

# STEADY STATE OPTIMAL LOAD SHEDDING USING PARTICLE SWARM OPTIMIZATION

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## Abstract

Power systems experience active and reactive power shortages when a significant plant fails to generate power. It is essential to maintain a supply-demand balance when there is no alternative to bring power from a tie line grid other than the power source available. Otherwise, the system may face under-voltage and under-frequency, leading to cascading failure to eventual blackout. Load shedding is a crucial strategy to maintain supply-demand balance to mitigate such problems. The traditional method of load shedding failed to leverage an optimized approach, leading to suboptimal performance. This study investigates optimized load shedding that uses the Particle Swarm Optimization algorithm to shed load optimally and allocate available power, adhering to system operational constraints. The IEEE 14 bus test system is used for the study, where the generational loss case is explored. Simulation results demonstrated that, for 26.20% of the generational deficit, the proposed approach was able to shed 67.62 MW of total load, improving the voltage profile of load buses. The applied method is compared with the existing heuristic-IHS method to validate the findings.

**Keywords:** Optimal load shedding, Particle swarm optimization, Contingency, Power system stability

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## 1. Introduction

Electrical power delivery plays an instrumental role in keeping the country's economy running. In the event of a contingency, it is essential to deliver power smoothly, keeping the system within operational constraints for societal, industrial, and economic benefits. Contingency refers to events such as transmission failures, generation failures, and maintenance shutdowns. Such events lead to a supply-demand mismatch that perturbs the system's operational constraints, triggering cascading tripping and eventually leading to a blackout (Mageshvaran and Jayabarathi, 2015a). To overcome such problems, load shedding is an effective strategy for balancing generated and consumed power. Traditional load shedding approaches, such as under-frequency and under-voltage, often lacked optimization, leading to suboptimal performance. Conventional load-shedding techniques tend to be reactive, cutting off power to arbitrary loads to reduce grid stress. In contrast, optimized

load shedding strategies focus on preserving essential loads and decreasing disruptions through methodical load curtailment. Traditional strategy can result in outages affecting crucial infrastructure and financial losses from unpredictable power interruptions. Conversely, optimized techniques help sustain essential services while minimizing overall consequences.

For optimal load curtailment, (Mostafa et al., 1995) has formulated an expression that is the sum of the squares of the differences between the active and reactive powers. The active and reactive power demands are expressed using a voltage-dependent load model. In (Hajdu et al., 1968), systematic methods for reducing a power system's service interruption following a major fault were covered. In (Palaniswamy et al., 1985), the Second Order Gradient Technique (SOGT) was proposed to minimize load curtailment during a sudden major supply outage or tripping of tie-line breakers, taking into account the generator control effects as well as the voltage and frequency characteristics of loads during optimization.

In (Mostafa et al., 1996), the optimal load shedding technique with generator control effects, the voltage and frequency characteristics of loads were proposed, with

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power generation treated as a dependent variable in the dynamic problem formulation. The active and reactive powers of loads are assumed to be independent of bus voltages.

To address load shedding issues and reduce load loss, a sensitivity-based strategy has been proposed in (Subramanian, 1971). A weighted error criterion is used to provide varying priorities to loads in order to restrict the magnitude of the load being curtailed. The approach ignores operational and equipment constraints. (Mageshvaran and Jayabarathi, 2015a) suggested an enhanced Harmony Search method for curtailing the appropriate amount of load. In this case, the suggested approach outperformed traditional minimal-load-shedding optimization strategies.

The Artificial Bee Colony method was implemented in (Mageshvaran and Jayabarathi, 2015b). The optimization method provided allowed for a more rapid and comprehensive examination of promising regions of the search space, improved global search capabilities, and avoided premature convergence.

This study delves into the implementation of Particle Swarm Optimization (PSO) in the IEEE 14-bus test system under steady-state conditions to model generation loss and assess its efficacy in globally optimizing the amount of load to be shed. PSO was selected for the study because it seeks a global optimal solution by leveraging both the particle and swarm memory (Song and Gu, 2004).

The advantages of Particle Swarm Optimization are:

- PSO effectively addresses large-scale optimization problems due to its population-based strategy.
- PSO provides the ability to manage convergence speed and accuracy through parameters such as inertia weight, cognitive coefficient, and social coefficient.
- PSO is fundamentally straightforward to implement, requiring fewer parameters specific to algorithms to be set and adjusted in comparison to other methods.

