IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

IEEE POWER & ENERGY SOCIETY SECTION

Received June 10, 2021, accepted July 14, 2021, date of publication July 20, 2021, date of current version July 30, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3098902

Reconfigure the Distribution Network With Photovoltaic Connection to Minimize Energy Loss Based on Average Branch Power and an Advanced Branch Exchange Algorithm

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This work was supported by the Ho Chi Minh City University of Technology and Education, Vietnam, under Project T2020-40TĐ.

ABSTRACT The distribution network reconfiguration (DNR) minimize energy loss is one of the complicated problems and being studied substantially in recent years. Reconfiguration distribution network through the average branch power is a simple and effective method in obtaining fast optimization results even without using the load curve (for 24 hours). However, with high penetration of photovoltaic (PV) in the distribution network, the power flow on the branches at some survey time may change direction which leads to the average power on the branches might become zero when the energy loss is not minimal. Hence, determining accurately the average branch power in this case with PV participating grids is an important aspect in resolving problem of the distribution network reconfiguration with PV connection and minimizing energy loss. In order to solve this problem, an analytical technique based on load factor is presented in this paper for the purpose of determining accurately the average power on the branches via determining the amount of additional power on the branch when PV is installed in the power system. In addition, an advanced branch exchange method to quickly determine the configuration of the distribution network with PV while achieving the smallest energy loss is also proposed in the paper. The proposed method, which is tested on the IEEE 18 node and IEEE 33 node power system, shows the effectiveness of the proposed method in comparison with many other methods.

INDEX TERMS Distribution network, reconfiguration, energy loss, average power, load curve.

I. INTRODUCTION

In the electrical system, the distribution network plays a vital task in sending electricity to customers. The distribution network has a closed-loop system configuration while operating radial systems and often at low voltages so power losses are very huge. Therefore, reducing power loss is one of the important subject in the operation of the distribution network. Various methods have been used to reduce power losses in the distribution network, such as operating at higher voltage levels, installing compensation capacitors, installing distributed generation (DG), and reconfiguring distribution networks (DNR). In fact, DNR is an effective and popular method for the purpose of minimizing power loss [1], [2].

In addition, distribution network operation is often having problem recording the load's power accurately at certain time. Distribution networks with perpetually dynamic masses, operationalizing the switches in step with the load curve is ineffective. Hence, shaping the configuration to control over an amount of time for an uninterrupted power could minimize prices and losses, while load balancing may be a challenge for system planners and operators [3]. When the distribution network operates with actual load power that does not match maximum load power, it is impossible to reduce the possibility of power loss. Thus, the DRN issue to minimize power loss becomes the problem of DRN to minimize energy loss [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Emilio Barocio.

Besides, due to the deregulation of electricity, exhaustion of fossil fuel, environmental issues, developed technology as well as reasonable price of energy sources, the distributed generation (DG) such as photovoltaic (PV) has been widely installed in distribution networks in recent years [5]. The integration of DG units has significant impacts on the operation of distribution systems. Therefore, finding an effective method to solve DNR with PV problem is a challenge for system operator.

In general, there are two basic approaches to solve the DNR problem. The first is the heuristic methods such as the closed-loop cut method [1], the branch method and the constraints [6], the branch exchange method [7] and the conjecture method [8]. The heuristic methods show their effectiveness for the DNR problem but it is difficult to implement in real-time for large systems. For this reason, Civanlar *et al.* proposed a formula to reduce the complexity of heuristic method for the DNR problem [7]. The second way is to use metaheuristic algorithms to DNR such as genetic algorithm (GA) [9], ant colony search algorithm (ACSA) [10], cuckoo search algorithm (CSA) [11], harmony search algorithm (HSA) [12], fireworks algorithm (FA) [13], binary group search optimization (BGSA) [14], honey bee mating optimization (HBMO) [15], and runner root algorithm (RRA) [16]. The second approach usually achieves the optimal solution globally but often require complex computation and large processing time to converge. Thus, it is essential to choose the metaheuristic or heuristic method to solve the DNR problem depending on the problem's objective.

There are many studies dealing with DNR in order to minimize energy loss. In [16], the authors propose a heuristic method based on the moment load and node voltage statistics to DNR with the objective function of minimizing energy loss over a period of time. The method gives the correct results but the many parameters need to be calculated in order to the DRN. A method based on two-stage optimizations to reduce search space for DRN issue was proposed in [17]. The method uses a network graph to simplify electrical network, while optimal solution is obtained by firefly algorithm. In [18], NoisyNet deep Q-learning method was suggested to decrease computation time as well as improve optimization performance of DRN problem. In [19], the authors propose to use the load at three levels: high level, medium level, and low level to test the effectiveness of DNR. The DNR problem towards reducing energy loss based on fixed maximum load was proposed in [20]. A typical date load curve to find the optimal configuration in order to minimize the energy loss was proposed in [21]. The authors assumed that a daily repeating load curve should be chosen by a typical load curve for the calculation. For references [20], [21], the authors have given different calculation methods but these methods may lead to non-global optimization results. These methods choose a typical load for calculation that may lead to sub-optimal results because the load always changes over a period of time.

