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OPTIMAL LOCATION AND SIZING OF MULTIPLE DISTRIBUTED GENERATORS IN RADIAL DISTRIBUTION NETWORK USING METAHEURISTIC OPTIMIZATION ALGORITHMS

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Abstract. *The satisfaction of electricity customers and environmental constraints imposed have made the trend towards renewable energies more essential given its advantages such as reducing power losses and enhancing voltage profiles. This study addresses the optimal sizing and setting of Photovoltaic Distributed Generator (PVDG) connected to Radial Distribution Network (RDN) using various novel optimization algorithms. These algorithms are implemented to minimize the Multi-Objective Function (MOF), which devoted to optimize the Total Active Power Loss (TAPL), the Total Voltage Deviation (TVD), and the overcurrent protection relays (OCRs)'s Total Operation Time (TOT). The effectiveness of the proposed algorithms is validated on the test system standard IEEE 33-bus RDN. In this paper is presented a recent meta-heuristic optimization algorithm of the Slime Mould Algorithm (SMA), where the results reveal its effectiveness and robustness among all the applied optimization algorithms, in identifying the optimal allocation (locate and size) of the PVDG units into RDN for mitigating the power losses, enhance the RDN system's voltage profiles and improve the overcurrent protection system. Accordingly, the SMA approach can be a very favorable algorithm to cope with the optimal PVDG allocation problem.*

Key words: *Multi-objective function, Photovoltaic distributed generation, Radial distribution network, Optimal integration, Metaheuristic optimization algorithms.*

1. INTRODUCTION

After the rapid rise for electricity demand, the achievement of the balance between demand and electricity production become an essential challenge for researchers, among solutions. The conventional solution consists of creating new power stations, but this

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solution requires significant investments and costs. The Photovoltaic Distributed Generation (PVDG) is therefore, the alternative to solve this problem, because of its benefits and advantages [1]. The optimal allocation of PVDG units in Radial Distribution Network (RDN) plays an important role in benefits' maximizing, such as reducing the network losses and enhancing voltage profiles [2]. To achieve these benefits, the optimal allocation of PVDG units should be well done while considering the objective function, constraints, and the best choice of optimization algorithms [3]. The findings of research explicitly confirm that the location, size and type of PVDG units in RDNs significantly affect its technical, economic, and environmental parameters [4]. The impact of the PVDG sources can be either beneficial or disadvantageous to the RDN, based and related to the allocation of the PVDG units. Therefore, the correct placement of PVDG units in the RDN remains a barrier to reach their possible full benefits [5].

Recently, several techniques and algorithms have been implemented to find a solution for the problem of the optimal integration of the PVDG units in RDN considering different objective functions as: Applied Biogeography-Based Optimization (BBO) algorithm in [6], Moth Flame Optimization (MFO) algorithm in [7], Adaptive PSO (APSO) algorithm in [8], Sinusoidal Modulated PSO (SM-PSO) algorithm in [9], Spider Monkey Optimization (SMO) algorithm in [10], Artificial Bee Colony (ABC) algorithm in [11], Improved Artificial Bee Colony (IABC) algorithm in [12], applied the Grasshopper Optimization Algorithm (GOA) in [13], Gravitational Search Algorithm (GSA) in [14], Coyote Optimization Algorithm (COA) in [15], and used Krill Herd Algorithm (KHA) in [16]. Recently, applied Sine–Cosine Algorithm (CSA) in [17], Salp Swarm Algorithm (SSA) in [18], Harris Hawk Optimizer (HHO) algorithm in [19], Improved Equilibrium Optimization Algorithm (IEOA) in [20], Chaotic Grey Wolf Optimization (CGWO) algorithm in [21], Bat Algorithm (BA) in [22], and applied Ant Lion Optimizer (ALO) algorithm in [23].