The paper is organized as follows. Section II provides a system description and methodology. Here, a schematic of the IEEE 14 bus system and a flowchart describing the implementation of the PSO algorithm are provided. Results and concluding remarks are discussed in Sections III and IV, respectively.

## 2. Methodology

To model the load shedding problem, the IEEE 14-bus test system was selected. The analysis was performed in MATLAB on a PC equipped with an 11th Gen Intel Core i5 processor with 8 GB RAM. The IEEE 14-bus test system description is provided in Figure 1.

### 2.1. Problem Formulation

The mathematical formulation of the non-linear optimization problem for load shedding is detailed as follows

#### 2.1.1 Objective Function

The objective during emergency conditions is to minimize the difference between the connected load and the supplied power, subject to equality and inequality constraints (Mostafa et al., 1997):

$$F = \sum_{i=1}^{NB} [a_i(P_{di} - P'_{di})^2 + b_i(Q_{di} - Q'_{di})^2] \quad (1)$$

where  $F$  is the objective function,  $NB$  is the number of buses,  $P_{di}$  and  $Q_{di}$  are the active and reactive powers supplied to the load,  $P'_{di}$  and  $Q'_{di}$  are the connected active and reactive loads, and  $a_i$  and  $b_i$  are weighting factors.

#### 2.1.2 Equality Constraints

$$P(V) = P_{Gi} - P_{di}(V) - P_i(V, \delta) = 0 \quad (2)$$

$$Q(V) = Q_{Gi} - Q_{di}(V) - Q_i(V, \delta) = 0 \quad (3)$$

where  $P_{Gi}$  and  $Q_{Gi}$  are the active and reactive powers generated at bus  $i$ ,  $P_i(V, \delta)$  and  $Q_i(V, \delta)$  are the active and reactive power injections at bus  $i$  in terms of bus voltage magnitude  $V$  and phase angle  $\delta$ .

$$P_i(V, \delta) = V_i \sum_{j=1}^{NB} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (4)$$

$$Q_i(V, \delta) = V_i \sum_{j=1}^{NB} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (5)$$

where  $V_i$  and  $V_j$  are the voltage magnitudes at buses  $i$  and  $j$ ,  $Y_{ij}$  is the admittance between buses  $i$  and  $j$ , and  $\theta_{ij}$  is the admittance phase angle.

#### 2.1.3 Inequality Constraints

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad i = 1, \dots, NG \quad (6)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad i = 1, \dots, NG \quad (7)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i = 1, \dots, NB \quad (8)$$

where  $P_{Gi}^{min}$  and  $P_{Gi}^{max}$  are the minimum and maximum real power generations,  $Q_{Gi}^{min}$  and  $Q_{Gi}^{max}$  are the minimum and maximum reactive power generations,  $V_i^{min}$  and  $V_i^{max}$  are the minimum and maximum limits of bus voltages.

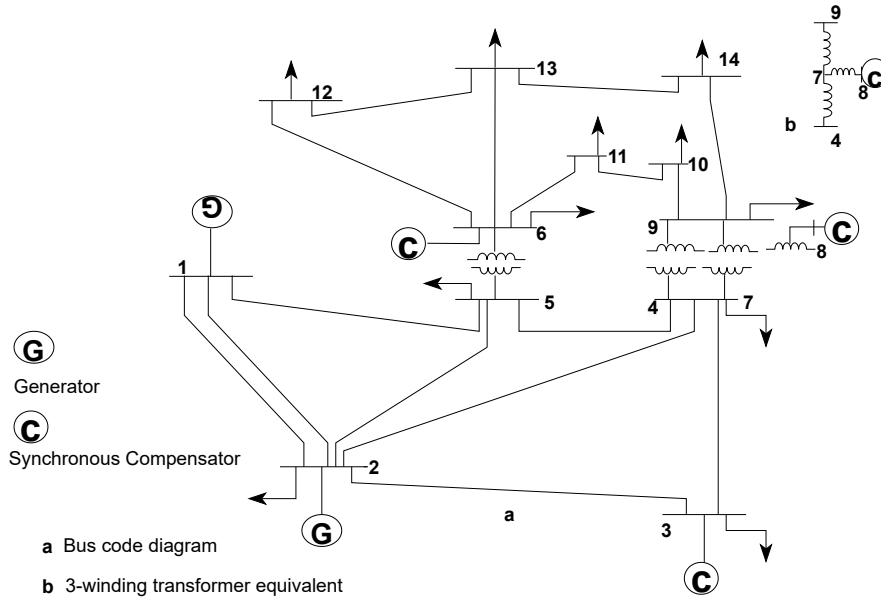


Figure 1. Schematic of IEEE 14 bus system, Source: (Freris and Sasson, 1968)

