Article

A Hybrid Optimization Approach for Power Loss Reduction and DG Penetration Level Increment in Electrical Distribution Network

Teketay Mulu Beza , Yen-Chih Huang and Cheng-Chien Kuo *

Department of Electrical Engineering, National Taiwan University of Science and Technology, 43, Sec. 4, Keelung Rd., Taipei 10607, Taiwan; mteke24@gmail.com (T.M.B.); m10707205@gapps.ntust.edu.tw (Y.-C.H.)

* Correspondence: cckuo@mail.ntust.edu.tw; Tel.: +886-920881490; Fax: +886-227376688

Received: 23 October 2020; Accepted: 13 November 2020; Published: 17 November 2020

Abstract: The electrical distribution system has experienced a number of important changes due to the integration of distributed and renewable energy resources. Optimal integration of distributed generators (DGs) and distribution network reconfiguration (DNR) of the radial network have significant impacts on the power system. The main aim of this study is to optimize the power loss reduction and DG penetration level increment while keeping the voltage profile improvements within the permissible limit. To do so, a hybrid of analytical approach and particle swarm optimization (PSO) are proposed. The proposed approach was tested on 33-bus and 69-bus distribution networks, and significant improvements in power loss reduction, DG penetration increment, and voltage profile were achieved. Compared with the base case scenario, power loss was reduced by 89.76% and the DG penetration level was increased by 81.59% in the 69-bus test system. Similarly, a power loss reduction of 82.13% and DG penetration level increment of 80.55% was attained for the 33-bus test system. The simulation results obtained are compared with other methods published in the literature.

Keywords: distributed generation; distribution network reconfiguration; power loss reduction; optimization; voltage stability index

1. Introduction

Energy is a major requirement for the economic development of a country. It is available in various forms in nature, but the most significant type is electrical energy, which has become integral to daily life [1,2]. However, electrical power distribution companies face substantial difficulties due to increasing load demand and deficiency of capital investment in transmission and distribution networks. In addition, the current transmission and distribution networks in most countries are relatively old [3].

Power loss reduction and voltage profile improvement are vital components of power systems due to existing distribution system contingency, financial losses of utilities, and power system interruptions [4]. Because of the steady growth in energy demand and substantial increase in the use of distributed generation, utilities are exploring alternatives to improve the technical specifications of the distribution networks in terms of power losses, customer interruption costs, and voltage stability, while increasing the penetration level of distributed generators (DGs). Optimal allocation of DGs, capacitor placement, and distribution network reconfiguration (DNR) are effective means of enhancing the reliability of power systems [5,6].

Recently, DGs are becoming increasingly attractive to utilities and consumers because these units produce energy close to the load, and are more efficient (less losses), easier to site and have less environmental impact [7–10]. DGs are primarily installed on the distribution and sub-transmission level networks. Their main technical benefits include [11–15]:

- Power loss reduction due to the proximity of load and generation.
- Voltage profile improvement.
- Improved reliability and security.
- Pollutant emission reduction from central power plants.
- Long term deferral of investment in transmission system expansion.
- Increasing loadability.

Previous research [12,16,17] strongly recommends the effective use of the existing distribution infrastructure with minimum expenditure to enhance the capacity of existing systems. It has been observed that the loadability or capacity of the distribution system is commonly restricted by two factors, i.e., thermal and voltage limits. The current carrying capacity of the conductor is called the thermal limit. The current carrying capacity is highly dependent on the maximum conductive design temperature of the conductor, which is also determined by the insulation class used [16]. However, the voltage limit is the maximum permissible voltage deviation for proper operation of the power system and connected load. The study in [17,18] indicated that the maximum load handling capacity of the distribution network is mainly dependent on the voltage limit rather than the thermal limit. Based on this previous research, the voltage limit constraints are prioritized in this paper.

It has also been noted that, because of its increasing use, renewable power generated from solar and wind must contribute to enhancing the voltage profile and delivering the required reactive power compensation [19,20]. Promising technology has been developed to regulate the active and reactive power of DGs. For example, some photovoltaic (PV) inverters incorporate special self-commutated line inverters and wind power plants using a doubly fed induction generator that can absorb and supply reactive power at various loading conditions. The capacity of solar and wind power generating units to support reactive power must be further improved through integration of STATCOMS, SVC, and other reactive support equipment, appropriately located and sized [12,21]. Various categories of DGs are described in the literature [18,22–24], as follows:

- Type I: DGs that inject only active power, e.g., PV systems.
- Type II: DGs that inject only reactive power, e.g., synchronous compensators.
- Type III: DGs that inject active power but absorb reactive power, e.g., induction generators.
- Type IV: DGs that inject both active and reactive power, e.g., synchronous generators.