This paper started by proposing a new approach to identify the optimal allocation of Photovoltaic sources that based on multiple PVDG units into RDN which demonstrated using a new proposed Multi-Objective Functions (MOF) that refer to minimize the Total Active Power Loss (TAPL), Total Voltage Deviation (TVD) and Total Operation Time (TOT) of overcurrent relays (OCR) by applying various novel optimization algorithms of Whale Optimizer Algorithm (WOA) in [24], Ant Lion Optimization (ALO) in [25], Grasshopper Optimization Algorithm (GOA) in [26], Salp Swarm Algorithm (SSA) in [27] and Slime Mould Algorithm (SMA) in [28], and validating their effectiveness on the standard test system IEEE 33-bus RDN.

The main contribution and novelty of this paper:

- Proposing a new multi-objective function that comprised three technical parameters to be minimized simultaneously.
- Evolving the parameter of the operation time of the overcurrent relays in the multi-objective function, where in addition to the simultaneous ameliorating of the voltage profiles and the reduction of the active power losses, minimizing the operation time of the OCR improved the protection system, raised the reliability and brings various economical and technical benefits as extending the lifetime of the equipment, also guaranteed the system's normal operation and the continuity of service, by doing the quick removal of the system's part where the fault current may occur.
- Applying the optimization on the standard radial distribution network IEEE 33-bus RDN.
- Studying the impact of the optimal integration of different cases of PVDG units on various technical parameters of the distribution network.

The rest of the study comprised 4 main sections followed by a list of references, where it is organized as, Section 2: indicates the evaluation of the proposed multi-objective functions applied in this paper, Section 3: presents the description of the applied algorithm of SMA, Section 4: demonstrates the optimal results and discussions, Section 5: contains the conclusions and the achievements including the future perspectives.

2. Mathematical Problem Formulation

2.1. Multi-Objective Functions

The interest of this paper is to find the optimal allocation of all PVDG cases into RDN, to optimize simultaneously the technical parameters of TAPL, TVD and TOT, while minimizing the developed MOF that considered as the sum of the technical indices of Total Power Loss Index (TAPLI), Total Voltage Deviation Index (TVDI) and the Total Operation Time Index (TOTI) of the overcurrent relays, for reason that the proposed indices are relative to unity. The MOF is formulated as:

$$MOF = Minimize \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} \sum_{i=1}^{N_R} [TAPLI_{i,j} + TVDI_j + TOTI_i] \tag{1}$$

The first index *TAPLI*, of line is expressed by [7, 8]:

$$TAPLI = \frac{TAPL_{After\ PVDG}}{TAPL_{Before\ PVDG}} \tag{2}$$

$$TAPL_{i,j} = \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} APL_{i,j} \tag{3}$$

$$APL_{i,j} = \alpha_{ij} (P_i P_j + Q_i Q_j) + \beta_{ij} (Q_i P_j + P_i Q_j) \tag{4}$$

$$\alpha_{ij} = \frac{R_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \text{ and } \beta_{ij} = \frac{R_{ij}}{V_i V_j} \sin(\delta_i + \delta_j) \tag{5}$$

where, R_{ij} represents the resistance fo the line. N_{bus} is the bus number, (δ_i, δ_j) and (V_i, V_j) denote the angles and voltages, respectively. (P_i, P_j) and (Q_i, Q_j) demonstrate active and reactive powers, respectively. V_1 is the voltage at the sub-station and equal to 12.66 kV.