## 2.2. Algorithm For PSO In Load Shedding

The detailed application-specific implementation of PSO drawn from (He et al., 2009) is given below:-

- Initialize the swarm with N particles and define the load shedding problem, ensuring correct operational parameters. Particle position depends on the number of decision variables. At any iteration  $t$ , each particle  $i$  has its position  $\mathbf{p}_i^t$  and its flight velocity  $\mathbf{v}_i^t$ . For each particle, a fitness value  $f$  in line with its position  $\mathbf{p}_i^t$  could be calculated, and this value represents the quality of that particle's position. Particularly in the IEEE 14-bus system, at each bus, we have to shed two loads: active and reactive. Therefore, the particle's position vector size equals  $\mathbf{p} = 2 \times 14$ , which is initialized according to the load shedding limits.

$$\mathbf{p} = [P_{LS_1}, Q_{LS_1}, P_{LS_2}, Q_{LS_2}, \dots, P_{LS_N}, Q_{LS_N}]$$

where:

- $P_{LS_i}$ : Active power shed at bus  $i$ ,
- $Q_{LS_i}$ : Reactive power shed at bus  $i$ ,
- $N$ : Total number of buses with loads

### Constraints:

Constraints, for particular  $i$  bus, are governed by the criticality of the buses. In general, the amount of load shed is 20% to 80% of the total load demand of the bus, keeping 20% for emergency state (Mageshvaran and Jayabarathi, 2015a).

$$0.2P_{D_i} \leq P_{LS_i} \leq 0.8P_{D_i}$$

$$0.2Q_{D_i} \leq Q_{LS_i} \leq 0.8Q_{D_i}$$

where:

- $P_{D_i}$ : Total active power demand at bus  $i$ ,
- $Q_{D_i}$ : Total reactive power demand at bus  $i$

These constraints keep  $P_{LS_i}$  and  $Q_{LS_i}$  within acceptable boundary so that active  $P_{D_i}$  and reactive  $Q_{D_i}$  are not less than load shed amount at  $i$ .

For minimization problem, minimum the value of fitness is, better is the particle position.  $p_{best_i,t}$  is the best personal position of the particle and  $g_{best,t}$  is the best position of all the particles. That is,  $g_{best,t}$  is the previous best yield of  $p_{best_i,t}$ . For next iteration  $t$ , particle position and velocity can be calculated using the following equation:

$$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot r_1 \cdot (p_{best_i,t} - x_i(t)) + c_2 \cdot r_2 \cdot (g_{best,t} - x_i(t))$$

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

where  $w$  is the inertia weight;  $c_1$  and  $c_2$  are acceleration constants;  $r_1$  and  $r_2$  are uniform random number between (0,1). After position and velocity update, new personal and global best solution can be obtained using:

$$p_{best_i}^{t+1} = \begin{cases} p_{best_i}^{t+1}, & \text{if } f(x_i^{t+1}) > f(p_{best_i}^t) \\ x_i^{t+1}, & \text{if } f(x_i^{t+1}) \leq f(p_{best_i}^t) \end{cases}$$

$$g_{best}^{t+1} = best(p_{best_1}^{t+1}, p_{best_2}^{t+1}, \dots, p_{best_N}^{t+1})$$

There are several equality  $N_{eq}$  and inequality constraints  $N_{inq}$  that arises in problem formulation. It is necessary to