Recently, numerous methods have proposed the DNR with DG problem. Beetle Antennae Search Algorithm [22], [23] have used to solve the DRN with DG problem. In [24], [25], the authors suggested DNR to minimize energy loss considering DGs. However, the authors only gave a long-term DNR schedule in operation. The authors in [26], [27] proposed to use the DG power which is fixed to calculate the minimum loss of energy and minimize the number of switches. The use of fixed DG power is not suitable since DGs are mainly photovoltaic (PV) and wind turbines (WT) whose power varies during the day. In [28], the authors presented the optimal method of DNR with load and PV changes over a period of time. The authors only demonstrated the optimal load selection method considering different times and numbers of conversions to maximize power. In [29], the authors used the Gravitational Search Algorithm (GSA) for DNR with PV connection. The simulation results on a 33-node distributed network has shown its effectiveness compared with Evolutionary Programming (EP) method. However, the calculated volume of GSA method is very large since there are many configuration hours of load and PV. A Pathfinder Algorithm (PFA) [30] was used to DNR with DGs for the purpose of determine the best configuration that provides the lowest power loss for the whole day (24 hours). The results of the proposed method tested on 18-node and 33-node distribution networks showed the effectiveness of the proposed method in the cases with DGs and without DGs.

The installation of DGs on the grid combined with DNR is a practical solution to reduce energy loss. The previous publications also considered the effect of DG in distribution power system, however the power flow direction on the branches was not mentioned in the studies. In fact, with a large size of DG in the distribution network, the power flow on the branches with DG at some survey time may be diverted from the transmission direction compared with the direction in the case without DG.

Although, the authors in [30] introduced the average power to solve the DNR with DG problem, the power flow direction on the branches was not considered. The power flow on the branches at some survey time may change direction and leading to the average power on the branches could reach zero while the energy loss is not minimal. Hence, determining accurately the average branch power in this case with PV participating grids is an important aspect in resolving problem of the distribution network reconfiguration with PV connection and minimizing energy loss. From the above point of view, this paper focuses on analyzing the effect of average branch power P_{BRavg} and proposes a new average branch power (P^{N}_{BRavg}) to solve the DNR with PV problem in order to minimize energy loss. In addition, advanced branch exchange method is also suggested in this paper to quickly determine the configuration of the distribution network with photovoltaic (PV) achieving the smallest energy loss. The results of the proposed method is tested on 18-node and 33-node distribution networks that have shown their effectiveness.

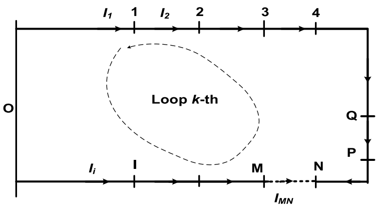

FIGURE 1. Simple distribution network.

The contributions of the paper are summarized as follows:

(i) Proposed the advanced branch exchange method to quickly determine the configuration of the distribution network with photovoltaic (PV) achieving the smallest energy loss.

(ii) Suggested the technique based on load factor for the purpose of determining accurately the average power on the branches via determine the amount of additional power on the branch when PV is involved in the distribution power system.

(iii) Minimizing energy loss target for distribution network with PVs in 24 hours.

II. BRANCH AVERAGE POWER WHEN PVs IS CONNECTED WITH DISTRIBUTION NETWORK

Figure 1 shows a simple distribution network. The DNR problem manifests itself through the operation of the open switches. There are two switches MN and PQ, each of them opens at a time. The objective function of the reconfiguration problem to reduce the energy loss is presented as equation (1) [30]

$$\text{Min}: \ \Delta A\,(X) = \sum\nolimits_{i=1}^{n} t_m \times \sum\nolimits_{i=1}^{N_{br}} R_i \times \left(\frac{P_i^2 + Q_i^2}{V_i^2}\right) \tag{1}$$

where, Ri: branch resistance (Ω); Pi: active power of the ith load (kW); Qi: reactive power of the ith load (kVAr); Vi: node voltage (kV); tm: survey time in 24 hours (h).

The formula (2) determines the difference in power loss between the loop distribution network and the radial distribution network [31].

$$\delta P_{MN} = \Delta P_{radial} - \Delta P_{mesh} = I_{MNpeak}^2 R_{Loop} \tag{2}$$

Based on the formula of energy loss and the load factor LF in the documents [32], [33] and the deviation of power loss in the formula (2), these factors are used to calculate the energy loss difference between the loop distribution network and the radial distribution network (branch MN) in 24h, as in the formula (3) and the formula (4).

$$\begin{aligned}\delta A_{MN} &= \sum\nolimits_{i=1}^{n} \Delta P_{iMN} T_i \\ &= \Delta P_{max} LLF = 24 R_{loop} I_{MNpeak}^2 LLF \\ &= 24 R_{Loop} \left(\frac{P_{MNpeak}^2 + Q_{MNpeak}^2}{V^2}\right) (aLF + (1-a)\,LF^2)\end{aligned} \tag{3}$$

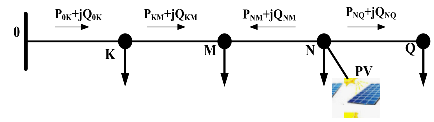

FIGURE 2. Distribution network with PV.