The second index, the *TVDI* is defined as [9, 13]:

$$TVDI = \frac{TVD_{After\ PVDG}}{TVD_{Before\ PVDG}} \tag{6}$$

$$TVD_j = \sum_{j=2}^{N_{bus}} \left| V_1 - V_j \right| \tag{7}$$

The third index is *TOTI* of the overcurrent relays, which can be represented as [21]:

$$TOTI = \frac{TOT_{After\ PVDG}}{TOT_{Before\ PVDG}} \tag{8}$$

$$TOT_i = \sum_{i=1}^{N_R} T_i \tag{9}$$

$$T_i = TDS_i \left(\frac{A}{M_i^B - 1} \right) \tag{10}$$

$$M_i = \frac{I_F}{I_P} \quad \text{and} \quad I_F = \frac{V_F}{Z_{ij}} \tag{11}$$

where, T_i is the operation time of OCR, *TDS* is the time dial setting, *M* is the multiple of pickup current. I_F and I_P represent the fault and the pickup currents, respectively. *A* and *B* are constants of the relay, set to 0.14 and 0.02, respectively. N_R is the number of OCRs. V_F is the phase fault voltage magnitude measured, Z_{ij} is the line impedance.

2.2. Equality Constraints

The equality constraints of the balanced power equations could be expressed as follows:

$$P_G + P_{PVDG} = P_D + APL \tag{12}$$

$$Q_G = Q_D + RPL \tag{13}$$

where, Q_G and P_G illustrate the total reactive and active powers from generator. Q_D and P_D are the load's total reactive and active powers. *APL* and *RPL* denote the active and reactive power losses, respectively. P_{PVDG} is the PVDG's output power.

2.3. Distribution Line Constraints

$$V_{\min} \le |V_i| \le V_{\max} \tag{14}$$

$$|1 - V_j| \le \Delta V_{\max} \tag{15}$$

$$|S_{ij}| \le S_{\max} \tag{16}$$

where, $V_{\min}$, $V_{\max}$ denote the minimum and maximum of voltage limits, $\Delta V_{\max}$ is the maximum of voltage drop limits. S_{max} and S_{ij} are the maximum and apparent power in the distribution line.

2.4. PVDG Units Constraints

$$P_{PVDG}^{\min} \le P_{PVDG} \le P_{PVDG}^{\max} \tag{17}$$

$$\sum_{i=1}^{N_{PVDG}} PVDG(i) \le \sum_{i=1}^{N_{bus}} P_D(i) \tag{18}$$

$$2 \le PVDG_{Position} \le N_{bus} \tag{19}$$

$$N_{PVDG} \le N_{PVDG.\max} \tag{20}$$

$$n_{PVDG,i} \,/\, Location \le 1 \tag{21}$$

where, P_{PVDG}^{min} and P_{PVDG}^{max} are the minimum and the maximum PVDG's output power. N_{PVDG} is the PVDG units' number. n_{PVDG} is the location of PVDG units at bus i.

3. THE SLIME MOULD ALGORITHM

The SMA is recent metaheuristic technique proposed in [28], basing on the nature behavior of slime mould which search and explore for food, surround it, and deliver enzymes to assimilate it. The characteristics of the slime mould may be described based on three principal steps, incorporating of approach food, wrap food, and oscillating, where the following subsections represents their mathematical forms.

3.1. Approach food

The model of slime mould's approach behavior is represented in a mathematical equation in order to imitate the contraction mode, the next rule is proposed:

$$\overrightarrow{X(t+1)} = \begin{cases} \overrightarrow{X_b(t)} + \overrightarrow{vb}.(\overrightarrow{W}.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}), & r < p \\ \overrightarrow{vc}.\overrightarrow{X(t)}, & r \ge p \end{cases} \tag{22}$$

where, vb represents a parameter set between [-a, a], vc reduces linearly from 1 to 0. t is the current iteration, X_b indicates the individual location including the highest concentration of odor found, X is the slime mould's location, X_A and X_B are two random individuals that determined among the swarm, W is the slime mould's weight.

The p may be formulated as follows:

$$p = \tanh\left|S(i) - DF\right| \tag{23}$$

where, $i \in 1,2, \ldots, n$. $S(i)$ is the X's fitness, DF is the best fitness acquired for the iterations.