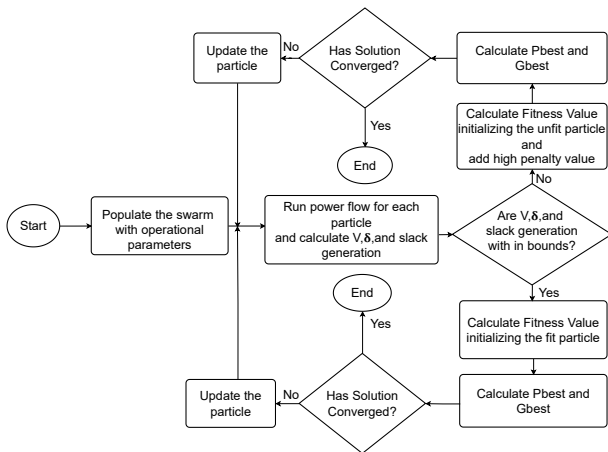


Figure 2. Flowchart describing implementation of PSO

satisfy these criteria. If the potential solution represented by the particle's position vector is not able to fulfill these constraints, then the fitness is penalized. In this way control variable will adjust itself to satisfy those constraints. For any optimization problem to be formed, it must have following structure:

$$\begin{aligned} &\min f(x) \\ &\text{subject to:} \\ &g_i(x) = 0, \quad i = 1, 2, \dots, N_{eq} \\ &h_j(x) \leq 0, \quad j = 1, 2, \dots, N_{inq} \end{aligned}$$

Problem having constraints can be transformed to problem without constraints using equation below:

$$\min f(x) + \sum_{i=1}^{N_{eq}} w_g \cdot g_i(x) + \sum_{j=1}^{N_{inq}} w_h \cdot \max(0, h_j(x))$$

where  $w_g$  and  $w_h$  are penalty factors which are of large value in case of minimization problem. Figure 2 describes how PSO was implemented for the given case.

### 2.3. Simulation Setup

Selection of input parameters like swarm size, number of iterations, cognitive coefficient, social coefficient, and inertia constant in PSO significantly shape the exploration and exploitation of search space for optimized values. PSO parameters applied in the study is provided in Table 1. The effectiveness of the selected parameter was validated through several independent runs that gave near to same results with low standard deviation. Incorrect selection of parameters can result in immature convergence, or solution being stuck either in local maxima or minima.

Table 1. Input Parameters For PSO

Parameters	Value
Swarm Size	12
Iteration	150
Inertia Weight	0.70
Cognitive Coefficient	1.5
Social Coefficient	1.5

Table 2. Loss of Generation

Case	Normal	Abnormal
Total Generation (MW)	270.99	270.99
Outage (MW)	0	71
Loss of Generation %	0	26.20

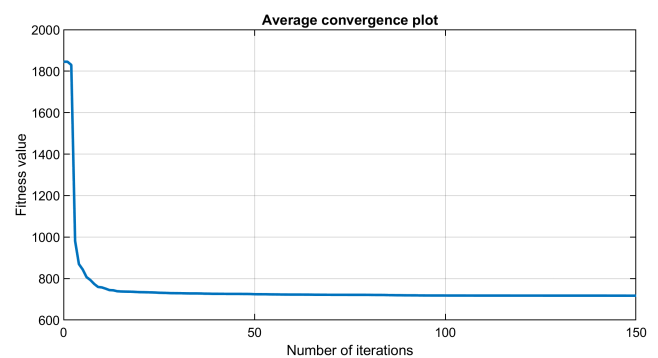


Figure 3. Average convergence characteristics of PSO under loss of generation 71MW

## 3. Results And Discussion

For analysis, generational deficit contingency was taken. Assumptions made in the study were as follows:

- The IEEE 14-bus system is considered a test case and is assumed to be in a steady-state condition.
- A static load model is used in a steady state condition.
- Maximum and Minimum bus voltage in each bus is in the limit of 1.1 pu and 0.95 pu, respectively.
- Equal priority is given to every bus.

### 3.1. Generational Contingency

In this case, the study created an outage of 71 MW in Bus 2 to examine the system supply-demand equilibrium before and after PSO-based load shedding and compared it with IHSA. Table 2 represents the total generation and loss of generation during normal and abnormal conditions, respectively.