The DGs considered in this paper (i.e., Type IV) inject active and reactive power. However, non-optimal DG placement and sizing increases power losses and influences the voltage profile of the power system.

A number of analytical and optimization-based approaches have been suggested in the literature for DG placement, sizing, and distribution network reconfiguration. Each of these studies has at least one main objective, and methods followed to achieve this objective. Aman et al. [12] proposed a hybrid particle swarm optimization method to find the optimal solution for maximizing loadability. Guan et al. [25] considered feeder reconfiguration with the presence of various DG models with the main objective of reducing real power loss. An analytical method of feeder overcurrent protection under conditions of high penetration of renewable energy resources connected to the distribution network has been considered [26]. The impacts of optimal allocation of renewable DGs in radial distribution networks in different optimization methods were discussed in [27,28]. Quezada et al. [29] presented an approach to determine yearly power loss fluctuations when DGs with different penetration and dispersal levels are connected to a distribution system. According to the study results, the variation of power loss as a function of DG penetration level depicts a characteristic U-shaped trajectory. Jain et al. [30] tried to reduce active power loss and enhance voltage stability via the installation of multiple distributed generators. A two-stage approach for evaluating the optimal network topologies to enhance the available delivery capability of distribution networks in support of multiple renewable energies was discussed in [31]. Tolabi et al. [32] discussed reconfiguration and optimal placement of

distributed generators with the objectives of power loss reduction and voltage profile enhancement. The authors also considered load balancing to make the system stable.

Chen et al. [33] proposed a model to reduce the overall cost of distribution networks using network reconfiguration and reactive power control of DGs. In recent years, distribution networks have faced several problems because of increasing energy demand and risky operational constraints. Essallah et al. [34] discussed a method for allocation and sizing of distributed generators to improve the voltage profile and reduce the total power dissipation in the electrical grid. The authors also recommended that power utilities effectively develop and exploit distribution networks to ensure continuity and reliability of customer service. Zongo et al. [35] examined minimization of active and reactive power loss, generation of reactive power, and voltage fluctuation. The authors combined the four factors into a single objective equation. However, to minimize the cost, only one distributed generator was used for the analysis.

Power system distribution networks have undergone several major changes because of the application of smart grid technology and the incorporation of distributed renewable energy resources. Din et al. [36] proposed optimal integration of DGs and distribution network reconfiguration to reduce distribution line loss and harmonic distortion. Similarly, in [37] proper coordination of load tap changers, switched shunt capacitors, step voltage regulators, and battery energy storage system (BESS) with high penetration of PVs were considered to minimize power loss and enhance voltage stability. Hung et al. [38] discussed the challenges of high penetration of distributed generation for traditional distribution networks. Power generated from distributed generators affects the power network flow direction, thereby influencing system power loss and voltage profile. The authors discussed an analytical method to compute the most favorable size and power factor of DGs to reduce energy dissipation and enhance loadability. The related literature, their main objectives, and the optimization methods followed are summarized in Table 1.

As depicted in Table 1, most of the studies focused on power loss reduction or voltage profile improvement. The other main concern was increasing the DG penetration level or maximum loadability. However, previous studies aiming to optimize both power loss reduction and DG penetration level increment while maintaining the voltage profile within the allowable limit are not yet adequate. Considering these research gaps, the contributions of this paper are:

- Power loss reduction and DG penetration level increment, while maintaining the voltage profile improvement within the permissible limit, are considered.
- Four scenarios, namely, the base case, only DNR, only DG installation, and simultaneous DG installation and DNR, are implemented using a hybrid optimization approach.
- The simulation results obtained for each scenario are compared with the base case and the references.

The remainder of this paper is arranged as follows: Section 2 describes the materials and methods followed, and Section 3 presents the particle swarm optimization algorithm. The simulation results and discussion are provided in Section 4, and a brief conclusion follows in Section 5.

Table 1. Different objectives and optimization methods used in literatures for distributed generator (DG) placement and distribution loss reduction.