The vb is formulated as follows:

$$\overrightarrow{vb} = [-a, a] \tag{24}$$

$$a = \arctan h(-\left(\frac{t}{\max\_t}\right) + 1) \tag{25}$$

The W is formulated and listed as next:

$$\overrightarrow{W(SmellIndex(l))} = \begin{cases} 1 + r.\log\left(\dfrac{bF - S(i)}{bF - wF} + 1\right), & condition \\ 1 - r.\log\left(\dfrac{bF - S(i)}{bF - wF} + 1\right), & others \end{cases} \tag{26}$$

$$SmellIndex = sort(S) \tag{27}$$

where, *condition* designates that *S(i)* ranks first part of population, *r* is random value between [0, 1], *bF* represents the optimal fitness determined in the iterative process currently, *wF* represents the worst value of fitness in the current iterative, *SmellIndex* is the sequence of fitness values sorted.

3.2. Wrap food

The mathematical formulation of slime mould's location update is as next:

$$\overrightarrow{X^*} = \begin{cases} rand.(UB - LB) + LB, & rand \le z \\ \overrightarrow{X_b(t)} + \overrightarrow{vb}.(W.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}), & r \le p \\ \overrightarrow{vc}.\overrightarrow{X(t)}, & r \ge p \end{cases} \tag{28}$$

where, *LB* and *UB* are the low and up limits for the range of search, *rand* and *r* represent values randomly between [0, 1].

3.3. Oscillating

The value of *vb* oscillates randomly in the range of [-a, a] and gradually addresses 0 as the iterations raise. The value of *vc* oscillates in range [-1, 1] and tends to 0 at last.

Algorithm 1 Pseudo-code of SMA

```
Initialize the parameters pop-size, Max_iteration;
Initialize the slime mould's positions X_i (i=1,2, …, n);
While (t ≤ Max_iteration)
    Calculate the slime mould's fitness;
    Update bestFitness, X_b
    Calculate the W by Eq. (26);
    For each search portion
        Update p, vb, vc;
        Update positions by Eq. (28)
    End For
    t=t+1
End While
Return bestFitness, X_b;
```

4. Test System, Optimal Results and Analysis

The selected algorithms were implemented in the software of MATLAB (version 2017.b) with a PC comprised of processor Intel Core i5, 3.4 GHz, including 8 GB of RAM.

Figure 1 represents the single diagram of the standard IEEE 33-bus RDN [29, 30], which operates with a base voltage equal to 12.66 kV, including active load demand power of 3715.00 kW and reactive load demand power of 2300.00 kVar.

It comprised 32 branches and 33 buses, and everyone of these buses is protected and covered by an overcurrent relay considered as primary, also followed by another overcurrent relay considered as backup, where a Coordination Time Interval (CTI) set between them above 0.2 seconds. Generally, it is calculated for the whole system, 31 OCRs and between them 31 CTIs.

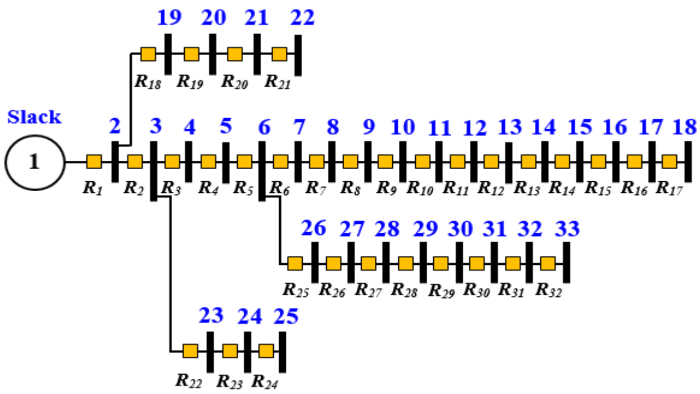


Fig. 1 Single diagram of test system IEEE 33-bus RDN.