The total connected load in the system is given by Table 3. The study used the GS method for load-flow calculations of the test system. The amounts of active and reactive power supplied are nearly the same as those provided by NR with VDLM (Mageshvaran and Jayabarathi, 2015a) after load

Table 3. Comparison of active and reactive power supplied under normal operating conditions for IEEE 14 bus test system

Bus	GS Method		NR with VDLM	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	0	0	0	0
2	21.7	12.7	21.971	12.859
3	94.2	19	94.20	19
4	47.8	-3.9	47.746	-3.896
5	7.6	1.6	7.614	1.603
6	11.2	7.5	11.20	7.5
7	0	0	0.0	0.0
8	0	0	0.0	0.0
9	29.5	16.6	29.668	16.132
10	9	5.8	8.789	5.664
11	3.5	1.8	3.458	1.778
12	6.1	1.6	6.088	1.597
13	13.5	5.8	13.45	5.778
14	14.9	5	14.617	4.905
<b>Total</b>	<b>259</b>	<b>73.5</b>	<b>258.801</b>	<b>72.920</b>

Table 4. Comparison of active and reactive power under normal operating conditions for the IEEE 14-bus system

Bus	GS: Normal Condition		NR with VDLM	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	199.9964	-8.7049	200.0	-16.5
2	71	34.4166	72.0	43.6
3	0	26.8258	0	25.1
6	0	21.3213	0	12.70
8	0	24.4007	0	17.6
<b>Total</b>	<b>270.9964</b>	<b>98.2595</b>	<b>272.0</b>	<b>82.50</b>

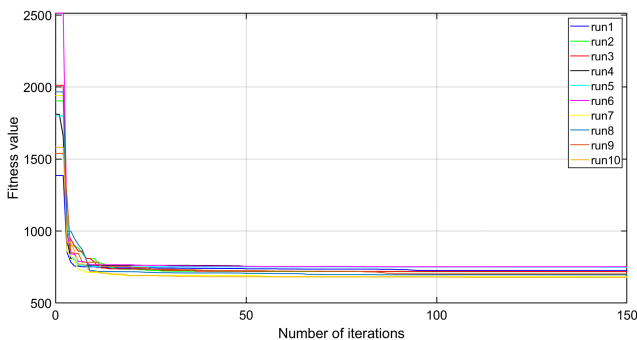


Figure 4. Convergence plot of 10 independent runs of the PSO algorithm under loss of generation 71MW

flow. The total connected load for the system is 259 MW, with active power generation of 270.9964 MW, using the GS method, as represented in Table 4. The bus voltage varied between 1.01 pu and 1.09 pu in the GS method, whereas it varied between 1.01 pu and 1.08 pu in NR with VDLM. The main aim of the study is to restore the system from an abnormal state to a normal state while minimizing the required load shedding. Table 5 shows the active and

Table 5. Comparison of active and reactive power supplied under abnormal operating conditions (loss of generation) for IEEE 14-bus system

Bus	PSO Method		IHSA	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	0	0	0	0
2	17.36	10.16	17.51	10.562
3	75.36	15.2	72.298	15.672
4	38.24	-3.066	32.25	-2.603
5	6.08	1.28	5.630	1.232
6	6.6384	6	7.462	5.994
7	0	0	0.0	0.0
8	0	0	0.0	0.683
9	23.6	13.28	20.276	11.930
10	1.8	4.634	7.543	4.217
11	0.7	1.44	2.682	1.842
12	1.485	1.28	4.576	1.138
13	8.188	4.64	12.041	4.874
14	11.92	4	11.081	3.914
<b>Total</b>	<b>191.3725</b>	<b>58.8480</b>	<b>192.51</b>	<b>59.41</b>

Table 6. Comparison of active and reactive power generation under abnormal operating conditions (loss of generation) for the IEEE 14-bus system

Bus	PSO		IHSA	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	199.9977	-13.6189	200.0	-16.5
2	0	39.0783	0	43.6
3	0	11.4621	0	25.1
6	0	9.2276	0	12.70
8	0	20.2917	0	17.6
<b>Total</b>	<b>199.9977</b>	<b>66.44</b>	<b>200</b>	<b>82.50</b>

Table 7. Comparison of active power (MW) losses under normal and abnormal operating conditions (loss of generation) for IEEE 14-bus system

Condition	PSO(MW)	IHSA(MW)
Normal	11.9964	13.2
Abnormal	8.624	7.49

reactive power supplied following the generational loss of 71MW, or 26.20% of normal generation, obtained from the proposed PSO method. The PSO method is compared with IHSA (Mageshvaran and Jayabarathi, 2015a). The amount of load shed obtained from the PSO method was 26.11% or 67.627MW of total connected load, i.e., 259MW. Whereas IHSA, following the generation loss of 72MW, or 26% of normal generation, was able to shed 66.5MW, or 25.676% of total connected load.

