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Minimization of load shedding by sequential use of linear programming and particle swarm optimization

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Abstract

Minimization of load shedding during contingency conditions is solved as an optimization problem. As a new topic, instead of local load shedding, total load shedding of a large power system is considered. Power generation rescheduling is considered to minimize the load shedding, as well. Different importance factors for buses are also considered. The linear programming method (LP) is used to solve this problem in a short period of time without considering some power system constraints. Particle swarm optimization (PSO) is also used to solve the problem by considering all power system constraints, but with a longer solving time. Finally, a new method, the sequential use of LP and PSO, is proposed, which is faster than PSO and considers all constraints. The IEEE 14 bus test system is used to compare the performance of the mentioned methods and a comparison of the proposed algorithm and genetic algorithm is accomplished.

Key Words: *Contingency, generation rescheduling, load shedding, linear programming, PSO*

1. Introduction

The emergency state may occur in a power system as a consequence of a sudden increase of system load, the unexpected outage of a transmission line, a generator, or failure in any of the system components. This state may result in some problems such as line overloading, underfrequency, voltage collapse, and angle instability [1].

Generation rescheduling and/or load shedding can be used to overcome the mentioned problems effectively. Generation rescheduling means changing the active and reactive power of generators to decrease the severity of contingency.

Load shedding is a usual operation in emergency and extreme emergency states in which the system is driven toward collapse. In the emergency state, if the controllers of the power system cannot drive the system to a "normal state," the load shedding has to be applied as soon as possible. Much literature has been published on generation rescheduling and load shedding to alleviate line overloading [2].

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It is a common practice for utility companies to perform load shedding by using underfrequency relays to disconnect the predetermined load when the frequency drops below set values [3]. A load shedding method that considers the frequency decay rate is also applied for utilities in reference [4].

The load shedding problem has been solved by many mathematical techniques, such as linear programming (LP), nonlinear programming, and the interior point method [5-7]. These algorithms are fast, but they need some approximation in the power system model. In other words, some constraints cannot be considered in these schemes.

In some other research projects, the load shedding problem has been solved by evolutionary algorithms such as the genetic algorithm (GA) and particle swarm optimization (PSO). These evolutionary algorithms are rigorous and can consider all constraints, but they have low convergence speeds [8, 9].

In order to achieve an algorithm that has the advantages of the mentioned algorithms, “rigorous and fast,” a new algorithm is proposed by combining the LP and PSO methods. In order to obtain the minimum load interruption, load shedding was applied to the network generally. In this way, energy suppliers may pay the least amount of cost for energy not supplied (ENS).

To reveal the superior advantages of the proposed algorithm, each of the 3 algorithms (LP, PSO, and proposed method) were applied to the IEEE 14 bus test system in the event of 2 critical contingencies, and the results were compared. The procedure in reference [8] was also evaluated and applied to this problem, and the results were compared with this paper’s proposed methods.

2. Problem formulation

Elimination of transmission lines over loadings in contingency conditions by means of load shedding and generator rescheduling is formulated as an optimization problem with nonlinear constraints as follows:

2.1. Objective function

The objective function is the sum of the weighted difference between the precontingency and postcontingency active power of all of the power system buses, shown as:

$$\sum_{i=1}^{N_{BUS}} \alpha_i . (P_{Di}^0 - P_{Di}^p). \tag{1}$$

2.2. Constraints

The equality and inequality constraints are described in Eqs. (2-8). Active and reactive power balance equations are expressed as Eqs. (2) and (3).

$$\sum_{i=1}^{N_{BUS}} (P_{Gi}^p - P_{Di}^p) - P_L^p = 0 \tag{2}$$

$$\sum_{i=1}^{N_{BUS}} (Q_{Gi}^p - Q_{Di}^p) - Q_L^p = 0 \tag{3}$$

Control variable constraints are the real power of generators and the load demand of buses, which are shown by Eqs. (4) and (5), respectively.

$$P_{Gi}^{\min} \leq P_{Gi}^{p} \leq P_{Gi}^{\max} \tag{4}$$

$$P_{Di}^{\min} \leq P_{Di}^{p} \leq P_{Di}^{0} \tag{5}$$

In Eq. (5), we have restricted load shedding of buses between the precontingency value and a minimum amount, i.e. $P_{Di}^{\min}$. In other words, it has been assumed that the load shedding in bus i cannot be greater than $P_{Di}^{0} - P_{Di}^{\min}$. Operating constraints are as follows:

$$|S_{ij}| \leq S_{ij}^{\max}, \tag{6}$$

$$Q_{Gi}^{\min} \leq Q_{Gi}^{p} \leq Q_{Gi}^{\max}, \quad i \in N_G, \tag{7}$$

$$V_i^{\min} \leq V_i^{p} \leq V_i^{\max}, \quad i \in N_{BUS}. \tag{8}$$

This object is achieved by optimal determination of control variables. Control variables are shown schematically in Figure 1.

P_{G1}^{p}	$\cdots$	$P_{GN_G}^{p}$	P_{D1}^{p}	$\cdots$	$P_{DN_{BUS}}^{p}$

Figure 1. Schematic diagram of control variables.