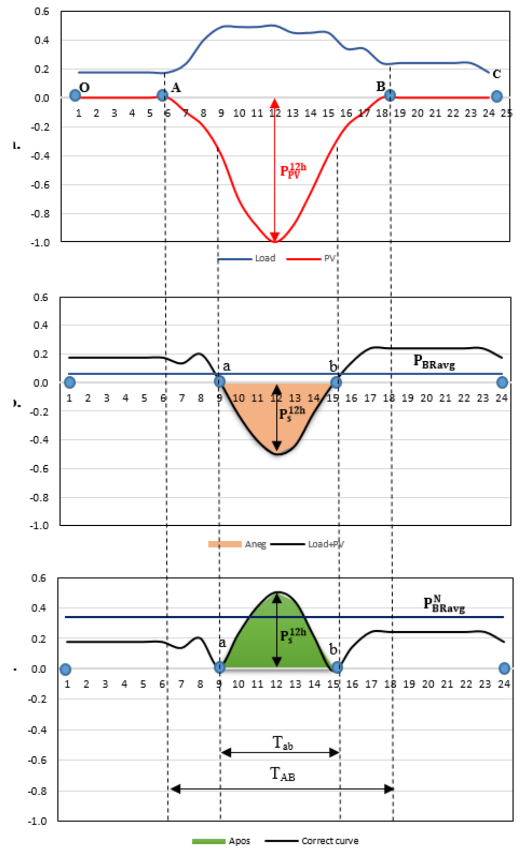

FIGURE 3. Power of load and PV for 24h.

$$\begin{aligned}&= \frac{24R_{Loop}}{V^2}\left(\left(\frac{P_{MNavg}}{LF}\right)^2 + \left(\frac{Q_{MNavg}}{LF}\right)^2\right) \\ &\quad \times (aLF + (1-a)\,LF^2)\end{aligned} \tag{4}$$

With:

$$LLF = a(LF) + (1-a)LF^2; \quad a = \frac{LLF - LF^2}{LF - LF^2}$$

$$LF = \frac{P_{avg}}{P_{peak}}; \quad LFF = \frac{(P^2)_{avg}}{(P)_{peak}^2};$$

where: a constant depending on LLF and LF; LLF:loss factor; LF:load factor; P_{peak}: maximum active power (kW); Q_{peak}: maximum reactive power (kVAR); P_{BRavg}: branch average active power (kW); Q_{BRavg}: branch average reactive power (kVAR).

From the formula (4), the energy loss deviation (δA) is determined through the branch average power (P_{BRavg}) and LF. The LF characteristic loads are easily determined over a surveyed period [33].

Considering a distribution system with PV as shown in Figure 2. Figure 3 shows the power of the load and PV during the 24h survey period. Figure 3a shows the load curve and power curve of PV. Figure 3b shows the combined PV and load curve, here showing the lower (A_{neg}) energy (negative part) that makes the branch average power (P_{BRavg}) very small. Figure 3c shows the portion of negative energy (A_{neg}) converted to positive energy (A_{pos}) which will give the new branch average power (P^{N}_{BRavg}) in accordance with the amount of power transferred on the branch.

The MN branch is considered having the power (with PV) transmitting in the opposite direction of the previous power (without PV). The DNR problem to reduce energy loss (in 24h) is determined such as δA in the formula (4) is the lowest. However, the δA value will not be accurate when P_{BRavg} is abnormal. The power transferred on the branch (with PV) has a direction that changes at some time, comparing to the previous direction (without PV). At this point, the P_{BRavg} on the branch can be very small, which will result in determining this branch will have the smallest loss. In fact, P_{BRavg} may be very small but the loss on this branch is not the smallest when there is back power transfer at some point in time. The branch power (with PV) has a direction change at some points compared to the previous direction (without PV) as shown in Figure 3b. At this time, P_{BRavg} of branch MN is greater than P_{BRavg} of branch PQ because the average branch power due to the reverse transmission power will result in the change in the P_{BRavg} value. Therefore, it is necessary to consider the effect of the P_{BRavg} direction on the branch in DNR in the presence of PV.

To evaluate the effect of power transfer on the branch when PV is present, considering the distribution network is shown in Figure 2. Without the participation of PVs, branch power will be transmitted in one direction from source to load at each time in 24h. When a PV participates in the distribution network with a power greater than that of branch MN, there will be reverse transmission power in the branch MN, depending on PV's operating time. At this time, P_{BRavg} on branch MN is calculated according to the standard method, it will not serve to calculate the correct energy loss according to formula (4) but it needs to be adjusted.

Figure 3b shows that, because the effect of PV is absent or negligible at the time from 0 to A and B to C, so the power of branch MN has forward direction. But at the time A to B, it has the influence of PV on branch MN, so the power of branch MN has the opposite direction compared to the time from 0 to A and B to C. Therefore, the P_{BRavg} of MN branches in a 24-hour period is very small. This leads to the use of the branch average power method that will open the switch with the smallest energy loss, formula (4). Therefore, when PV is involved, it is necessary to correct the branch average power to accurately determine the open switched branch with the smallest energy loss.