Table 6 compares the active and reactive power generation obtained by PSO and IHSA under abnormal operating conditions. It can be observed that, in PSO, Bus 1 generated 199.9977MW with 71 MW of generational loss, and, with 72

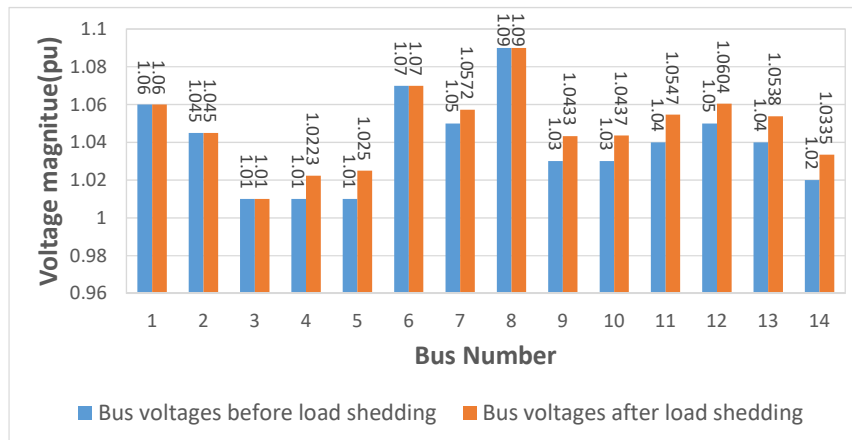


Figure 5. Bus voltages at normal conditions and after load shedding under loss of generation 71 MW for the IEEE 14-bus system

Table 8. Active and Reactive power to be shed at each bus due to loss of generation (using PSO)

Bus	P(MW)	Q(MVAR)
1	0	0
2	4.34	2.54
3	18.84	3.8
4	9.56	-0.833
5	1.52	0.32
6	4.561	1.5
7	0	0
8	0	0
9	5.9	3.32
10	7.2	1.165
11	2.8	0.36
12	4.614	0.32
13	5.311	1.16
14	2.98	1
<b>Total</b>	<b>67.627</b>	<b>14.651</b>

MW of generational loss, Bus 1 generated 200MW in IHSA. In both methods, Bus 1 generated power at its full capacity. Table 7 compares the active power losses at normal and abnormal states for the proposed PSO method and IHSA. Likewise, Table 8, obtained from PSO, shows the amounts of active and reactive power to be shed at each bus due to a 71MW loss of generation from Bus 2.

The average convergence characteristic of the PSO method is shown in Figure 3. The proposed method converged in 20 iterations, with a low standard deviation across different runs. The mean runtime to convergence was 21.01 seconds, including all particle power flow evaluations. To examine how the algorithm performed for a 71MW

generational loss, 10 independent runs were carried out. The convergence fell in the range of 10 to 30 iterations, Figure 4. This confirms the convergence credibility of PSO. The system voltage profile before and after load shedding using the PSO algorithm is shown in Figure 5. It can be observed that the voltage profile for load buses has improved. Take Bus 4, for example. Before load shedding, the bus voltage was 1.01 pu; after load shedding, it improved to 1.0223 pu.

#### 4. Conclusion

The study implemented the PSO algorithm to shed load optimally in the IEEE-14 bus system. The proposed method is compared with the existing heuristic, IHSA. Comparison is based on power supplied, power generated, system losses, and convergence. The results conclude that PSO can also be a helpful tool for optimization problems, given its simplicity in producing approximate optimized results. PSO produced near-optimal results with stable convergence, proper constraint handling, and a minimum convergence time of 21.01 seconds, compared with IHSA. Future work can focus on appropriate tuning of PSO input parameters, as optimized results depend on their selection, and most meta-heuristic approaches do not guarantee optimal results. Thus, sensitivity analysis of the results is also recommended in future work. It is also suggested to apply PSO in a larger system other than the IEEE 14 bus system and add load prioritization in every bus, rather than considering flat values, to make the problem formulation more realistic and practical.

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