause a decrease in the reliability of the electric power system and the quality of the electrical energy that is distributed and cause damage to the equipment concerned, so action is needed to reduce it. Another problem in the distribution network is a power loss and voltage drop with the main parameters of resistance current and feeder reactance, affecting customer service quality and channel operating costs. It is normally expected that the voltage at each load point along the feeder is within the allowable normal voltage limits [2], [4], [5]. So, it is necessary to reconfigure the system so that the load is transferred from the heavily loaded feeder to the less loaded feeder. The feed conductor's maximum load current can be considered a reference. However, the load transfer must be made to meet certain predetermined objectives. In this case, the goal is to ensure the network has minimal real power loss.

Reconfiguration can also be defined as the rearrangement of the network to minimize the total apparent power loss incurred. This reconfiguration resets the network configuration by opening and closing the switches located on the distribution network to reduce power losses in the distribution network and to increase the distribution system's reliability so that the efficiency of the electric power distribution increases.

There have been many studies conducted on network reconfiguration on a network system, such as simple branch exchange [6]–[9], tie switch addition through manual checking [10]–[12], then based on optimization methods such as heuristic algorithm [13], [14], ant colony optimization [15]–[17] and artificial bee colony [5], [18]–[20].

Based on previous research and the problems described above, the authors use exhaustive search techniques and particle swarm optimization (PSO) to compare the two methods to study the discussion of reducing power losses and improving voltage profiles that produce more optimal processes and results. Our research to compare with two methods has never been done before. This research is applied to the IEEE 33-Bus system, which was analyzed using the Newton-Raphson power flow analysis method to determine the voltage profile, active power flow (P), and reactive power (Q). This research aims to get a network reconfiguration that can reduce losses and improve the voltage profile according to the IEEE Std 1159-2019 [21], as well as improve the quality of the electric power system.

2. THE PROPOSED METHOD

2.1. Network reconfiguration

Network reconfiguration is changing the configuration form of the distribution network by operating remotely controlled switching on the distribution network without causing risky consequences to the operation and form of the distribution network system. Under normal operating conditions, network reconfiguration is carried out for two reasons: reducing power losses in the system with switching optimization. Second, get a balanced loading to prevent excessive loading on the network [14], [15].

2.2.1. Reducing power losses in the system with switching optimization

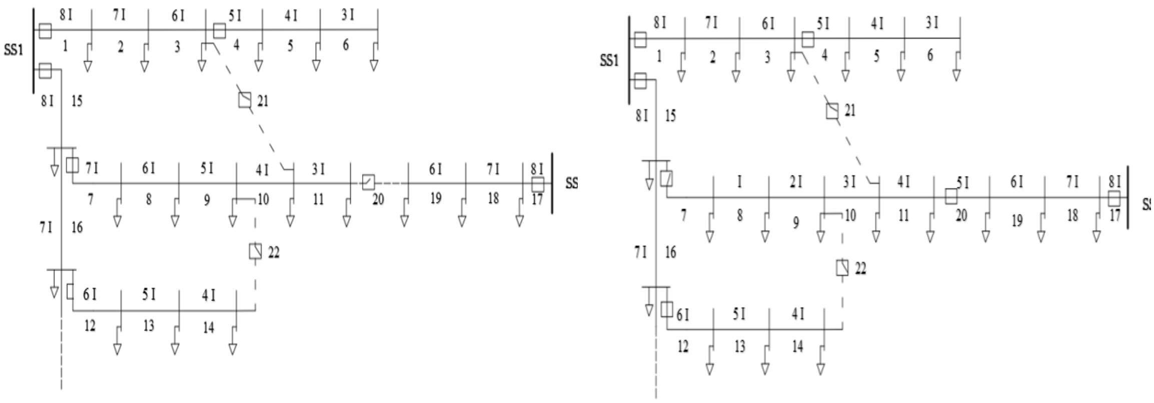
Network reconfiguration can reduce losses in an electricity network by changing the switching configuration on the channel. This method is often also called switching optimization. Switching optimization can reduce power losses, but system overload must still be considered so that the shape of the reconfiguration is affected by the load and the resistance of the existing lines in the system. If there is a change in the load value, then the best configuration form of the system also changes the value of the power losses. There are two types of switches in the electric power distribution system: sectionalizing switches and tie switches. Sectionalizing switches are normally closed (NC), while tie switches are normally open (NO). Sectionalizing switches function as protection to isolate faults and network reconfiguration. When tie switches are closed, a loop will form in the system. Therefore, one of the sectionalizing switches in the loop must be opened to maintain the system [12].