References	Objectives	Optimization/Solution Methods Used
Aman et al. [12]	Maximum loadability	Hybrid particle swarm optimization
Guan et al. [25]	Power loss reduction	Decimal coded quantum particle swarm optimization
Nassif et al. [26]	Feeder over current protection with large penetration of DGs	Analytical approach
Ali et al. [27]	Power loss reduction	Satin Bowerbird Optimization (SBO) Algorithm and Ant Lion optimizer (ALO) Algorithm
Gong et al. [28]	Power loss reduction and voltage profile improvement	Electromagnetism-like mechanism (ELM)
Quezada et al. [29]	Power loss reduction	Iterative search technique with load flow
Jain et al. [30]	Power loss reduction and voltage profile improvement	PSO
Liu et al. [31]	Maximizing DG capacity	Binary particles swarm optimization (BPSO)
Tolabi et al. [32]	Power loss reduction and voltage profile improvement	Combination of a fuzzy and ant colony optimization (ACO)
Chen et al. [33]	Minimization of cost	Hybrid particle swarm optimization
Essallah et al. [34]	Power loss reduction and voltage profile improvement	Analytical approach
Zongo et al. [35]	Minimization of power loss and voltage deviation	PSO and Newton Raphson Power Flow (NRPF)
Din et al. [36]	minimize line losses and total harmonic distortion (THD)	Genetic algorithm (GA)
Aryanezhad et al. [37]	Power loss reduction and voltage profile improvement	Genetic algorithm (GA)
Hung et al. [38]	Power loss reduction and enhancing loadability	Analytical approach
Hamida et al. [39]	Power loss reduction and minimizing annual operating costs	Fuzzy set theory and evolutionary technique based on the Pareto optimality

2. Materials and Methods

The distribution network reconfiguration (DNR) problem is to find an appropriate configuration of a radial network that ensures minimum power loss. Thus, in this paper, in addition to DNR, DG placement and sizing to minimize real power loss and increase the DG penetration level while maintaining the voltage profile within the allowable limit is taken into account. For an n-bus distribution network, the objective function is to minimize the total active power loss ($P_{Total Loss}$); the associated constraints are defined below:

$$P_{Loss\ 1,2} = R_{1,2} \times \frac{(P_{1,2}^2 + Q_{1,2}^2)}{|V_1|^2} \quad (1)$$

$$P_{Total\ Loss} = \sum_{k=1}^n P_{Loss\ 1,2,3,...,n} \quad (2)$$

where $P_{Loss\ 1,2}$ and $R_{1,2}$ are the active power loss and resistance of the cable between the sending and receiving bus, respectively.

The percentage power loss reduction and the percentage DG penetration level increment can be expressed as shown in Equations (3) and (4), respectively.

$$\frac{P_{Loss\ base} - P_{Loss\ DG,DNR}}{P_{Loss\ base}} \times 100 \quad (3)$$

$$\frac{S_{DG}(kVA)}{S_{Load}(kVA)} \times 100 \quad (4)$$

where $P_{Loss\ base}$ and $P_{Loss\ DG,DNR}$ are the power losses of the base case and that of simultaneous DG and DNR, respectively. The DG size, voltage limit, and radiality constraints are described in Equations (5)–(8). S_{DG} is the total power injected by the DGs and S_{Load} is the total system load.

$$0.1 \times \sum_{k=2}^n S_{Load} \leq \sum_{k=2}^n S_{DG} \leq \sum_{k=2}^n S_{Load} \quad (5)$$

$$V_{min} \leq |V_k| \leq V_{max}, \quad 0.9 \leq |V_k| \leq 1.0 \quad (6)$$

$$\text{Radiality: Status} = 1 \text{ (radial)} \quad (7)$$

$$\text{Status} = 0 \text{ (non-radial)} \quad (8)$$

Voltage Stability Index for Optimal DG Placement

Maintaining a reliable and safe operation of a power system service is a crucial and demanding task. Voltage fluctuation occurs due to the incapability of the distribution system to deliver the electrical power demanded by the load. When DGs are optimally connected in the distribution system, the bus voltages will improve and voltage stability will be enhanced. To determine the optimal location of the DGs, a voltage stability index (VSI) approach is used in this paper. To analyze the VSI, consider a radial distribution network as depicted in Figure 1.