For Figure 3a, there are cases where the power of the load and PV are considered as follows:

Case 1: The power on the branch transmits one way from the source to load. Transmission direction is not affected by PV. The value P_{BRavg} is calculated according to formula (5).

$$\sum\nolimits_{i\varepsilon 0C} P_{BRavg} = \frac{\sum_{i\varepsilon 0A}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon 0A} t_i} + \frac{\sum_{i\varepsilon AB}(P_{PV}t_i - P_{Load}t_i)}{\sum_{i\varepsilon AB} t_i} + \frac{\sum_{i\varepsilon BC}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon BC} t_i} \tag{5}$$

Case 2: Power on branch has reverse direction at some time by effect of PV. The P^{N}_{BRavg} is calculated by the formula (6).

$$\sum\nolimits_{i\varepsilon 0C} P^{N}_{BRavg} = \frac{\sum_{i\varepsilon 0A}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon 0A} t_i} - \frac{\sum_{i\varepsilon AB}(P_{PV}t_i - P_{Load}t_i)}{\sum_{i\varepsilon AB} t_i} + \frac{\sum_{i\varepsilon BC}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon BC} t_i} \tag{6}$$

where, P_{Load}: active power of the load (kW); P_{PV}: the power of PV (kW); t_i: surveyed time (h).

From the two formulas (5) and (6) when connecting with PV, the average branch power value P^{N}_{BRavg} is presented as formula (7).

$$\begin{aligned} &\sum\nolimits_{i\varepsilon 0C} P^{N}_{BRavg} - \sum\nolimits_{i\varepsilon 0C} P_{BRavg} \\ &\quad = 2\frac{\sum_{i\varepsilon AB}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon AB} t_i} \\ &\Leftrightarrow \sum\nolimits_{i\varepsilon 0C} P^{N}_{BRavg} \\ &\quad = \sum\nolimits_{i\varepsilon 0C} P_{BRavg} + 2\frac{\sum_{i\varepsilon AB}(P_{Load}t_i - P_{PV}t_{i)}}{\sum_{i\varepsilon AB} t_i} \\ &\quad = \sum\nolimits_{i\varepsilon 0C} P_{BRavg} + 2P_{BRavgAB} = \sum P_{BRavg} + P_{BRneg} \end{aligned} \tag{7}$$

Figure 3b shows the A_{neg} energy in the lower part (negative value). If we calculate the power branch average P_{BRavg}, this value is inaccurate. Therefore, the A_{neg} value converted to the upper A_{pos} (positive value), and the average power on the branch receives the correct P^{N}_{BRavg}, as shown in Figure 3c. The value P^{N}_{BRavg} is the exact branch average power value of the system and P_{BRneg} is the amount of branch power to compensate for P_{BRavg} to get P^{N}_{BRavg} for the branch with the power current transmitted back to the source. At this time, P^{N}_{BRavg} is adjusted so that δA is calculated correctly (branch MN) according to the formula (4). Therefore, the DNR results will be accurate. The added value P_{BRneg} of the distribution network with PV, the amount of additional power needed to increase for each branch, is calculated by the formula (8).

From Figure 3, with 2 parts of the supply energy of PV (A_{PV}) and the remaining energy of the system (A_{neg}). Consider an isosceles triangle with base AB and altitude P^{12h}_{s}. Calculating the approximation at the maximum time at 12h, we have:

$$A_{neg} = T_{ab}\frac{P_s^{12h}}{2} = T_{AB}\frac{P_s^{12h}}{P_{PV}^{12h}}\frac{P_{HT}^{12h}}{2} = T_{AB}\frac{(P_s^{12h})^2}{2P_{PV}^{12h}} = T_{PV}\frac{(P_s^{12h})^2}{2P_{PV}^{12h}}$$

$$\Leftrightarrow A_{neg} = 24P_{BRneg} = \frac{(P_s^{12h})^2 T_{PV}}{2P_{PV}^{12h}}$$

$$\Leftrightarrow P_{BRneg} = \frac{(P_s^{12h})^2 T_{PV}}{2P_{PV}^{12h}24} \quad (8)$$

where, A_{PV}: energy of PV (kWh); P_s^{12h}: the power of the system at 12h (kW); P_{PV}^{12h}: PV power at 12h (kW); $T_{AB} = T_{PV}$: PV power generation time (h); T_{ab}: Time the power of the system is negative (h); P_{BRneg}: average power the branch should add (kW).

The value of P_{BRavg}^N is calculated using formula (9). Updating the P_{BRavg}^N value on the branches in the system with a power on the backward branch. The switch is defined open through δA as the minimum between the loop distribution network and the radial distribution network, as shown in the formula (10). Here, PV only generates active power, so it only adds active power without adding reactive power on the branch.

$$P_{BRavg}^N = P_{BRavg} + P_{BRneg} \quad (9)$$

$$\delta A = \frac{24R_{Loop}}{V_i^2}\left(\left(\frac{P_{BRavg}^N}{LF}\right)^2 + \left(\frac{Q_{BRavg}}{LF}\right)^2\right) \times (aLF + (1-a)LF^2) \quad (10)$$

III. USING ADVANCED BRANCH EXCHANGE METHOD FOR DNR PROBLEMS WITH PV CONNECTION

The branch exchange algorithm [7] proves to be one of the most effective algorithms for the DNR problem of loss reduction. The branch exchange method can quickly determine the distribution network configuration with the highest energy loss reduction based on heuristic rules combined with empirical formulas for loss reduction. However, the branch exchange algorithm applied in previous studies has not considered the effect of the power flow direction on the branches when PVs is connected on gird. With the increasing penetration of PVs on the distributed network, finding an effective DNR algorithm is one of the challenges for researchers.