Network reconfiguration in a distribution system is carried out by opening sectionalizing switches NC and closing tie switches NO. This switching is carried out so that the radiality of the network is maintained and all loads are energized. Normally open tie switches are closed to transfer load from one feeder to another, while suitable disconnect switches are opened to restore the radial structure. Switch pairs are selected via a comprehensive formula for change in the loss. The branch swap process is applied repeatedly until no more loss reduction is available. Several loops can represent the radial distribution network. Add tie switches and sectionalizing switches are also needed to speed up service recovery for consumers by connecting undisturbed areas of the feeders concerned with the feeders around them. Thus, the disturbed parts of the feeder are localized, and other good feeder parts can immediately be operated again by removing the switch connected to the disturbance point and connecting the good feeder parts to the surrounding feeders.

An example of the concept of switching optimization (SO) can be seen in Figures 1(a) and (b). In Figure 1(a), the two substations have the same amount of load (8×I), but to supply SS1 power (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16) use small conductors with a small resistance value of 0.25R while SS2 (17, 18 and 19) use larger conductors with a resistance value of 0.3R. Also, assume that the resistance value of the tie switch conductors (20, 21, and 22) is 0.25R. The current in each load is I, and each branch in the system is the same length. The total power losses obtained in the system are 175.7 I2 R. Meanwhile, after switching optimization is carried out, namely closing the tie switch 20 and opening sectionalizing switch 7, as shown in Figure 1(b). The total power losses obtained are 157.95 I2 R. A new, the better configuration is obtained by performing switching optimization due to the poor switching position in the initial state [11], [21].

2.2.2. Load balancing to prevent excessive loading on the network

We used the same system before the network reconfiguration was carried out in Figure 1(a). The total load for each bus can be seen in Figure 2. If we count the number of loads before reconfiguring the system, it is 47 on SS1 and 13 on SS2. An example of a simple reconfiguration for load balancing is to close the tie switch 20 and open the sectionalizing switch 7 with the aim of moving the load from SS1 (heavy load) to SS2 (lighter load) so that the total load from the feeder connected to SS1 and SS2 is the same, namely 30 [22], [23].



(a) (b)

Figure 1. The state of switching optimization; (a) before switching optimization and (b) after switching optimization

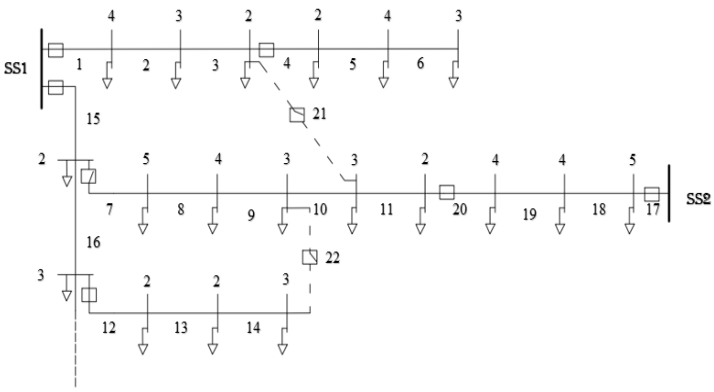


Figure 2. Configuration diagram of load balancing

2.3. Exhaustive search techniques

Exhaustive search techniques for reconfiguring distribution networks are used to reduce line losses under normal operating conditions. The complete search technique for loss reduction has three types of methods. They are minimum branch current, minimum voltage difference, and voltage difference-based closing/opening switches. This initial meshed topology provides a minimum loss configuration for the system, and as the network is reconfigured, a minimal loss radial configuration will occur. The loss reduction can be easily calculated from two load flow studies of the system configuration before and after the feeder reconfiguration. When switching is performed, the network needs to be maintained in a radial shape [24], [25].