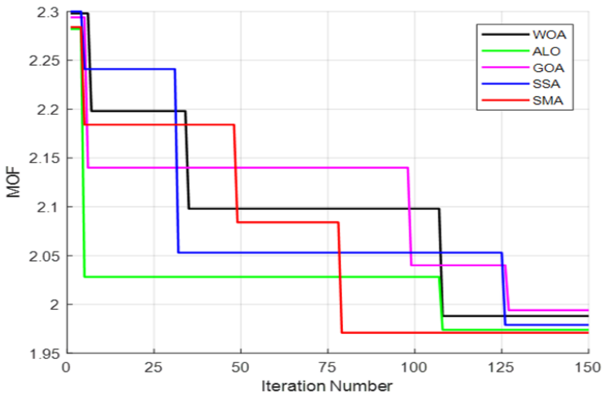
Figure 2 showed the curves of convergence after applying the various metaheuristic algorithms for all the studied cases of optimal integration into the RDN test system.

To improve the comparison between the various applied metaheuristic optimization algorithms, their convergence curves are implemented and shown in figure 2, while the optimization for all algorithms was carried out for a maximum number of iterations equal to 150, and a search agent parameter set to 10, including 2 dimensions for the formulated problem (location and sizing).

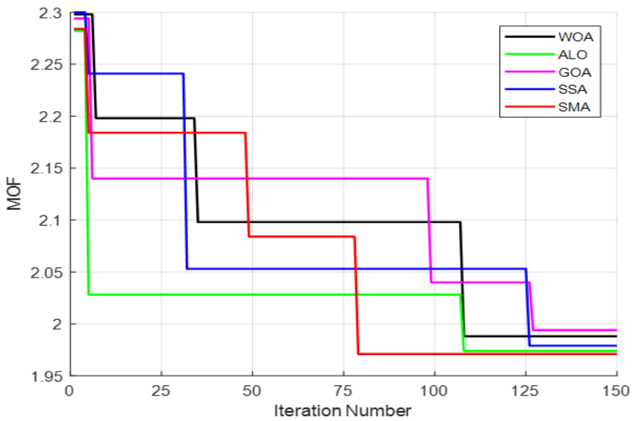
It is obvious among all the applied optimization algorithms, that the SMA was the superior algorithm which showed good efficiency and performance in reaching the best results of MOF minimization until 2.088, 1.971 and 1.894 for the optimal allocation into RDN of all cases studied of one, two and three PVDG units respectively, performing with a quick convergence characteristic for all the cases of PVDG integration into RDN, where the SMA converged after 75 iterations.

Tables 1 and 2, illustrate the allocation of all the cases studied of optimal integration and the results obtained after that presence into RDN for all the applied algorithms.

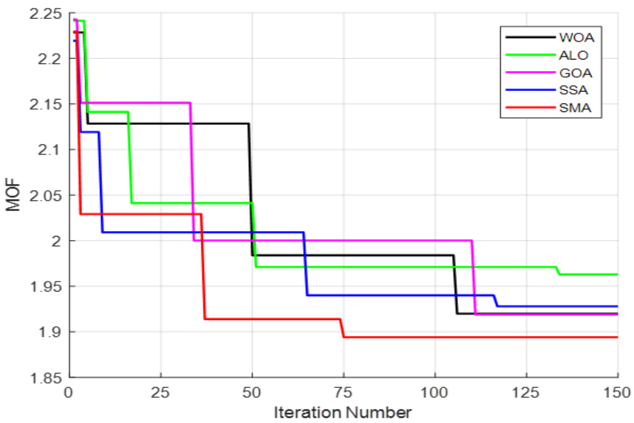
From tables 1 and 2, where is mentioned the results after applying of the various algorithms for the optimal allocation of the cases studied into test system RDN. It is clear among all of them, that the SMA provided the best minimization of the three technical indices simultaneously represented as MOF with values until 2.088, 1.971, and 1.894 for the three cases of one, two and three PVDG integration into RDN, respectively. The rest of the applied algorithms also showed a good efficiency in delivering some good results separately, as examples, the WOA provided the minimum of TAPL for the case of three PVDG until 80.391 kW, the GOA provided the minimum of TOT for the case of two PVDG units until 20.286 seconds.