From Equation (10), the energy loss deviation δA_i and δA_j in the ith loop and jth loop, respectively, are shown in formulas (11) and (12).

$$\delta A_i = \Delta A_{initial} - \Delta A_i \quad (11)$$

$$\delta A_j = \Delta A_{initial} - \Delta A_j \quad (12)$$

As shown in Equation (11) and (12), the value $\Delta A_{initial}$ is the initial energy loss of the distribution network before the reconfiguration, ΔA_i and ΔA_j are the energy loss, respectively when opening and closing a pair of switches in the ith and jth loops

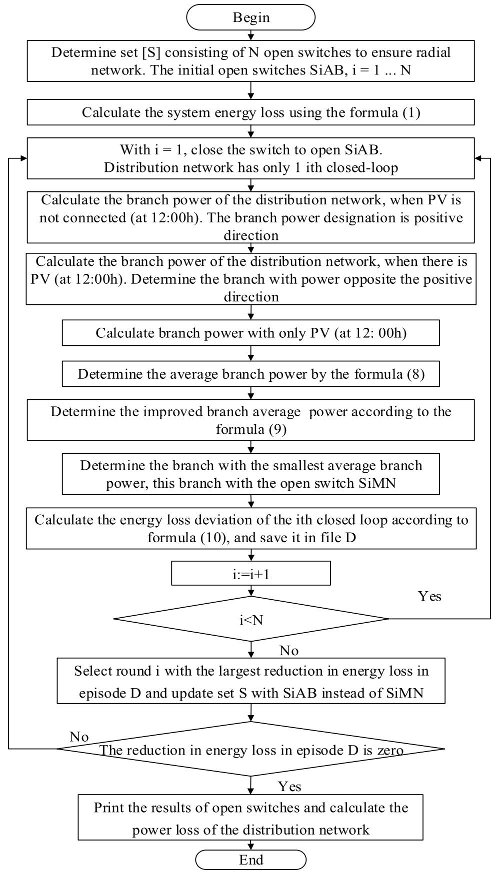

FIGURE 4. Modified branch exchange algorithm for the DNR problem with PVs.

We have: Eq. (11) - (12) $\Leftrightarrow \delta A_i - \delta A_j = \Delta A_j - \Delta A_i$ (13)

From formula (13) shows:

$$\text{If } \delta A_i > \delta A_j \text{ then } \Delta A_i < \Delta A_j \quad (14)$$

From the formula (14) demonstrates in many distribution network configurations that considering when opening/closing 01 switch pairs, the configuration with the largest energy loss deviation δA, the energy loss of that configuration is the lowest

Therefore, the distribution network reconfiguration problem with PV to minimize the energy loss becomes the problem of determining the distribution network configuration with PV achieving the smallest energy loss deviation. From the above point of view, this paper has proposed an advanced branch exchange algorithm in determining the configuration with the largest energy loss deviation when PV is connected on gird. The proposed method is improved from the DNR algorithm to reduce power loss without PV effect of Civanlar [7] (called branch switching algorithm). The algorithm flowchart of performing DNR with PV is shown in Figure 4.

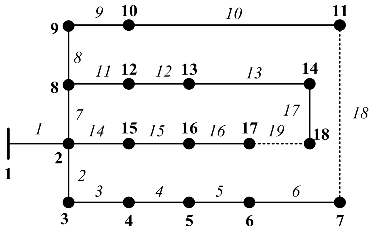

FIGURE 5. The 18-node system.

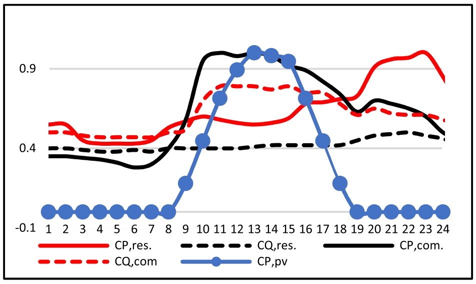

FIGURE 6. Load curve and PV generator curve.

TABLE 1. The proportion of MRes. and Mcom. load types in each node in the 18-node system.

Node	MRes	MCom	Node	MRes	MCom	Node	MRes	MCom
1	0	0	7	0	1	13	0	1
2	0	0	8	0	1	14	0	1
3	1	0	9	0	1	15	1	0
4	1	0	10	0	1	16	1	0
5	1	0	11	0	1	17	1	0
6	1	0	12	0	1	18	0	1

IV. SIMULATION RESULTS

In this study, the 18 node distribution network is used to describe of step performed DRN by proposed method. Besides, the 33 node distribution network is tested to evaluate the proposed method's effectiveness compared with other method for the DNR problem when the distribution network has PVs connection.

A. DISTRIBUTION NETWORK 18-NODE

The 10 kV distribution network has 18 nodes, 19 branches, 17 closed switches, and two opened switches {17, 18}. The single line diagram is shown in Figure 5 [7]. The loads include commercial (Mcom.), residential (Mres.) like Table 1. The loads' curve of each type of load and PV power generation curve are shown in Figure 6 [30]. The 18-node distributed network is tested DNR for 2 case with different sizes of PV for evaluating effect of PV on average branch power.

When the distribution network has not connected PV with initial open switches {18, 19}, the energy loss is 1514.0 kWh [4]. It can be seen that without a PV connection, the power transmission direction of the branches is shown in Figure 7.

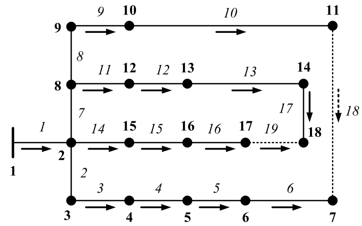

FIGURE 7. The power transmission direction of the branch power without PV connection.

