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Penalty factor-based optimization algorithm for distributed generation sizing in distribution network

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Abstract: The installation of distributed generation (DG) can be used to minimize the total power loss in the distribution network. Besides that, other power system performances such as voltage profile, stability index, and total harmonic distortion can also be improved via DG. Although many works on DG have been done, most researchers have assumed that the distribution line is in an ideal condition (unlimited capacity limit). On the contrary, all practical lines should have their own capacity limit. Therefore, the main contribution of this paper is to determine the optimal DG output that can fulfill the maximum allowable line capacity limit (MALCL). Furthermore, a penalty factor in rank evolutionary particle swarm optimization analysis is also proposed to handle the constraint. A 33-bus distribution system is used as a test system to investigate the performance of the optimization technique. The results showed that the line capacity increment caused by optimal DG output is always less than the MALCL value. Furthermore, the total power loss value in the system is increased when the MALCL set by utility is reduced. In terms of optimization performance, the proposed algorithm gives faster computing time and consistent results compared to conventional particle swarm optimization.

Key words: Distributed generator, distribution network, line capacity limit, power loss reduction, rank evolutionary particle swarm optimization

1. Introduction

Recently, there has been growing interest in the implementation of distributed generation (DG) among researchers. The implementation of distributed generators in the distribution system can potentially improve the overall performance of the system. With the optimal configuration of the DG, the power loss in the distribution system, in particular, can be minimized. The main factor that allows the DG to reduce power loss in the system is the fact that the DG is normally located near the load area. For a passive network (without DG), the total power consumption in the distribution network is solely supplied by the grid. If the load located at the end of the distribution feeder is bigger, the current that flows in the entire feeder (from transmission-distribution substation to the load location) will be high, which consequently affects the total power loss (I^2R). The situation worsens when the R/X ratio in the distribution system is also high.

On the contrary, with the presence of DG, some of the required power demand can be supplied by the DG units. This can significantly reduce the amount of power that needs to be supplied by the grid. This is the main reason why many researchers have applied optimization methods to obtain the optimal DG output, such as by using particle swarm optimization (PSO) [1,2], evolutionary programming [3,4], the artificial bee colony

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algorithm [5], and the artificial immune system algorithm [6], to reduce the total power loss in the network, either for a single DG unit [7,8] or using multiple DG units [9,10]. Furthermore, the analysis of DG is not only limited to the optimal DG output. Various studies related to DG have also been conducted to fully utilize the benefit of DG implementation, such as on the optimal DG location [1,7], on the effects on the protection system [11–13] and power system economics [14,15], on minimizing total harmonic distortion (THD) [16,17], and others.

The works of Mouti et al. [5] and Hengsritawat et al. [18] are examples of studies on the optimal DG location and size optimization. In their analyses, these authors considered different modes of DG units in the system. Their studies concluded that a different mode of DG affects the optimal location and power loss value. The THD factor can also be incorporated into DG analysis [16,17]. By presenting the load in the system as a harmonic distribution load, the optimal DG output that reduces the power loss and THD value can be determined. Both papers used the weight summation approach to handle the multiobjective optimization problem. Furthermore, investigation of the effects of DG from an economic perspective was done by Moshtagh et al. [19]. They considered the cost of electricity on the consumer side during optimal DG analysis. Since the implementation of DG units will indirectly affect the amount of payment needed to be made by the electricity user, it is important to have suitable DG size, which can give the lowest electricity cost. With this factor, the benefit from DG installation can be experienced by the consumers.

On the other hand, the line capacity limit issue is highlighted in this research. With the installation of DG into the system, the direction and amount of the current flow in the system will be changed. The changes may cause some of the lines in the network to exceed their capacity limit. This factor, however, has been ignored by many researchers, with the assumption that the distribution line is in an ideal condition (unlimited capacity limit). Hence, the relationships between optimal DG output, capacity limit, and power loss value will be investigated thoroughly. By analyzing the unlimited capacity condition, the amount of capacity increments in the system is identified. The value of allowable capacity increment limit is varied to see its impact on the power loss. Thus, by fulfilling the limitation of the maximum allowable line capacity limit (MALCL), system collapse due to the DG installation can be avoided. A modification of the existing rank evolutionary particle swarm optimization (REPSO) [20] will be introduced in this study to handle the MALCL constraint. This paper is organized as follows. Section 2 presents the problem formulations with the list of constraints used in this study. Section 3 introduces the REPSO methods with a new penalty factor (PF) implementation to handle the capacity limit constraint. Section 4 describes the impacts of line capacity limit on the power system as well as the performance of the REPSO method in solving the optimization problem. In the last section, the conclusion of the presented work is presented.