2.4. Particle swarm optimization

PSO is a stochastic optimization technique based on a population and social behavior of a flock of birds or fish. PSO has been successfully applied to some research and other applications in recent years. This shows that with the PSO method, better and faster results are obtained compared to other methods. Another reason why PSO is more attractive is its use of fewer parameters. With one easy version, PSO can work well in various applications. This study uses the fitness function equation in PSO with the objective function, namely system power losses [4], [7], [11], [24].

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \left(\alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}\left(Q_i P_j + Q_i P_j\right)\right) \tag{1}$$

$$\alpha_{ij} = \frac{r_{ij}}{|v_i||v_j|}\cos\left(\delta_i - \delta_j\right) \tag{2}$$

$$\beta_{ij} = \frac{r_{ij}}{|v_i||v_j|}\sin\left(\delta_i - \delta_j\right) \tag{3}$$

$$P_L = \sum_{k=1}^{n} Loss_k \quad (4)$$

Where P_i and P_j are active power on bus i and bus j; Q_i and Q_j are reactive power on bus i and bus j; V_i and V_j are bus voltage i and bus j; δ_i and δ_j are angle of bus i and bus j; r_{ij} is resistance between bus i and bus j; $Loss_k$ is power losses at point k; n is number of buses; and P_L is power losses in the system.

3. METHOD

The single-line diagram of this network system is in the form of the initial system configuration needed to reconfigure the network. This network system consists of 33 buses, 32 sectionalizing switches, and five tie switches which operate with a nominal voltage of 12.66 kV [21], [26], [27]. The loops formed by these five tie switches are grouped to speed up data processing and programming. This group of loops will be used as a possible choice of switches that can be opened or closed to get a network configuration solution in which each loop must have one open switch to keep the system radial. The single-line diagram can be seen in Figure 3.

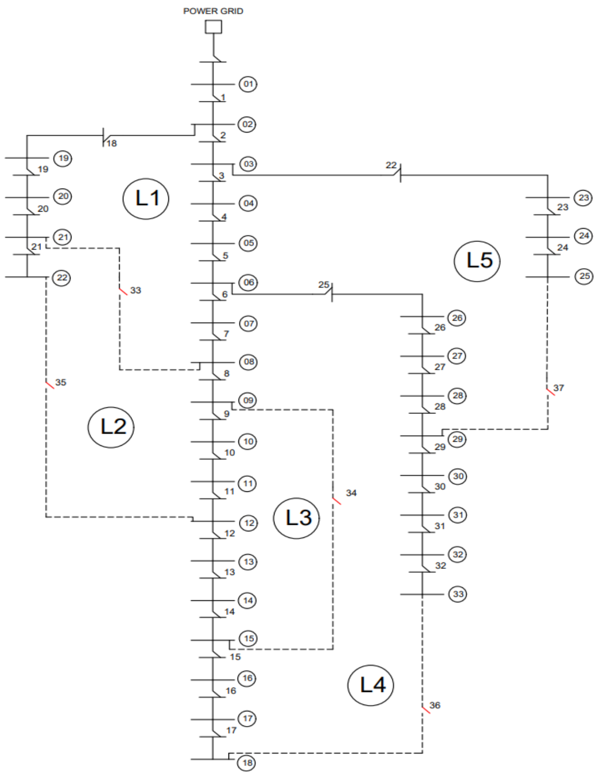


Figure 3. Single line diagram IEEE 33 Buses

The IEEE 33 Bus distribution network system's transmission data is shown in Table 1. Meanwhile, load data can be seen in Table 2. The data obtained was modeled on the ETAP software, then obtained the value of power losses and voltage drop on the IEEE 33 Bus system, which aims to be used as an initial reference in the case under study. In the second step, the authors use the exhaustive search techniques method. In the third step, the researcher designed the PSO program using MATLAB software. The next step compares these two methods to get the best network configuration solution on the IEEE 33 Bus system.

The reconfiguration scheme is modeled with the exhaustive search technique method to get the ideal switching location using three methods. First, the reduction is based on minimum branch currents. Second, the reduction is based on minimum voltage differences. Third, closing/opening switches based on voltage differences is done manually. At the same time, the next scheme is the PSO program method which also plays a role in getting the ideal network reconfiguration which is carried out using an algorithm to reduce power losses and improve voltage profiles.