TABLE 2. Switching is open in the case of PV with a power of 560 kW.

Case	PV (kW)	Open switch	ΔA (kWh)
Initial	-	{18, 19}	1514.0
	560	{18, 19}	1345.5
P_{BRavg}	560	{17, 18}	1325.1
P^N_{BRavg}	560	{17, 18}	1325.1

TABLE 3. Switching is open in the case of PV with a power of 3000 kW.

Case	PV (kW)	Open switch	ΔA (kWh)
Initial	-	{18, 19}	1514.0
	3000	{18, 19}	1196.5
P_{BRavg}	3000	{18, 13}	1312.0
P^N_{BRavg}	3000	{18, 19}	1196.5

Case 1: Distribution network with a connection of 1 PV at node 18 with $P_{PVmax} = 560$ kW.

Table 4 presents results of P^N_{BRavg} and δA_{MN} when PV is installed at node 18 with case $P_{PVmax} = 560$ kW. In which, P^{12h}_S (without PV) and P^{12h}_S (with PV) is the power of the system at 12h in the case without PV and with PV respectively. As observed from Table 4, the distribution network 18 node has 2 Loops (Loop 1 and Loop 2). For case 1, when PV is connected at node 18 with PV =560 kW which is less than the load power at node 18 (600 kW), there is no power transmitted back from the initial on the branches. Hence, the branches' power direction of the case 1 as shown in Figure 8 which is similar to transmission direction in the case without PV (Figure 7). It can be seen that when PV is installed at load node with power which is less than load power, there is no additional power on the branch and the P_{BRneg} on the branches is zero as shown in Table 4 (column 8). From Table 4 (column 7, column 8), it can be seen that, the average branch power PBRavg is similar the improved branch average power P^N_{BRavg} that shows the two closed loops' calculation results with the power per branch and the deviation of each closed loop's respective branch energy loss.

Table 2 shows the test results of initial case before DRN and after using improved branch average power. The initial open switch case energy loss result is 1514 kWh without PV, with PV being 1325.1 kWh. The P_{BRavg} and P^N_{BRavg} methods give the same open switching result and have the energy loss

TABLE 4. P^N_{BRavg} and δA_{MN} when PV install at node 18 with P_{PVmax} = 560 kW.

Branches	Switch	P_s^{12h} (Without PV)	P_s^{12h} (With PV)	Change direction (Yes/No)	P_{BRneg} (kW)	P_{BRavg} (kW)	P^N_{BRavg} (kW)	Q_{BRavg} (kVAR)	δA (Wh)
Loop 1									
2 - 15	14	1671.2	1388.8	No	0	1379.6	1379.6	325.4	1075.3
15 - 16	15	1337.1	1055.8	No	0	990.9	990.9	242.1	556.9
16 - 17	16	1005.1	724.5	No	0	603.9	603.9	159.5	208.8
17 - 18	19	668.5	388.4	No	0	211.1	211.1	77.2	27.0
14 - 18	17	68	348.1	No	0	23.5	23.5	79.3	3.7
13 - 14	13	332.1	52	No	0	279.9	279.9	11.8	42.0
12 - 13	12	832.9	552.4	No	0	600.7	600.7	134.1	202.7
8 - 12	11	1234.7	953.5	No	0	857.8	857.8	225.6	421.1
2 – 8	7	2997	2714.2	No	0	1984.6	1984.6	597.7	2299.2
Loop 2									
2 – 3	2	1650.8	1650.8	No	0	1504.6	1504.6	432	1390.8
3 – 4	3	1372.8	1372.8	No	0	1180.5	1180.5	347	859.4
4 – 5	4	1096	1096	No	0	857.6	857.6	262	456.4
5 – 6	5	820	820	No	0	535.2	535.2	178	180.5
6 – 7	6	544.4	544.4	No	0	213.3	213.3	93	30.7
7 - 11	18	144.1	144.1	No	0	43.1	43.1	8.5	1.1
10 - 11	10	256	256	No	0	299.6	299.6	74.2	54.1
9 - 10	9	656.5	656.5	No	0	556.3	556.3	159	190.0
8 – 9	8	1157	1157	No	0	876.7	876.7	267	476.7
2 – 8	7	2919.9	2919.9	No	0	2004.6	2004.6	662	2528.2
Switch open: {17, 18}									

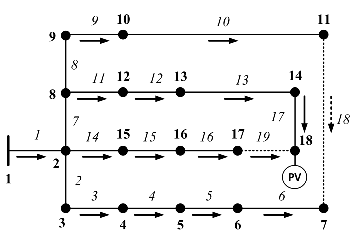

FIGURE 8. The power transmission direction of the branch power with P_{PVmax} = 560 kW.

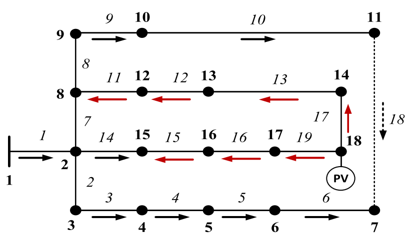

FIGURE 9. The transmission direction of the branch power with P_{PVmax} = 3000 kW.

of 1325.1 kWh because the PV power is small so there is no back-propagation branch.