2. Problem formulation

The main objective in this study is to obtain the minimum active power losses due to different DG connections, considering the MALCL. The total power loss in the system is obtained using the well-known power loss equation, as shown in Eq. (1):

$$P_{losses} = \sum_{L=1}^{n} |I_L^2| R_L, \tag{1}$$

where:

L = Number of lines in the system.

n = Total number of lines in the system.

I_L = Line current.

R_L = Line resistance.

Furthermore, some constraints have also been included to ensure that the results of the DG output do not affect the security of the existing system. The constraints are listed as follows:

(a) DG operation constraint

All DG units are only allowed to operate within the acceptable limit. P_{DG}^{min} and P_{DG}^{max} are the lower and upper bounds of the DG output. The enforcement technique is used in the optimization analysis if the DG is beyond the range during the updating process.

$$P_{DG}^{\min} \leq P_{DG\_operate} \leq P_{DG}^{\max} \quad (2)$$

(b) Power injection constraint

In order to avoid the power injection to the substation, the total power output from the DG unit must be less than the summation of total load and power loss. With this constraint, no excessive power would be injected into the substation.

$$\sum_{m=1}^{k} P_{DG\_m} < P_{Load} + P_{Losses}, \quad (3)$$

where:

k = Number of DG units.

m = Number of DG units in the system.

(c) Power balance constraint

The total power generated in the network, which is from the DG unit and substation, must be equal to the summation of total load and the total power losses.

$$\sum_{m=1}^{k} P_{DG\_m} + P_{Substation} = P_{Load} + P_{Losses} \quad (4)$$

(d) Voltage bus constraint

The voltage value for all buses in the network must be within the acceptable limit. The allowable voltage variant is $\pm 5\%$ from the rated voltage value.

$$0.95p.u \leq V_{operate\_n} \leq 1.05p.u, \quad (5)$$

where:

n = Number of buses in the system.

(e) Line capacity increment (LCI) and MALCL

The LCI in the distribution network refers to the current increment in the line after the DG connection, given by Eq. (6).

$$LCI_i = \frac{I_{new(withDG)\_i} - I_{initial\_i}}{I_{initial\_i}} \times 100\%, \quad (6)$$

where:

I = Line current.

i = Line number.

3. REPSO with PF implementation

REPSO is implemented in this study to solve the optimal DG output considering the LCI limit. REPSO is the hybridization of evolutionary programming (EP) and PSO, with the objective of achieving faster and accurate solutions [20]. The same REPSO algorithm is used in this research. However, REPSO is implemented with a PF to handle certain constraints. Figure 1 shows an illustration of particles' movement in REPSO. In the original PSO, no comparison is done after the particle has been updated (Figures 1a and 1b). However, in REPSO, the previous and current populations' particles are combined and several particles that provide the best solution will be forwarded (selected) to the next iteration (Figure 1c). The main difference between REPSO and the original PSO is the combination and selection process, which is simulated from the EP algorithm (Figure 2, Step 5).