From Figure 1, the branch current I_{12} can be computed using Equation (9):

$$I_{12} = \left[\frac{P_2 + jQ_2}{V_2} \right]^* \quad (9)$$

$$V_2 \angle \delta = V_1 \angle 0 - (R + jX)I_{12} \quad (10)$$

$$V_2 \angle \delta = V_1 \angle 0 - (R + jX) \left[\frac{P_2 + jQ_2}{V_2} \right]^* \quad (11)$$

$$V_2 \angle \delta = V_1 \angle 0 - (R + jX) \left[\frac{P_2 - jQ_2}{V_2 \angle -\delta} \right] \quad (12)$$

$$V_2^2 = V_1 V_2 \angle -\delta - (R + jX)(P_2 - jQ_2) \quad (13)$$

$$V_2^2 = V_1 V_2 \cos \delta - jV_1 V_2 \sin \delta - (R + jX)(P_2 - jQ_2) \quad (14)$$

$$(V_2^2 + P_2 R + Q_2 X) + j(P_2 X - Q_2 X) = V_1 V_2 \cos \delta - jV_1 V_2 \sin \delta \quad (15)$$

Separating real and imaginary parts and considering $\delta = 0$:

$$V_2^2 + P_2 R + Q_2 X = V_1 V_2 \cos \delta \quad (16)$$

$$P_2 X - Q_2 X = -V_1 V_2 \sin \delta \quad (17)$$

$$V_2^2 + P_2 R + Q_2 X = V_1 V_2 \quad (18)$$

$$P_2 X - Q_2 X = 0 \Rightarrow R = \frac{P_2 X}{Q_2}, \quad (19)$$

$$V_2^2 + P_2 \left(\frac{P_2 X}{Q_2} \right) + Q_2 X = V_1 V_2, \quad (20)$$

According to Murty et al. [40] for stable bus voltage, $b^2 - 4ac \geq 0$. Hence the voltage stability index (VSI) will be:

$$V_1^2 - 4 \left(\frac{P_2^2}{Q_2} + Q_2 \right) X \geq 0 \quad (21)$$

Rearranging:

$$VSI = \frac{4X}{V_1^2} \left(\frac{P_2^2}{Q_2} + Q_2 \right) \leq 1 \quad (22)$$

where X , V_1 , P_2 , and Q_2 are the inductive resistance (ohms), voltage (kV), real load (kW), and reactive load (kvar), respectively, as shown in Figure 1.

Figure 1. Equivalent circuit model for radial distribution.

The VSI magnitude must be less than one during normal operating situations. When the magnitude of VSI is approaching zero, the system is expected to be more stable. When the magnitude of VSI is high, the distribution system is vulnerable to instability. The bus with a high VSI magnitude is more sensitive and is the favored location for DG placement [40]. The single line diagrams of the 33-bus and 69-bus test systems used for this study are shown in Figure A1a,b of Appendix A, respectively. The data used for these analyses, that is, for the 33-bus and 69-bus systems, were taken from Aman et al. [12].

Using Equation (22), the candidate locations for the placement of the DGs for the 33-bus and 69-bus test systems are determined as depicted in Figure 2a,b.

Figure 2. Voltage stability index (VSI) for: (a) 33-bus test system; (b) 69-bus test system.

As shown in Figure 2a, the maximum values of VSI are at the 6th bus (5th branch), 8th bus (7th branch), 28th bus (27th branch), and 14th bus (13th branch) for the 33-bus test system. The bus number next to the branch number with the maximum VSI value is the candidate location for DG placement. Hence, buses 6, 8, 28, and 14 are candidate buses for DG placement. Similarly, from Figure 2b, buses 57, 5, 7, and 61 are the candidate buses based on the value of VSI for the 69-bus test system. Once the candidate buses for the placement of the DGs are determined, the optimal sizes of the DGs are computed based on an analytical approach considering the constraints given in Equation (5). That is, the sizes of the DGs are incremented in steps of 5% considering minimization of power loss and increase in the penetration level of the DGs. Once the candidate locations of the DG placement were determined using VSI analysis, the PSO algorithm was used to integrate DG placement and DNR.