Case 2: Distribution network with a connection of 1 PV at node 18 with P_{PVmax} = 3000 kW.

With connecting PV to the initial open switches {18, 19} the energy loss achieved 1196.5 kWh as shown in Table 3. The DNR is performed by branch switch in a closed loop of the two rounds as follow.

From Table 5 and Figure 9 shows the direction of power transmission of branches when PV is 3000 kW. For Loop 1, branch 2-15 (switching 14), branch 2-8 (switching 7) has a system power of P_s^{12h} (with PV) at 12 o'clock with constant direction (No) compared to system power P_s^{12h} (without PV) at 12h, so there is no P_{BRneg} added to these branches. In addition, branches 15–16 (switch 15), 16–17 (switch 16), 17–18 (switch 19), 14 – 18 (switch 17), 13–14 (switch 13), 12–13 (switch 12), 8–12 (switch 11) with system power P_s^{12h} (with PV) at 12 h has a direction of change (Yes) compared to system power P_s^{12h} (without PV) at 12 h. At this time, the average branch power P_{BRneg} is no longer accurate to determine the value of δA_{MN}. Therefore, these variable power branches need to be supplemented with a P_{BRneg} amount of 4.5, 40.65, 114.8, 410.3, 227.1, 74, 11.8 kW respectively. Therefore, the branch average power value is redefined with new values as shown in Table 5. At this point, branch 17-18 (switch 19) with δA_{MN} value of 32.7 which is the smallest, so the switch in Loop 1 is defined to be open as switch 19. Similarly, Loop 2 has no backward branch power compared to the initial. Table 5 shows the calculation results of the 2 loops with branch power and corresponding branch energy loss deviation of the two closed loops.

When PV power is 3000 kW at node 18, with minimum δA value, open switch for Loop 1 is 19 and for Loop 2 is switch 18. Table 3 shows the test results with the original case, the use case of P_{BRavg} and P^N_{BRavg} improved branch average power. The initial open switch case energy loss result is 1514 kWh without PV, with PV being 1196.5 kWh. The P_{BRavg} method for an open switch {18, 13} with an energy

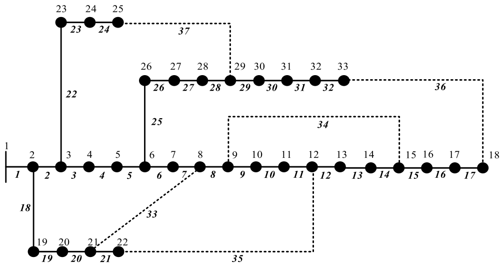

FIGURE 10. The 33-node system.

loss of 1312.0 kWh, and the P^{N}_{BRavg} method for an open switch {18, 19} with an energy loss of 1196.5 kWh. Thus method P^{N}_{BRavg} gives the smallest energy loss when using the improved average branch power.

The problem of using average power is simple and easy to calculate. However, the impact of PV on the distribution network will make δA no longer accurate. This leads to determining whether the open switch has the smallest energy loss. Therefore, it is necessary to calculate the improved average power when the distribution network has PV to determine the lowest energy loss branch. Thus, with the improved branch average power method, the open branch results in the smallest energy loss.

B. DISTRIBUTION NETWORK 33-NODE

The 12.66 kV distribution network has 33 nodes, 37 branches, 32 closed switches, and five open switches {33, 34, 35, 36, 37}. Figure 10 shows the original diagram. The node, line, and power data are given in the reference [3]. The curve load factor and power generation curve of PV are shown in Figure 6 [29].

Figure 10 shows the execution sequence of the improved branch switching algorithm using the improved average branch power. In order to implement this method, in each closed loop changes the open switches by determining the minimum energy loss deviation. This operation is done until the open switch coincides with the previous open switch, then stop. The final selected result will be determined with the lowest energy loss.

The proposed method was performed and compared with the curve method (TOPO of PSS - ADEPT), the GSA method [29], and the EP method [29]. Table 6 presents the energy loss results of proposed method, other methods and the energy loss before DRN.

From Table 6 it can be seen that when distribution network has 3 PVs participating in nodes 6, 18, and 22 [29], with open switches {33, 34, 35, 36, 37}; the initial energy loss is 3304.82 kWh. However, after DRN using proposed method the energy loss reduces to 2075.51 kWh that is better than Curve method, EP method and similar to the GSA method. The proposed method's energy loss obtained 2075.51 kWh with open switches {7, 10, 14, 17, 28}, while the Curve method is 2243.98 kWh with open switches {7, 9, 14, 32, 37}, and EP method is 2334.28 kWh with open switches {7, 10, 14, 31, 37}.

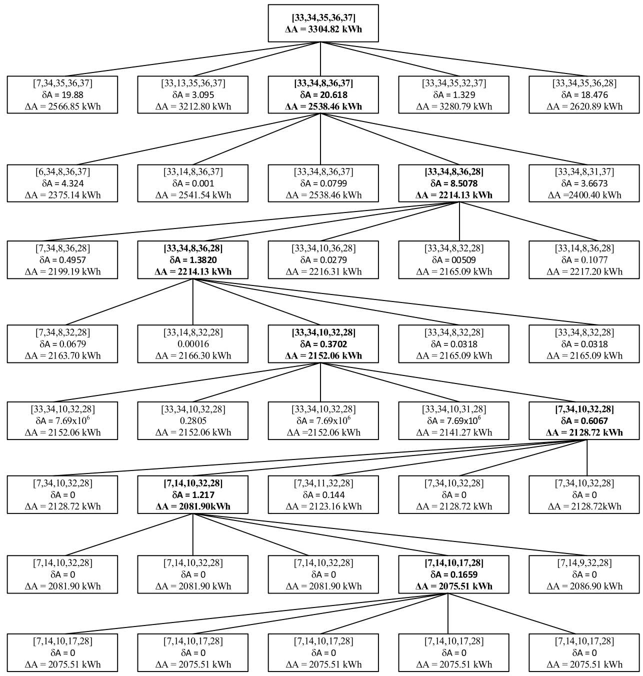

FIGURE 11. The optimization process of a 33-node distributed network.