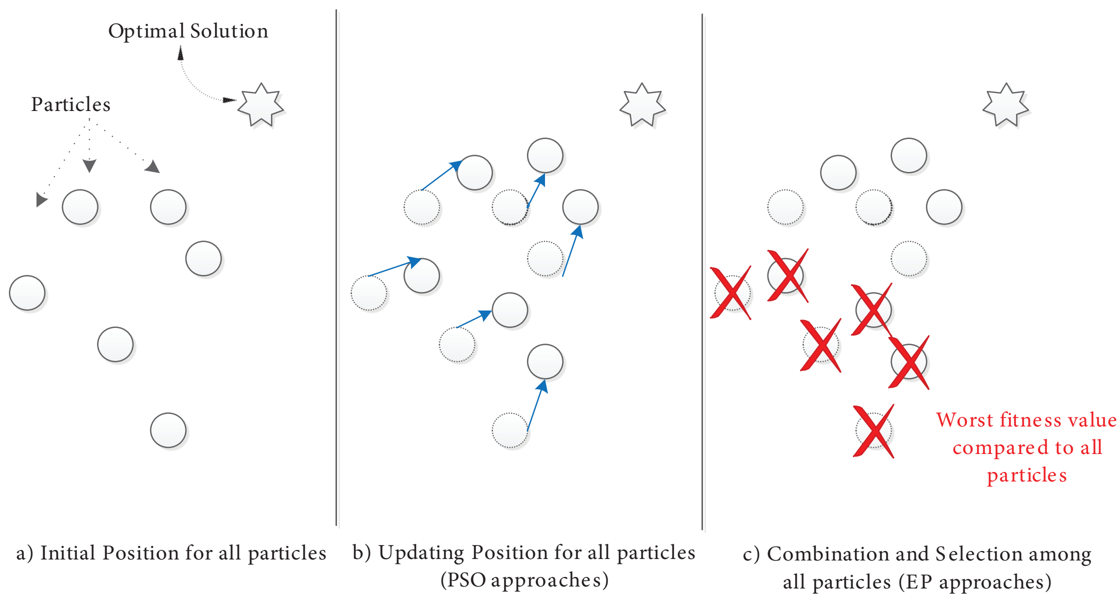

Figure 1. Illustration of REPSO algorithm in searching for the optimal solution.

The power loss in the network is greatly influenced by the DG output. Therefore, it is crucial to find the optimum DG output, so that the power loss is minimized. To apply the REPSO algorithm for this purpose, the DG output is selected as a variable (particle – "x_i") and the power loss as an objective function (fitness value – "y_i"). A set of initial DG outputs is determined randomly and is included in the bus data. Power flow analysis is performed to get the power loss, which is configured as one of the objective functions (y), and the voltage profile.

Next, all the constraints discussed in the previous section are also checked, as shown in Figure 2 (Step 1). The filtering process has increased the searching ability of REPSO in determining the optimal results. Besides that, most of the parameters will be restricted within the constraints during the updating process, except for the line capacity limit. Thus, the concept of PF is used to overcome the line capacity limit constraint in the optimization analysis. Although the PF is not a new technique (perhaps the Pareto method is another possible solution), it has helped REPSO to get the solution and fulfill the constraint.

Step 1	Randomize *N* number of *DG outputs* (particle - x_i).

Initialization	Check whether the random number fulfils **ALL constraints** or not.
	If yes **then**
	Save the *DG output*
	else
	Delete and rerandomize *new DG output*
	end if

Step 2	Calculate the *Power Loss* (fitness value - y_i) for successful *DG output*
Step 3	Determine the G_{best} and P_{best}, based on the y_i value and calculate velocity value (v_i).

Step 4	Find the *new DG outputs* (x_i^{new})
	Check the x_i^{new}
	if $x_i^{new} < x_{max}$ **or** $x_i^{new} > x_{min}$ **then**
	Calculate the *line capacity increment (LCI)* value
	if x_i^{new} cause *LCI* exceeded *MALCL* value
	$y_i^{new} = y_i^{new}$ + **Penalty Factor (PF)**
	else
	Proceed with the x_i^{new} and y_i^{new}
	end
	else
	Assigned the $x_i^{new} = x_{max}$ for $x_i^{new} > x_{max}$
	Assigned the $x_i^{new} = x_{min}$ for $x_i^{new} < x_{min}$
	end if

Step 5	**Combined** the previous population (x) with the new population (x^{new})
EP	**Sort** the population based on the y value (Best to Worst) **Select** the top N - "x" as the successful population

Step 6	Check the stopping criteria
	If all populations give similar results **then**
	Stop and show the optimal results
	else if iteration number>iter max **then**
	Stop and show the optimal results
	else
	Continue to **Step 4**
	end

Figure 2. Pseudocode of REPSO with PF implementation.