3. Particle Swarm Optimization (PSO) Algorithm

The PSO algorithm is a population-based and self-adaptive method initiated in 1995 by Kennedy and Eberhard, and adapted from food searching behavior of birds and fish (particles) [41–43]. The particles move within the search space towards the optimal position at a particular speed and frequently adjust their positions to reach the optimal location. The position and velocity of the i th particle in the d -dimensional search space are denoted x_i and v_i as follows in Equations (23) and (24) respectively.

$$x_i = (x_{i1}, x_{i2}, \dots, x_{id}) \quad (23)$$

$$v_i = (v_{i1}, v_{i2}, \dots, v_{id}) \quad (24)$$

The movement of the particles is led by their own experience (p_{best-i}^k) and the group experience (G_{best}^k). The final location visited by the i th particle until the k th iteration is taken as $p_{best-i1}^k, p_{best-i2}^k, \dots, p_{best-id}^k$, where the best position of all p_{best-i}^k in the group is defined as G_{best}^k . The velocity and position of every particle are updated based on Equations (25) and (26), respectively.

$$v_i^{k+1} = wv_i^{k+1} + c_1r_{1i}(p_{best-i}^k - x_i^k) + c_2r_{2i}(G_{best}^k - x_i^k) \quad (25)$$

$$x_i^{k+1} = v_i^{k+1} + x_i^k \quad (26)$$

where k is number of iterations, w is inertia weight, V_i is velocity of the i th particle, c_1 and c_2 are the acceleration coefficients for cognitive and social components, respectively, and r_1 and r_2 are independently and uniformly distributed random numbers between 0 and 1. The inertia weight is defined in Equation (27).

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \quad (27)$$

where w_{max} , w_{min} , $iter$, and $iter_{max}$ are initial inertia weight factor, final inertia weight factor, current iteration number, and maximum iteration number, respectively. Once the candidate locations of the DGs were determined using the VSI approach, the optimal size of the DGs and the appropriate DNR were computed using the PSO algorithm to achieve minimum power loss and better DG penetration level.

4. Results and Discussions

Using the VSI approach for DG allocation, and the PSO algorithm for DG sizing and DNR, computations were performed to reduce the total power loss and to enhance the voltage profile of the IEEE-33-bus and IEEE-69-bus test systems. In addition to power loss reduction and voltage profile improvement, the increase in the DG penetration level was also taken into account. The simulation was performed using the MATLAB version 8.1 environment on a PC with CORE i5, 3.20 GHz, and 7.9 GB RAM. The results obtained for the 33-bus and 69-bus test systems are discussed as follows.

4.1. For IEEE-33 Bus Test System

The results obtained for the IEEE-33-bus radial distribution network, taking the base MVA of $S_b=100$ MVA, and the base voltage of $V_b = 12.66$ kV, are described as follows. The real and reactive power loads of the system are 3715 kW and 2300 kvar respectively. The normally closed sectional switches and tie switches for the base case scenario are assigned 1–32 and 33–37 respectively, as depicted in Figure A1a of Appendix A.

In this paper, four different scenarios are taken into account. These scenarios are: base case, only DG scenario, only DNR scenario, and simultaneous DG and DNR. The power loss reduction and voltage profile improvements in each scenario are depicted in Figures 3 and 4, respectively. Simultaneous DG installation and DNR provides the minimum power loss, that is loss reduction of 82.13%, compared with the base case power loss of 211 kW. Furthermore, a significant improvement of voltage profile and DG penetration is achieved relative to other scenarios. When we consider only DG placement and increase the size of the DG for a better penetration level, the voltage profile near the DG location point is higher (more than 1 PU), as shown in Figure 4. This voltage increase is one of the limitations of the scenario of only DG placement. However, when the proposed method is used, the voltage profile is improved and smoothed (near to 1 PU), the power loss reduction is improved (Figure 3), and the DG penetration level is increased from 3323.86 to 3519.38 kVA. In Table 2, the percentage power loss reduction, DG penetration level increment, the tie switches opened, voltage magnitude improvement, and other details of the proposed system are presented. The simulation results are compared with references [44–46].

Figure 3. Power loss reduction for the 33-bus test system.

Figure 4. Voltage profile improvements for the 33-bus test system.

For simultaneous DG installation and DNR, the percentage loss reduction and DG penetration level for the 33-bus system in comparison with references [44–46] is presented in Figure 5. As shown in the figure, the percentage power loss reduction is 82.13%, which is superior to all of the references. Similarly, a significant percentage increase in DG penetration is achieved compared with references [45] and [44]. The result highlights that the proposed method optimizes both loss reduction and DG penetration level while maintaining the voltage profile within the permissible range.