(a)



(b)



(c)

Fig. 2 Convergence curves of applied optimization algorithms: a) One PVDG, b) Two PVDG, c) Three PVDG.

Table 1 Optimal allocation of the studied cases of PVDG units.

Algorithms Applied	PVDG Number	PVDG Buses	P_{PVDG} (MW)
WOA	1 PVDG	6	2.890
	2 PVDG	12 – 28	1.004 – 1.510
	3 PVDG	12 – 24 – 28	1.069 – 1.035 – 1.349
ALO	1 PVDG	26	2.865
	2 PVDG	12 – 28	1.071 – 1.590
	3 PVDG	5 – 11 – 29	1.500 – 0.937 – 1.062
GOA	1 PVDG	26	2.866
	2 PVDG	12 – 28	0.991 – 1.7597
	3 PVDG	5 – 10 – 29	1.5000 – 0.9337 – 1.083
SSA	1 PVDG	27	2.870
	2 PVDG	12 – 27	1.011 – 1.800
	3 PVDG	5 – 12 – 28	1.204 – 0.923 – 1.287
SMA	1 PVDG	27	2.877
	2 PVDG	12 – 27	0.932 – 2.000
	3 PVDG	5 – 13 – 30	1.557 – 0.787 – 1.077

Table 2 Optimized parameters with PVDG integration.

Algorithms Applied	PVDG Number	TAPL (kW)	TVD (kV)	TOT (sec)	MOF
Basic Case	---	210.987	22.939	20.574	---
WOA	1 PVDG	112.251	13.077	20.363	2.109
	2 PVDG	91.622	12.356	20.303	1.988
	3 PVDG	80.391	12.077	20.281	1.920
ALO	1 PVDG	115.490	13.039	20.359	2.104
	2 PVDG	94.170	12.444	20.288	1.974
	3 PVDG	87.094	11.887	20.279	1.963
GOA	1 PVDG	115.491	13.027	20.359	2.103
	2 PVDG	95.870	12.394	20.286	1.994
	3 PVDG	87.644	11.925	20.281	1.919
SSA	1 PVDG	121.030	12.963	20.354	2.108
	2 PVDG	95.660	12.267	20.292	1.979
	3 PVDG	89.775	11.887	20.278	1.928
SMA	1 PVDG	121.181	11.887	20.353	2.088
	2 PVDG	96.865	12.178	20.288	1.971
	3 PVDG	83.780	11.761	20.279	1.894

Figure 3 illustrates the bus voltage profiles results after applying SMA for all cases studied of PVDG integration into RDN.

The curves illustrated in figure 3 based on using the metaheuristic optimization algorithm of SMA confirm its efficiency and reliability in providing the best results that led to the ameliorating of the voltage profiles after integrating all cases of PVDG units into RDN, while this enhancement was associated to the minimization of voltage deviation, as long as it indicates the value of RDN's voltage and how much it is far from the nominal voltage value of 12.66 kV. Besides, noticing much better results from the case of three PVDG units, due to the optimal allocation of the multiple PVDG with the sizes of 1.5570 MW, 0.7878 MW and 1.0778 MW in buses 5, 13 and 30 of RDN, respectively.

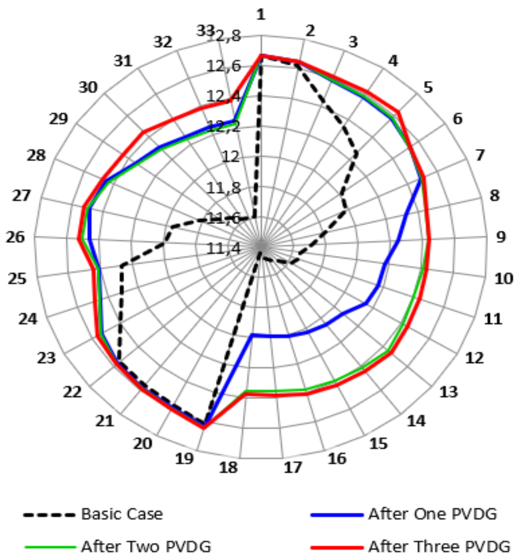


Fig. 3 Bus voltage profiles for all cases studies.