Table 1. Data transmission

Line	From bus	To bus	Resistance (Ω)	Reactance (Ω)	Line	From bus	To bus	Resistance (Ω)	Reactance (Ω)
1	1	2	0.09	0.04	20	20	21	0.40	0.47
2	2	3	0.49	0.25	21	21	22	0.70	0.93
3	3	4	0.36	0.18	22	3	23	0.45	0.30
4	4	5	0.38	0.19	23	23	24	0.89	0.70
5	5	6	0.81	0.70	24	24	25	0.89	0.70
6	6	7	0.18	0.61	25	6	26	0.20	0.10
7	7	8	0.71	0.23	26	26	27	0.28	0.14
8	8	9	1.03	0.74	27	27	28	1.05	0.93
9	9	10	1.04	0.74	28	28	29	0.80	0.70
10	10	11	0.19	0.06	29	29	30	0.50	0.25
11	11	12	0.37	0.12	30	30	31	0.97	0.96
12	12	13	1.46	1.15	31	31	32	0.31	0.36
13	13	14	0.54	0.71	32	32	33	0.34	0.53
14	14	15	0.59	0.52	33	21	8	2	2
15	15	16	0.74	0.54	34	9	15	2	2
16	16	17	1.28	1.72	35	12	22	2	2
17	16	18	0.73	0.57	36	18	33	0.5	0.5
18	2	19	0.16	0.15	37	25	19	0.5	0.5
19	19	20	1.50	1.35					

Table 2. Load data

Bus	Active power (kW)	Reactive power (kVAR)	Bus	Active power (kW)	Reactive power (kVAR)
2	100	60	17	60	20
3	90	40	18	90	40
4	120	80	22	90	40
5	60	30	23	90	50
6	60	20	24	420	200
7	200	100	25	420	200
8	200	100	26	60	25
9	60	20	27	60	25
10	60	20	28	60	20
11	45	30	29	120	70
12	60	35	30	200	600
13	60	35	31	150	70
14	120	80	32	210	100
15	60	10	33	60	40
16	60	20			

4. RESULTS AND DISCUSSION

The single-line diagram of this network system is in the form of the initial system configuration needed to reconfigure the network. This network system consists of 33 buses, 32 sectionalizing switches, and five tie switches. Meanwhile, the reconfiguration scheme is modeled with the exhaustive search technique method using three methods: reduction based on the minimum branch current (with reconfiguration 1), reduction based on the minimum voltage difference (with reconfiguration 2) and closing/opening the switch based on the voltage difference is done manually (with reconfiguration 3). The next scheme is the PSO program method, which also obtains the ideal network reconfiguration, which is carried out using an algorithm to reduce power loss and improve the voltage profile.

4.1. Load flow analysis in the initial condition

Analysis of power flow on the IEEE 33 Bus network in the initial condition using the Newton-Raphson method produces power flow, power losses, and voltage profiles on each bus. The results of the voltage profiles as shown in Figure 4. After conducting a load flow study, the results obtained are the voltage profile values for each bus on the IEEE 33 Bus system, where 21 buses have voltage profile values outside the IEEE Standard 1159-1995 (+5%, -5%) [9] among others bus 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 26, 27, 28, 29, 30, 31, 32, and 33. This system has the lowest voltage profile on bus 18 at 91.309%. More details as shown in Figure 4.

One of the factors that affect the value of power losses and voltage profiles in the system is the line impedance of the system. In the situation before reconfiguration, bus 18 is the lowest voltage profile value because this bus has the largest total line impedance. It must be passed from the source to the bus compared to other buses in the system before reconfiguration. The reaching bus 18 from the source, 17 lines must be passed, such as buses 1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18. As shown in Table 3, the initial power losses are 202.7 kW and 135.1 kVAR with open switches on buses 33, 34, 35, 36, and 37.