Figure 5. Comparison with references for the 33-bus test system: (a) percentage loss reduction; (b) DG penetration level increment.

Table 2. Simulation outputs of the 33-bus test system.

Scenarios	Items	Ref. [45]	Ref. [44]	Ref. [46]	Proposed
Base case	Switch opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	Power Loss (kW)	202.68	202.685	210.99	211.00
	Minimum voltage in p.u (bus)	0.9108	0.9131(18)	-	0.9038(18)
Only Reconfiguration	Switch opened	7, 9, 14, 28, 32	7, 9, 14, 32, 37	7, 9, 14, 28, 32	32, 33, 34, 35, 36
	Power Loss (kW)	139.98	139.55	139.97	113.73
	% loss reduction	30.93	31.15	33.66	46.1
	Minimum voltage in p.u (bus)	0.9413	0.9378 (32)	-	0.9534(23)
Only DG installation	Switch opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	DG size	3254.5 kW	2731 kW	3709.1 (kVA)	3323.86 kVA
	DG position	14, 24, 30	11, 24, 29	14, 32	6, 8, 14, 28
	Power Loss (kW)	74.26	74.213	113.15	49.7568
	% loss reduction	63.26	63.39	46.37	76.42
	% DG penetration level	74.48	62.5	84.89	76.07
	Minimum voltage in p.u (bus)	0.9778	0.962(33)	-	0.982(33)
DG and DNR	Switch opened	8, 9, 27, 33, 36	7, 10, 13, 27, 32	7, 10, 14, 28, 32	32, 33, 34, 35, 36
	DG size	3254.5 kW	2689 kW	4074.1 (kVA)	3519.38 (kVA)
	DG position	14, 24, 30	15, 21, 29	9, 25	6, 8, 14, 28
	Power Loss (kW)	62.98	57.287	58.86	37.70
	% loss reduction	68.93	71.74	72.1	82.13
	% DG penetration level	74.48	61.54	93.24	80.55
	Minimum voltage in p.u (bus)	0.9826	0.976(32)	-	0.9841(31)

4.2. For IEEE-69 Bus Test System

The results obtained for the IEEE-69 bus radial distribution network with a base MVA of $S_b = 100$ MVA and base voltage of $V_b = 12.66$ kV are described as follows. The real and reactive power loads of the distribution network are 3801.89 kW and 2693.8 kvar, respectively. The normally closed sectional switches and the tie switches are numbered 1–68 and 69–73, respectively, for the base case scenario of the 69-bus test system as depicted in Figure A1b of Appendix A. Similar to the IEEE-33 bus system, four scenarios are considered. These scenarios are: base case, only DG scenario, only DNR scenario, and simultaneous DG and DNR. The power loss reduction and voltage profile improvements in each scenario are depicted in Figures 6 and 7, respectively. Power loss reduction of 89.76% and DG penetration level increment of 81.59% compared with the base case scenario are achieved from simultaneous DG installation and DNR. The voltage profile also improved significantly as depicted in Figure 7. The percentage power loss reduction, DG penetration level increment, the tie switches opened, voltage magnitude improved, and other details of the proposed system compared with the base case are presented in Table 3. When the proposed method is used, the voltage profile is improved and smoothed (near to 1 PU), the power loss reduction is improved (Figure 6), and the DG penetration level increases to 3801.79 kVA. The comparison of simulation results with the related references is presented in the same table.

Figure 6. Power loss reduction for the 69-bus system.

Figure 7. Voltage profile improvement for the 69-bus system.

Table 3. Simulation outputs of the 69-bus test system.