Figure 4 shows the bus voltage deviation after applying the SMA for all cases studied of PVDG integration into test system RDN.

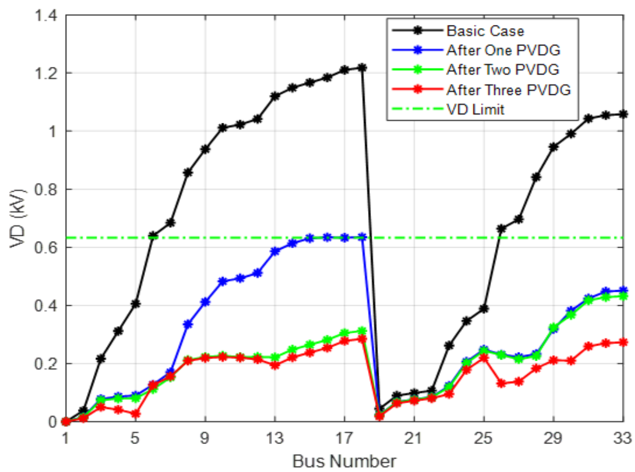


Fig. 4 Bus voltage diviation for all cases studied.

From figure 4, applying of the SMA on the test system RDN occurs the minimization of the total bus voltage deviation from 22.939 kV until 11.887 kV, 12.178 kV and 11.761 kV for the integration of one, two and three PVDG units in RDN, respectively, with much superior and better results for the case of three PVDG unit integrating into RDN when taking into consideration a minimum limit of voltage deviation equal to 5 % (0.633 kV). The bus voltage deviation's minimization consequently led to the improvement of the voltage profiles in all test system's buses as mentioned previously in figure 3 if the voltage deviation is known as the nominal voltage value of 12.66 kV minus its voltage value at the basic case.

Figure 5 represents the branch power loss by applying the SMA for all cases studied.

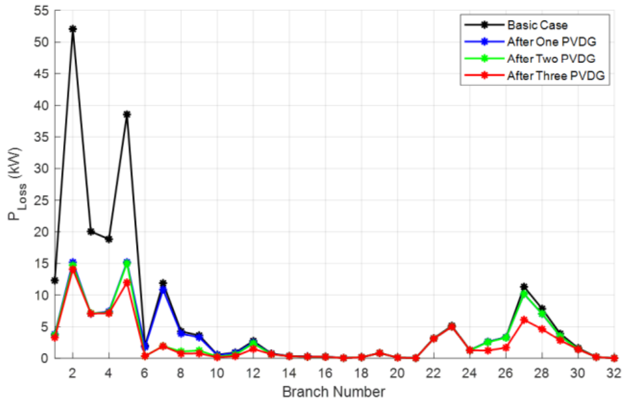


Fig. 5 Branch power loss for all cases studied.

The second parameter of MOF, which is minimized based on using the SMA, is the active power losses, where it is clearly got reduced in all the system branches after the optimal integration of all cases studied of PVDG units. Besides, the TAPL were clearly minimized from the total value at the basic case of 210.980 kW until 121.181 kW, 96.856 kW and 83.780 kW for studied cases of one, two, and three PVDG units respectively, with noticing superior and best results from the case of three PVDG units' integration into RDN.

Figure 6 demonstrates the OCR's operation time after applying SMA for all cases.