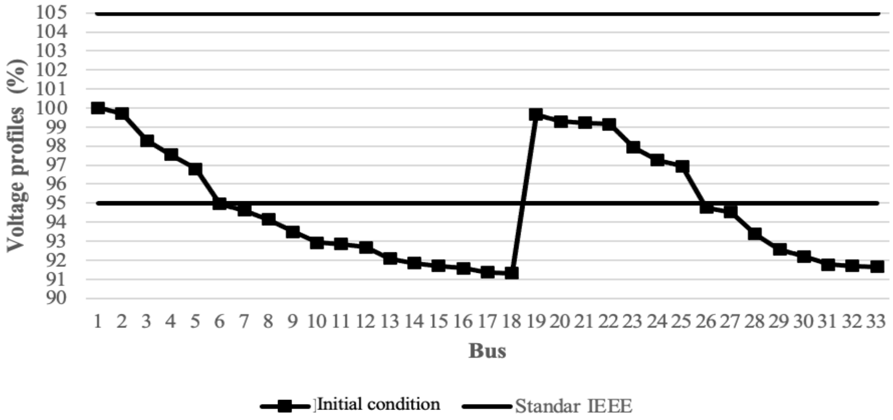


Figure 4. Voltage profile in the initial condition

Table 3. Load flow analysis in the initial condition

Open switch	Total power generator		Total power load		Power losses	
	(MW)	(MVAR)	(MW)	(MVAR)	(kW)	(kVAR)
33, 34, 35, 36, 37	3.91	2.43	3.71	2.30	202.7	135.1

4.2. Simulation results with exhaustive search technique

The exhaustive search technique method is modeled using the ETAP software, with three methods: the reduction method based on minimum branch currents (with reconfiguration 1), the reduction method based on the minimum voltage difference (with reconfiguration 2), and the switch closing/opening method based on voltage differences (with reconfiguration 3). It obtains the value of minimal power losses and the optimal voltage profile.

4.2.1. The reduction method based on minimum branch currents (with reconfiguration 1)

Analysis of the power flow in the initial conditions obtained an active power of 202.7 kW and a reactive power of 135.1 kVAR. A reduction method based on minimum branch current by closing all tie switches so that the configuration is fully integrated. After calculating the power flow again, the active power is 123.3 kW, and the reactive power is 87.9 kVAR. This is the least power loss the system to achieve the most appropriate radial state in terms of power loss by opening a sectionalizing switch in each loop. So that the radiality of the system is maintained and no load is isolated. The power flow results are then sorted by all branch currents (branch), and the branch with the minimum current is opened. That way, the minimum current will be redistributed in the new configuration. Repeat the power flow calculation and open the switch with the next minimum branch current so that there are different loops so that no load is isolated, and the radial structure is maintained. Since there are five loops, five sectionalizing switches are opened in each loop until the final configuration is reached.

The final configuration achieved in this method is by opening switches 10, 14, 32, 07, and 28. The total losses obtained are active power of 140.7 kW and reactive power of 105.4 kVAR. The results are that eight buses have voltage profile values outside the IEEE standard (+5% -5%), including buses 16, 17, 18, 29, 30, 31, 32, and 33. This system has the lowest voltage profile at bus 32 at 94.129%. For more details, as shown in Figure 5. Further, the value of power losses on each conductor after reconfiguration using the minimum branch current (with reconfiguration 1) can be seen in Table 4. As seen in this table, after reconfiguration 1 the power losses have decreased.

4.2.2. Reduction method based on minimum voltage difference (with reconfiguration 2)

The final configuration achieved is by opening switches 11, 32, 06, 14, and 37. The total power losses obtained are active power of 145.3 kW and reactive power of 111.2 kVAR. The results of the power flow study obtained results in the form of voltage profile values at each bus in the system, which can be seen in Figure 6. 11 buses have voltage profile values outside the IEEE (95% - 105%) including buses 09, 10, 15, 16, 17, 18, 29, 30, 31, 32 and 33, as seen in Figure 6. This system has the lowest voltage profile on bus 33 at 93.564%. Further, the value of power losses on each conductor after reconfiguration using reduction based on the minimum voltage difference (with reconfiguration 2) can be seen in Table 5. As seen in this table, after with reconfiguration 2 the power losses have decreased.