By adding the PF in the fitness value as shown in Step 4, the particles that exceed the capacity limit are omitted as unwanted solutions (will not be assigned as local best (P_{best}) or global best (G_{best})). However, the PF value must be large enough for REPSO to recognize the "unwanted" solution. For example, if the fitness value is in the range of tens (10–99), the PF value can be assigned to 1000 or larger. The performance of REPSO after the implementation of the PF is discussed in the next section.

4. Results and discussion

The proposed PF for the optimization algorithm (REPSO) is tested on a modified 33-bus radial distribution network (Appendix). The following results can be observed.

4.1. Impacts on line capacity limit

In the modified 33-bus distribution network, the active load on each bus has been increased by 100% to show the usefulness of inserting the LCI limit as a constraint in the optimization analysis. Other parameters such as the reactive power load, line parameter, base voltage, and base power remain the same as in [21]. The initial power loss in the system without any DG unit is 686.5 kW.

From Figure 3, the locations of DG units are assumed at bus 6, bus 16, and bus 25 due to some constraints such as the availability of energy resources and geographical restrictions. Table 1 shows the outcome of the REPSO algorithm with and without consideration of the MALCL in the analysis. From the results, it can be observed that without consideration of MALCL, the optimal DG output for DG_1, DG_2, and DG_3 is 3.4536 MW, 1.0799 MW, and 1.5459 MW, respectively. The power loss in the system has been reduced to 86.707 kW (87.4% reduction). However, this combination of DG output yields 34.01% of LCI in the system. Thus, for a heavily loaded network condition, the 34.01% LCI increment can cause the system to collapse. Therefore, most utilities have set the maximum capacity increment that is allowed after the DG connection.

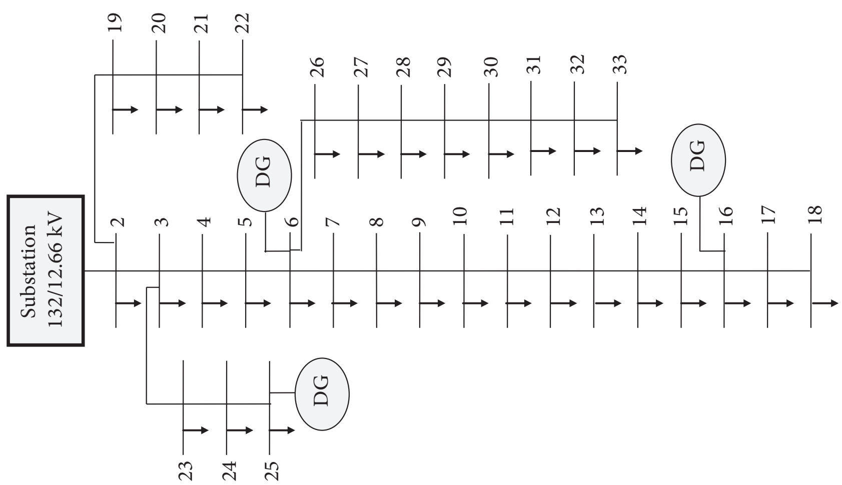

Figure 3. The 33-bus radial distribution system with the existence of DG units in PV mode.

Table 1. Comparisons of results for different cases.

MALCL	DG_1 (MW)	DG_2 (MW)	DG_3 (MW)	Power losses	LCI (%)
WL	3.45364	1.07999	1.54590	86.70721	34.0085
33%	3.45747	1.07252	1.53425	86.72134	32.9624
30%	3.45788	1.04893	1.58870	86.89314	30.0000
28%	3.53205	1.03147	1.54546	87.28062	28.0000
25%	3.50091	1.00183	1.51213	87.41875	25.0000
23%	3.58888	0.97836	1.52572	87.72853	23.0000
20%	3.57083	0.92984	1.58023	88.91643	20.0000

MALCL: Maximum allowable line capacity limit (constraint).
WL: Without limit.
LCI: Line capacity increment in the network (actual amount in network).

By using the proposed algorithm, the optimum DG output considering the MALCL, which is set by the utility, can be determined. From Table 1, it can be observed that the maximum LCI value that appeared in the system for all cases is less than or equal to the MALCL. By adjusting the output of the DG unit, the magnitude of current flow in the lines changes. At the same time, it will change the LCI value in the system. Figure 4 shows an example of line current results with and without considering the MALCL (set to 30%).