The test results on the 33-node distributed network showed the influence of PV on the DNR problem. Figure 11 shows the execution sequence to determine the configuration to be selected next based on the comparison of the δA value between configurations in a class and using formula (14) to select the best configuration. With the configuration with the largest δA value, the energy loss of that configuration is the lowest. Therefore, the configurations run until δA is zero then stop and confirm the result. The proposed method gives DNR results similar to GSA method with the lowest energy loss and better than other methods. However, in this method contains a total of 80 times the power flow calculation: 40 times (with PV) and 40 times (without PV), as shown in Figure 11. Meanwhile, the GSA method used for calculation with the number of power flow calculations is dependent on the selection population (N=100), the number of iterations (Ir=5) and the number of orders of the load curve (24 hours). Thus, the number of times GSA's power flow calculation is equivalent to 12000 times. The proposed method implements the advanced branch switching technique which does not require complex computations and also is simple and accurate via considering the improved average branch power when the distribution network contains PV. The experimental results of the 33-node distributed network show the influence of PV on the DNR problem when using branch average power. This outcome shows that open switches that have the lowest energy loss with a significantly reduced number of computations compared with other methods.

V. CONCLUSION

The paper uses the improved average power method combined with advanced branch exchange method to quickly

TABLE 5. P^N_{BRavg} and δA_{MN} when PV install at node 18 with $P_{PVmax} = 3000$ kW.

Branches	Switch	P_s^{12h} (Without PV)	P_s^{12h} (With PV)	Change direction (Yes/No)	P_{BRneg} (kW)	P_{BRavg} (kW)	P^N_{BRavg} (kW)	Q_{BRavg} (kVAR)	δA (Wh)
Loop 1									
2 - 15	14	1671.2	166.2	No	0	1046.5	1046.5	325.4	642.8
15 - 16	15	1337.1	164.4	Yes	4.5	658.9	663.4	242.1	266.9
16 - 17	16	1005.1	494	Yes	40.65	272.4	313.1	159.5	66.1
17 - 18	19	668.5	830	Yes	114.8	120.2	235.0	77.2	32.7
14 - 18	17	68	1569	Yes	410.3	307.8	718.1	79.3	279.4
13 - 14	13	332.1	1167.3	Yes	227.1	51.4	278.5	11.8	41.6
12 - 13	12	832.9	666.4	Yes	74	269	343.0	134.1	72.6
8 - 12	11	1234.7	266	Yes	11.8	525.7	537.5	225.6	181.9
2 – 8	7	2997	1490	No	0	1651	1651.0	597.7	1650
Loop 2									
2 – 3	2	1650.8	1402	No	0	1460	1460	432	1315.2
3 – 4	3	1372.8	1124	No	0	1136	1136	347	800.4
4 – 5	4	1096	848	No	0	813	813	262	413.9
5 – 6	5	820	572	No	0	491	491	178	154.7
6 – 7	6	544.4	297	No	0	169	169	93	21.1
7 - 11	18	144.1	102	No	0	87.4	87.4	8.5	4.4
10 - 11	10	256	503	No	0	601	601	74.2	208.0
9 - 10	9	656.5	904	No	0	344	344	159	81.5
8 – 9	8	1157	1406	No	0	921	921	267	521.7
2 – 8	7	2919.9	769	No	0	1619	1619	662	1735.6
Switch open: {18, 19}									

TABLE 6. DNR results of the method for the 33-node distribution network.

Method	Switch open	ΔA (kWh)
Initial	{33, 34, 35, 36, 37}	3304.82
Curve method TOPO of PSS - ADEPT	{7, 9, 14, 32, 37}	2243.98
EP [29]	{7, 10, 14, 31, 37}	2334.28
GSA [29]	{7, 10, 14, 17, 28}	2075.51
Method proposed	{7, 10, 14, 17, 28}	2075.51

find the optimal configuration of distribution network with PV obtaining the smallest energy loss. The method which is tested on a distributed network 33 nodes, shows the effectiveness of the proposed method with the minimum objective function of the energy loss. The energy loss of this study is better than many other methods. The proposed method's energy loss obtained 2075.51 kWh, while the Curve method is 2243.98 kWh and EP method is 2334.28 kWh. The analytical results show that proposed technique is an effective method to find an optimized solution with fast computation time and higher accuracy than the compared EP and GSA methods. This method determined optimal configuration after 40 times, while EP and GSA depends on the large population size and the convergence speed of each method.

ACKNOWLEDGMENT

This work was the result of the project supported by the Ho Chi Minh City University of Technology and Education, Vietnam, and conducted at the Power System and Renewable Energy Laboratory (C201).

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