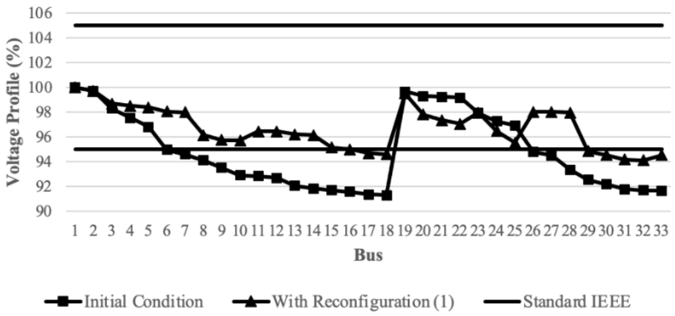


Figure 5. The voltage profile on uses the reduction method based on the minimum branch current

Table 4. Load flow analysis with reduction method based on minimum branch currents

Reconfiguration condition	Open switch	Total power generator		Total power load		Power losses	
		(MW)	(MVAR)	(MW)	(MVAR)	(kW)	(kVAR)
Initial condition	33, 34, 35, 36, 37	3.91	2.43	3.71	2.30	202.7	135.1
With reconfiguation 1	7, 10, 14, 28, 32	3.85	2.40	3.71	2.30	140.7	105.4

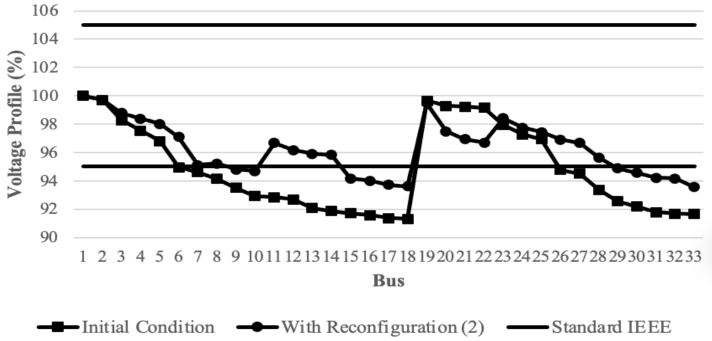


Figure 6. The voltage profile uses the reduction method based on the minimum voltage difference

Table 5. Load flow analysis with reduction method based on minimum voltage difference

Reconfiguration condition	Open switch	Total power generator		Total power load		Power losses	
		(MW)	(MVAR)	(MW)	(MVAR)	(kW)	(kVAR)
Initial condition	33, 34, 35, 36, 37	3.91	2.43	3.71	2.30	202.7	135.1
With reconfiguation 2	6, 11, 14, 32, 37	3.86	2.41	3.71	2.30	145.3	111.2

4.2.3. Switch closing/opening method based on voltage difference (with reconfiguration 3)

The final configuration achieved in this method is by opening switches 10, 06, 14, 32, and 37. The total losses obtained are active power of 144 kW and reactive power of 110 kVAR. The results are that eleven buses have voltage profile values outside the IEEE standard (+5% -5%), including buses 09, 10, 15, 16, 17, 18, 29, 30, 31, 32 and 33. This system has the lowest voltage profile at bus 33 at 93.716%. For more details, as shown in Figure 7. Further, the value of power losses on each conductor after reconfiguration using the switch closing/opening method based on voltage difference (with reconfiguration 3) can be seen in Table 6. As seen in this table, after reconfiguration 3 the power losses have decreased.

4.3. Simulation results of with particle swarm optimization

The network system is reconfigured using an algorithm with the PSO method. This method is applied to find the switching location to get the optimal configuration. The social behavior of flocks of birds or fish inspires this method. This method is initialized by a random population working together to find the optimal solution to an objective function by updating each generation. PSO parameters are initialized to find the optimal reconfiguration, as shown in Table 7.

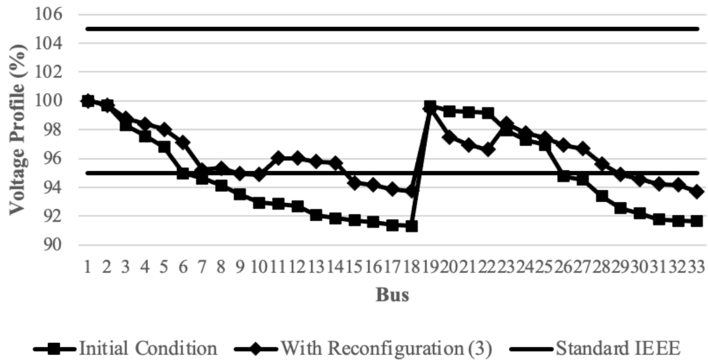


Figure 7. The voltage profile uses the switch closing/opening method based on the voltage difference