The LCI value for all lines after the DG has operated at the optimal value is shown in Figure 5 (for MALCL = 30%). The negative results in the figure show the reduction of current flow in the line due to the DG operation. Most of the lines operated below the initial capacity value, except line 15–16, which has the LCI value of 29.9998% (≈30%). From this figure, it is proven that the inclusion of a PF can ensure that the LCI value in the system is always lower than the MALCL setting. In summary, the output from DG units can be fully utilized in the system for unlimited capacity of lines. However, in practical systems, there is always a certain line capacity limit during the system operation. Therefore, for a network that requires the LCI limitation, the inclusion of line capacity limit as a PF in REPSO can give optimal DG output that fulfils the MALCL condition.

4.2. Impact on line losses

Figure 6 shows the relationship between power loss and LCI value in the system when the MALCL is considered. From the figure, it can be seen that the power loss in the system increases exponentially when the LCI decreases. The highest power loss increment of 88.92 kW occurred when the MALCL is limited to 20% (2.55% higher than the case without limitation on MALCL). However, the power loss is still less than the case without DG analysis (686.5 kW). Thus, the installation and optimal operation of DG can reduce the power loss in the system, even when the MALCL is considered.

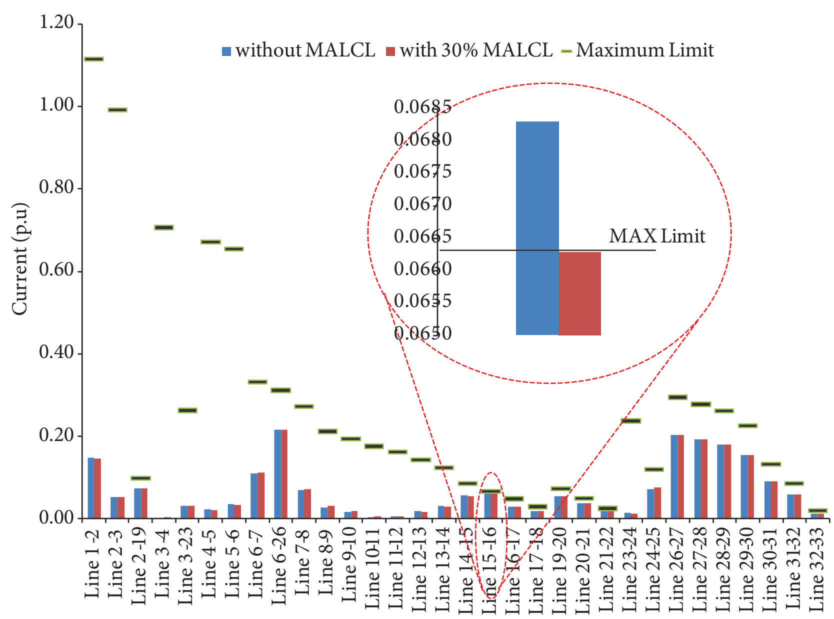

Figure 4. Comparison current flow with and without considering MALCL.

4.3. Impact on voltage profile

The implementation of MALCL in the analysis also influences the voltage profile of the network, as shown in Figure 7. It can be seen that the voltage profile of the system is improved when less burden exists on the line. For example, in the case of 20% MALCL, the voltage profile is better than when MALCL is considered as 23%. In summary, imposing the MALCL in the system increases the system stability; no line can cross the MALCL when DG is placed. Furthermore, the bus voltage in the system is also improved when the MALCL constraint is applied.

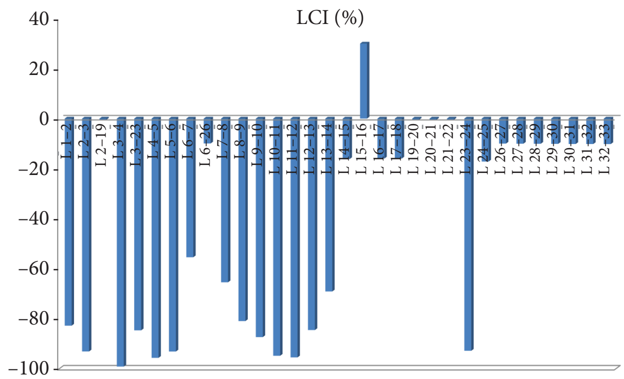

Figure 5. The LCI value for all lines in the system.