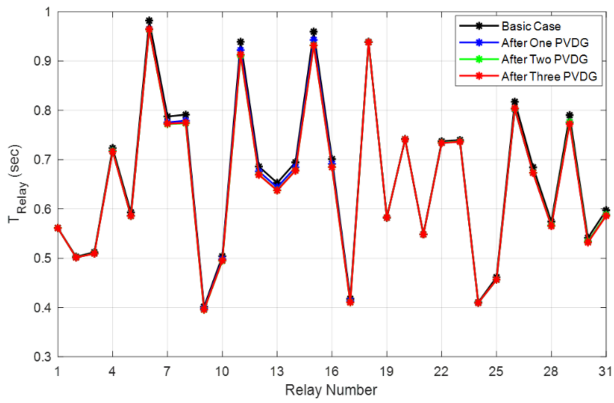


Fig. 6 Overcurrent relay operation time for all cases studied.

The last MOF parameter, which is minimized using the SMA, based on the optimal allocation of all cases studied, is the OCR's operation time. It is obviously got reduced almost in all the primary OCRs, also from a total value at the basic case of 20.570 seconds until 20.353 seconds, 20.288 seconds, and 20.279 seconds for one, two and three PVDG units respectively, with much better results and clear impact after the optimal integration for case of three PVDG units.

For reason that the operation time of the OCRs is related and associated proportionally to the level of fault current that may occur in system's lines, this minimization represents a result of the voltage profiles improvement which also raised the level of the fault current as mentioned in the previous equations (10) and (11). That minimization of the TOT provided wide economical and technical benefits to the studied system.

Figure 7 illustrates the graphical comparison for power losses (active and reactive) with inclusion of the minimum bus voltage value after PVDG integration into test system RDN.

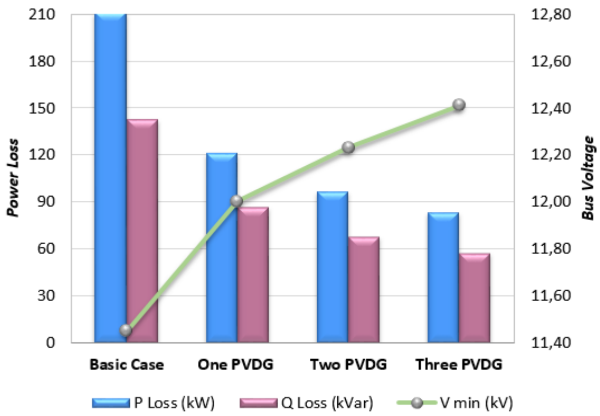


Fig. 7 Comparison the power losses and minimum bus voltage.

The analysis of figure 7 reveals that the minimum voltage's value of the RDN kept increasing proportionally while active and reactive power losses were being minimized after the optimal integration for all studied cases of PVDG units into RDN. It is also noticed that the best results of V_{min} raising, total active power loss and total reactive power loss minimization were achieved when optimally integrating the case of three PVDG units into RDN.

Injecting three sizes of active powers at three different locations of the test system RDN, was the reason that those best results of minimizing the TAPL and TRPL until 83.780 kW and 57.570 kVar respectively, were being achieved, including a better minimum voltage value equal 12.402 kV.

5. CONCLUSION

In this paper, a study of comparison was carried out between the recent optimization algorithms to find a solution to the problem of identifying the optimal allocation of all PVDG units' cases into the radial distribution network by minimizing simultaneously the technical parameters of TVD, TAPL and TOT of the overcurrent relays.

The results proved the robustness and efficiency of the SMA approach which delivered the best MOF's minimization of with quick convergence characteristics. The rest of the algorithms also showed good effectiveness and provided suitable results but in terms of each parameter on its own.

In addition, when comparing the results provided by the SMA, the case of three PVDG units was the best choice, which led to simultaneously reducing active power losses, ameliorating of system voltage profiles and enhancement of the protection system against fault current. Basing on the previous discussion, the next work will focus on testing other recent optimization algorithms to solve a more complex MOF that gathered various technical and economic indices.

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