Scenarios	Items	Ref. [45]	Ref. [44]	Ref. [46]	Proposed
Base case	Switch opened	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	Power Loss (kW)	224.89	225	224.95	224.98
	Minimum voltage in p.u (bus)	0.9092	0.9092(65)	-	0.9092(65)
Only Reconfiguration	Switch opened	14, 57, 61, 69, 70	14, 58, 61, 69, 70	14, 57, 61, 69, 70	14, 56, 61, 69, 70
	Power Loss (kW)	98.59	98.59	98.59	98.59
	% loss reduction	56.16	56.19	56.17	56.18
	Minimum voltage in p.u (bus)	0.9495	0.9495(61)	-	0.9495(61)
Only DG installation	Switch opened	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	DG size	2982.6 kW	2431 kW	3635.00 (kVA)	3401.6 (kVA)
	DG position	2, 11, 18	11, 17, 61	61	5, 7, 57, 61
	Power Loss (kW)	72.44	72.626	104.86	36.8381
	% loss reduction	67.79	67.72	53.39	83.63
	% DG penetration level	64.01	52.17	78.01	73.00
	Minimum voltage in p.u (bus)	0.9890	0.9688(65)	-	0.975(27)
Simultaneous DG and DNR	Switch opened	14, 58, 64, 69, 70	14, 58, 63, 69, 70	13, 17, 38, 57, 63	13, 53, 69, 70, 73
	DG size	2982.6 kW	2683 kW	4102.5 (kVA)	3801.79 (kVA)
	DG position	2, 11, 18	11, 17, 61	61	5, 7, 57, 61
	Power Loss (kW)	41.13	37.111	160.81	23.03
	% loss reduction	81.71	83.51	28.51	89.76
	% DG penetration level	64.01	57.58	88.05	81.59
	Minimum voltage in p.u (bus)	0.9828	0.9816(63)	-	0.9871(25)

From Table 3, considering the simultaneous DG installation and DNR scenario, the percentage power loss reduction and DG penetration level for the 69-bus system compared with references [44–46] is presented in Figure 8. As depicted in the figure, a percentage power loss reduction of 89.76% is achieved, which is superior to the results of all of the references. Similarly, a significant percentage increase in the DG penetration level is achieved compared with references [44,45]. The result in the 69-bus system also highlights that the proposed method optimizes both loss reduction and DG penetration level, while maintaining the voltage profile within the permissible limits. This is consistent with the important applications of dispersed power generation stated in [47,48].

Figure 8. Comparison with references for the 69-bus test system: (a) percentage power loss reduction; (b) DG penetration increment.

5. Conclusions

In this paper, a hybrid of analytical and PSO approaches are discussed for minimization of distribution line losses and improvement of DG penetration level while maintaining the voltage profile improvement within the permissible limits. To achieve the proposed objective, different scenarios of DG placement and DNR are tested. These scenarios include the base case, only DNR, only DG installation, and simultaneous DG installation and DNR. Of these scenarios, simultaneous DG installation and DNR minimized power loss, maximized DG penetration level increment, and improved the voltage profile. Compared with the base case scenario, power loss reduction of 89.76% and DG penetration level increment of 81.59% were achieved for the 69-bus test system. Similarly, power loss reduction of 82.13% and DG penetration level increment of 80.55% were attained for the 33-bus test system. It can also be concluded that there was a significant decrease in power dissipation and enhancement of the voltage profile using the DG with a lagging power factor because of its reactive power support to the system. Hence, DGs that operate with a lagging power factor and deliver reactive power to the system improve the outputs compared to a DG with a unity power factor, as depicted in Tables 2 and 3. Similarly, simultaneous DG installation and DNR provides better voltage flattening capability, in addition to power loss reduction and DG penetration level increment, compared with only DG installation and only DNR. However, when the DG penetration increases consistently, power loss increases and the voltage profile deviates from the permissible limit.

From the analysis, it is observed that when only loss reduction is considered, the DG penetration level is slightly lower. This limits the peak load handling capability of the power system. Conversely, consideration of only DG penetration level increment sometimes increases power loss and system instability due to voltage swelling. Therefore, optimizing power loss reduction and DG penetration level increment is a critical issue for stable and reliable power delivery.

Author Contributions: Conceptualization, C.-C.K. and T.M.B.; Data curation, Y.-C.H.; Formal analysis, T.M.B. and Y.-C.H.; Investigation, T.M.B. and C.-C.K.; Methodology, C.-C.K. and T.M.B.; Resources, Y.-C.H.; Supervision, C.-C.K.; Writing—original draft, T.M.B.; Writing—review & editing, C.-C.K., Y.-C.H. and T.M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Support for this research from the Bureau of Energy, Ministry of Economic Affairs of the Republic of China is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

See Figure A1

Figure A1. Single line diagram: (a) 33-bus test system; (b) 69-bus test system.

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