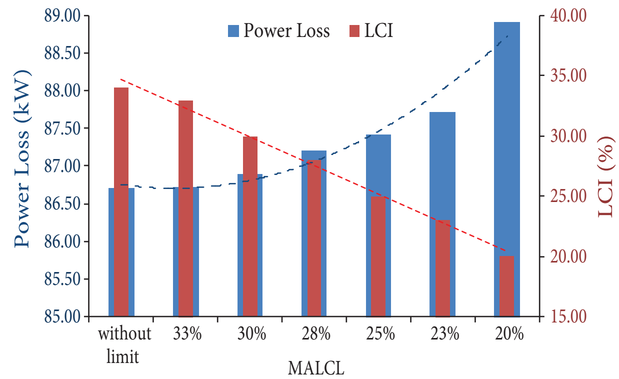

Figure 6. The power loss increment in the system due to MALCL constraint.

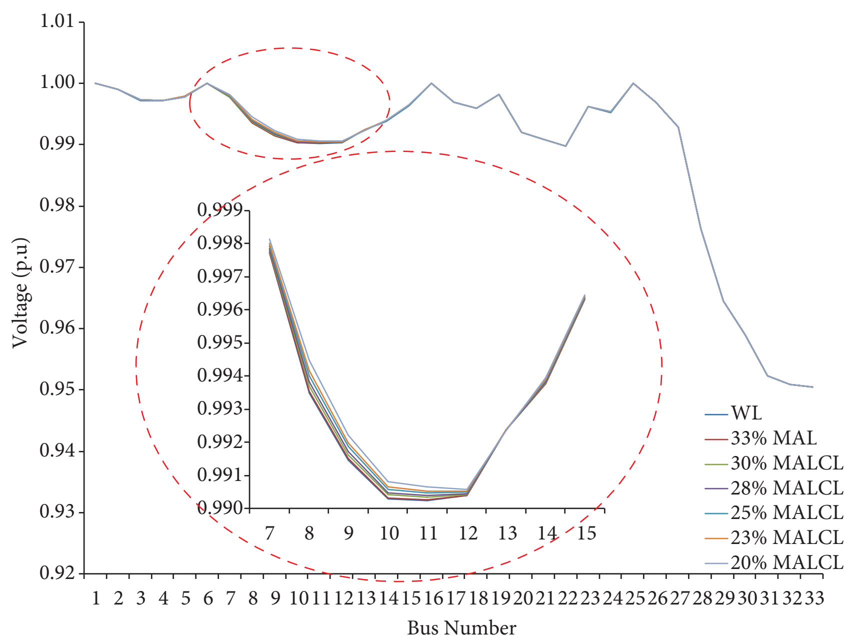

Figure 7. The voltage profile in the 33-bus system due to MALCL.

4.4. Validating REPSO performance with PSO

Table 2 shows the comparison of REPSO and PSO performance in solving the DG output when the MALCL is set to 28%. In order to make a fair comparison, the parameters for REPSO and PSO are set to be similar. The values for number of particles is set to 20 ($N = 20$) and the cognitive and social coefficient is 1.4 ($c_1 = c_2 = 1.4$). From the results, the REPSO algorithm is capable of giving a lower standard deviation (SD) value compared to the PSO algorithm. This means that REPSO provided consistent results in 10 analyses compared to PSO. Besides that, the REPSO also give the smallest power loss value, smallest minimum and maximum iteration, and smallest average computing time.

Table 2. Summary of results for case 2.

Performance in 10 trials with different random values	PSO	REPSO
Best	87.28066	87.28062
Worst	87.28570	87.28529
Average	87.28175	87.28158
SD	0.001462	0.001408
Min iteration	103	66
Max iteration	177	101
Average computing (s)/ complete process	242.1	201.1

The speed of REPSO in solving the optimization can also be seen from the convergence curve. By taking the “best” result that is achieved by REPSO and PSO in Table 2, the convergence curve for both results is shown in Figure 8. Although PSO reached the lower power loss value earlier than REPSO (at iteration 36), REPSO is capable of giving the minimum and converged result at iteration 66, before PSO does. This is due to the EP concept (combination, ranking, and selection) in REPSO. Thus, it is proven that REPSO can give faster solutions to obtain the optimal DG output considering the LCI limit in the analysis.