Table 6. Load flow analysis with switch closing/opening method based on voltage difference

Reconfiguration condition	Open switch	Total power generator (MW)	Total power generator (MVAR)	Total power load (MW)	Total power load (MVAR)	Power losses (kW)	Power losses (kVAR)
Initial condition	33, 34, 35, 36, 37	3.91	2.43	3.71	2.30	202.7	135.1
With reconfiguation 3	6, 10, 14, 32, 37	3.85	2.41	3.71	2.30	144.0	110.0

Table 7. Parameters of PSO

Parameter	Value
Number of swarms	31
Maximum iteration	20
C_1	2
C_2	2
Minimum inertia weight (W_{min})	0.4
Maximum inertia weight (W_{max})	0.9
Initial speed	0

The results of power flow study obtained results in the form of voltage profile values at each bus in the system, as shown in Figure 8. 7 buses had voltage profile values outside the IEEE (+5% -5%), including buses 17, 18, 29, 30, 31, 32 and 33. This system has the lowest voltage profile on bus 32 at 93.782%.

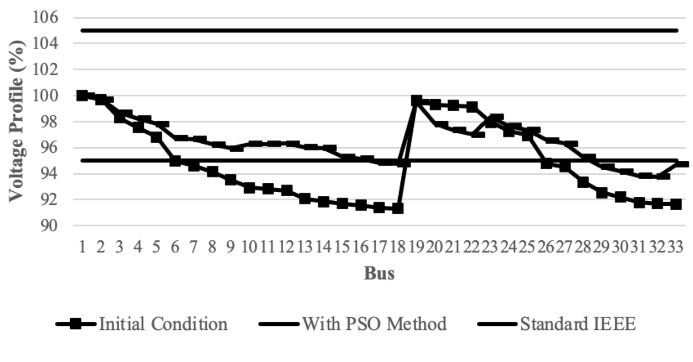


Figure 8. The voltage profile uses the PSO method

The power flow study also obtained the value of power losses on each conductor after reconfiguration using the reduction method based on PSO, which can be seen in Table 8. The analysis of other power flow studies obtained a summary of the data in the form of power losses in this system, namely the total active and reactive power losses, totally supplied power, and total load power before network reconfiguration.

Table 8. Load flow analysis with PSO method

Reconfiguration condition	Open switch	Total power generator		Total power load		Power losses	
		(MW)	(MVAR)	(MW)	(MVAR)	(kW)	(kVAR)
Initial condition	33, 34, 35, 36, 37	3.91	2.43	3.71	2.30	202.7	135.1
PSO method	7, 9, 14, 32, 37	3.85	2.40	3.71	2.30	139.6	102.3

4.4. Comparison results of all simulations

A comparison of the voltage profile for each case before (initial condition) and after reconfiguration using the exhaustive search technique and PSO methods can be seen in Figure 9. Network reconfiguration improves the voltage profile and reduces power losses in the system because it causes changes in the power flow to the system. Where in the state before the reconfiguration, bus 18 is the bus with the lowest voltage profile value because this bus has the highest total impedance value that must be passed from the source to the bus compared to other buses in the system before reconfiguration. The total impedance value from the source to bus 18 is 11.2267 Ω.

On the other hand, as for the state after the reconfiguration, bus 32 is the bus with the lowest voltage profile value using the PSO method. This is also because this bus has the largest total impedance value of the line that must be passed from the source to the bus compared to other buses in the reconfigured system. The total value of the impedance of the line that is traversed from the source to bus 32 is 6.4813 Ω.