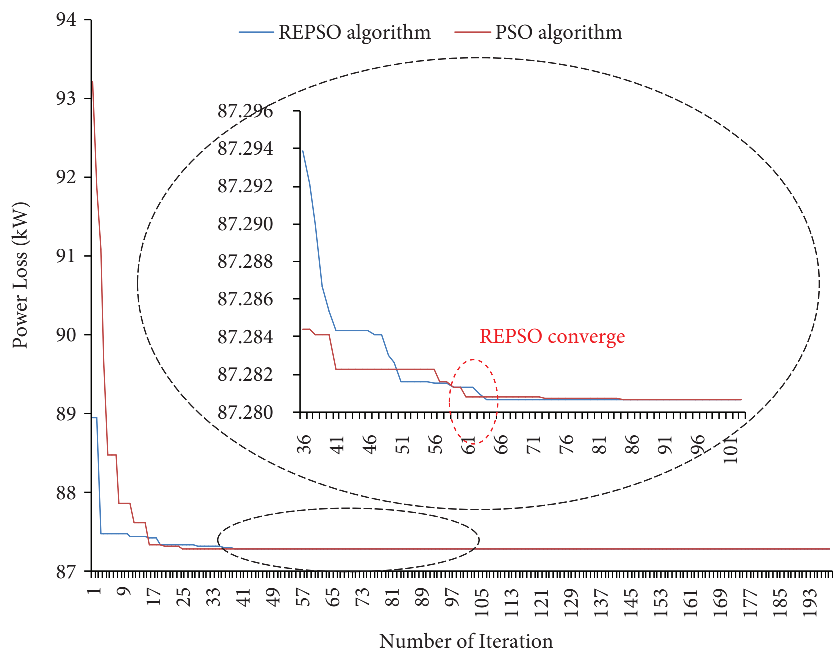

Figure 8. Comparison of convergence curves for PSO and REPSO.

5. Conclusion

A new PF-based REPSO is proposed in this study to fulfill the requirement of the MALCL. This strategy is useful in determining a suitable DG output considering the maximum LCI. From the results, it was found that in the process of fulfilling the MALCL, the power losses in the system increased. However, the implementation of the MALCL improved the voltage profile of the system. Furthermore, with the implementation of a PF, REPSO can ensure that the DG output will not cause any line to be overloaded. Comparing it with the conventional

PSO performance, REPSO gives consistent results, fast computing time, and lowest iteration number and power loss value. In conclusion, the implementation of the proposed technique should be considered to avoid power outage in the system.

Acknowledgment

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Appendix. Modified 33-bus system load data.

Bus	P-load (MW)	Q-load (MW)	P-gen (MW)	Q-gen (MW)
2	0.2	0.06	0	0
3	0.18	0.04	0	0
4	0.24	0.08	0	0
5	0.12	0.03	0	0
6	0.12	0.02	0	0
7	0.4	0.1	0	0
8	0.4	0.1	0	0
9	0.12	0.02	0	0
10	0.12	0.02	0	0
11	0.09	0.03	0	0
12	0.12	0.035	0	0
13	0.12	0.035	0	0
14	0.24	0.08	0	0
15	0.12	0.01	0	0
16	0.12	0.02	0	0
17	0.12	0.02	0	0
18	0.18	0.04	0	0
19	0.18	0.04	0	0
20	0.18	0.04	0	0
21	0.18	0.04	0	0
22	0.18	0.04	0	0
23	0.18	0.05	0	0
24	0.84	0.2	0	0
25	0.84	0.2	0	0
26	0.12	0.025	0	0
27	0.12	0.025	0	0
28	0.12	0.02	0	0
29	0.24	0.07	0	0
30	0.4	0.6	0	0
31	0.3	0.07	0	0
32	0.42	0.1	0	0
33	0.12	0.04	0	0