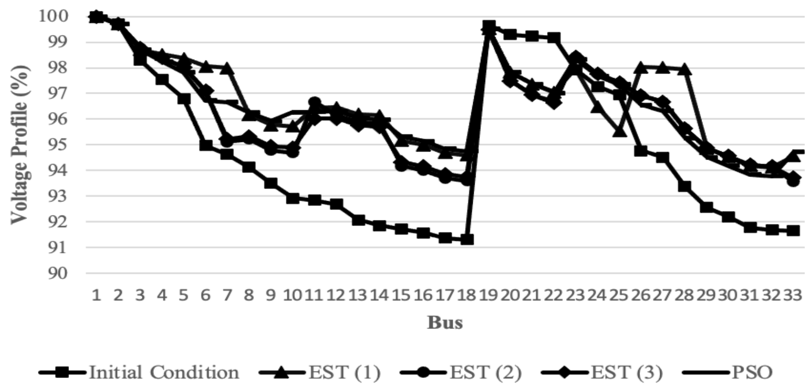


Figure 9. Voltage profile results by comparison of all simulations

5. CONCLUSION

From the results of the discussion and research conducted, the following conclusions are obtained: First, the initial condition of the IEEE-33 bus distribution system has an active power loss of 202.7 kW and a reactive power of 135.1 kVAR. This is in line with the minimum voltage profile of the system, which is 91.309% on bus 18 and has 21 buses outside the IEEE standard. The second, network reconfiguration using the exhaustive search technique (EST) with the reduction method based on the minimum branch current on the IEEE-33 Bus distribution system network, can reduce power losses in the system originally 202.7 kW by 62 kW to 140.7 kW, namely 30.59%. This is in line with the minimum voltage profile on the system, which was originally 91.309% on bus 18, which increased to 94.129% on bus 32. This method is superior in reducing power losses, improving the voltage profile of the other two methods in the EST, and improving 13 buses that fall outside the IEEE standard. The third, network reconfiguration using the PSO Algorithm on the IEEE 33 Bus distribution system network under balanced load conditions can reduce power losses in the system, which was originally 202.7 kW by 63.2 kW to 139.5 kW, which is 31.13%. This is in line with the system’s minimum voltage profile, originally 91.309% on bus 18, which increased to 93.782% on bus 32 and fixed 14 buses outside the IEEE standard. Last our conclusion, network reconfiguration using PSO on the IEEE 33 Bus distribution system network can produce the most optimal of the others.

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BIOGRAPHIES OF AUTHORS

Yulianta Siregar was born July 09, 1978 in Medan, North Sumatera Utara, Indonesia. He did his undergraduate work at University of Sumatera Utara in Medan, North Sumatera Utara, Indonesia. He received a Bachelor of Electrical Engineering in 2004. After a while, he worked for a private company. He continued taking a master's program in Electrical Engineering at the Institute of Sepuluh Nopember, Surabaya, West Java, Indonesia, from 2007-2009. He was in a Ph.D. program at Kanazawa University, Japan, from 2016-2019. Until now, he lectured at Universitas Sumatera Utara. He can be contacted at email: julianta_srg@usu.ac.id.

Tomi Saputra Jaya Tambun is a fresh graduate of Electrical Engineering bachelor's degree from Universitas Sumatera Utara in 2022. His research area field study is a high voltage, and electrical power system. He can be contacted at email: biodebataraja@gmail.com.

Sihar Parlinggoman Panjaitan was born march 06, 1964 in Medan, North Sumatera Utara, Indonesia. He did his undergraduate work at University of Sumatera Utara in Medan, North Sumatera Utara, Indonesia. He received a Bachelor of Electrical Engineering in 1989. He continued taking a master's program in Electrical Engineering at the Institute Technology Bandung, Indonesia, from 1996-1998. He lectured at Universitas Sumatera Utara from 1989-now. He can be contacted at email: siharppanjaitan@gmail.com.

Kasmir Tanjung was born April 12, 1960 in Sibolga, North Sumatera Utara, Indonesia. He did his undergraduate work at Universitas Sumatera Utara in Medan, North Sumatera Utara, Indonesia. He received a Bachelor of Electrical Engineering in 1992. He continued taking a master's program in Electrical Engineering at Universitas Sumatera Utara, Indonesia, from 2011-2013. He lectured at Universitas Sumatera Utara from 1992-now. He can be contacted at email: kasmir@usu.ac.id.

Syiska Yana is a lecturer in Electrical Engineering at the Universitas Sumatera Utara. He completed his final education at Masters level at the Electrical Engineering Study Program, Faculty of Engineering, Sepuluh Nopember Institute of Technology in 2010, Indonesia. He can be contacted at email: syiska.yana@usu.ac.id.