3. Solution method

3.1. Linear programming algorithm

Linear programming, and its application in electric power systems, is well known and has been used as an optimization technique in many papers [10].

In order to solve the problem mentioned in Section 2 by linear programming, a linearized network model must be used. This requires some approximation and simplification in network modeling [11].

In contingency analysis, the most interesting limits of the power system are branch flows and bus voltages. Considerably more attention has been paid to branch flows than bus voltages. This has given rise to the very extensive use of linearized active power models. The DC power flow model is too dubious in accuracy for use on most power systems. The use of an active power model makes the assumption that voltages and reactive flows change very little after a contingency. This assumption is most valid for strong high voltage transmission systems in which branch R/X ratios are small [12].

In the linear programming optimization method, the objective function is Eq. (1), according to following linear constraints.

$$P_{Gi}^{p} - P_{Di}^{p} - \sum_{j \in UN(i)} P_{ij}^{p} = 0 \tag{9}$$

$$P_{ij} = \frac{\theta_i - \theta_j}{X_{ij}} \tag{10}$$

$$P_{Di}^{\min} \leq P_{Di}^{p} \leq P_{Di}^{0} \tag{11}$$

$$P_{Gi}^{\min} \leq P_{G1}^{p} \leq P_{Gi}^{\max} \tag{12}$$

$$\left|P_{ij}^{p}\right| \leq P_{ij}^{\max} \tag{13}$$

3.2. PSO algorithm

Because some approximation is used in the LP method, some important constraints may not be satisfied. Indeed, a more accurate model of the system is required in order to access practical solutions. For example, lower and upper boundaries of a generator's reactive power loading, power losses in transmission lines, and some operating constraints such as voltage levels in contingencies must be considered. On the other hand, applying these constraints to the problem results in the nonlinearity of network modeling. The LP method cannot be applied to this problem and another method is required for optimization of this nonlinear problem with constraints.

In this paper, in order to solve this complicated optimization problem, the particle swarm optimization (PSO) algorithm was used. PSO is a population-based evolutionary technique that has many advantages over other optimization techniques [13].

Particle swarm optimization is a form of evolutionary computation technique based on natural systems. Each particle in the population is a feasible solution. Optimal regions of complex search spaces are found through the interaction of individuals in the population. The key advantages of PSO over other optimization techniques are as follows: lower sensitivity to the nature of the objective function, derivative-free property unlike many conventional techniques, easy implementation, etc. A complete comparison of this algorithm with other techniques was performed in reference [11].

The algorithm starts with N particles. Each particle represents a candidate solution to the problem. Each particle in the search space has a current position (x_i) and a current velocity (v_i). The value of each particle is determined by fitness function $(F(x_i))$.

Each particle moves about the cost surface with a velocity. The personal best position in the search space $(localbest_i)$ corresponds to the position where particle i represents the best fitness function. The global best position in the search space $(globalbest)$ represents the position yielding the best fitness function among all the $(localbest_i)$.

This algorithm is defined as follows:

$$x_i^{n+1} = x_i^n + v_i^{n+1}, \tag{14}$$

$$v_i^{n+1} = v_i^n + \rho_1.r_1.(x_i^{localbest} - x_i^n) + \rho_2.r_2.(x^{globalbest} - x_i^n). \tag{15}$$

1. Formation of initial population and initial velocities randomly.

2. Calculation of the value of each particle by fitness function.

3. Finding of the local best of each particle.

4. Finding of the global best of all the population.

5. The PSO algorithm updates the velocity for each particle, then adds that velocity to the particle position or values. Velocity updates are influenced by both the best global solution associated with the lowest cost ever found by a particle and the best local solution associated with the lowest cost in the present population, according to Eqs. (14) and (15):

   In these equations, superscript n+1 denotes the n+1th generation, and superscript n denotes the nth generation. Meanwhile, ρ_1, ρ_2 are the learning factors and r_1, r_2 are independent uniform random numbers. $x_i^{localbest}$ is the best local solution for the ith particle and $x^{globalbest}$ is the best global solution.

6. Repetition of steps b-e until the termination criteria are satisfied [14].

In Eq. (14), x_i indicates control variables, as shown in Figure 1.

3.3. Proposed sequential LP and PSO algorithm

As mentioned, the LP algorithm is appropriate for fast calculations, but in this method, the network cannot be modeled accurately and the network constraints are not considered completely. By using the PSO algorithm, it is possible to consider the network nonlinear model and its constraints accurately. Unfortunately, the PSO algorithm needs more time for calculation in comparison with linear programming.

In order to achieve a fast solution in addition to considering all necessary constraints, the LP and PSO algorithms were used sequentially as a new algorithm in this paper. In the proposed method, the solution obtained by the LP method was used as the initial population in the PSO algorithm. The PSO started its search from the vicinity of the optimum solution. In this way, it was possible to solve the nonlinear model of the system in a shorter time than that of PSO.

4. Case study

The IEEE 14 bus test system, which is shown in Figure 2, was selected as the case study for this paper [15]. Initial conditions of the system are shown in Table 1. The generator in the first bus was considered as the reference generator. Variables with a dark background are control variables.

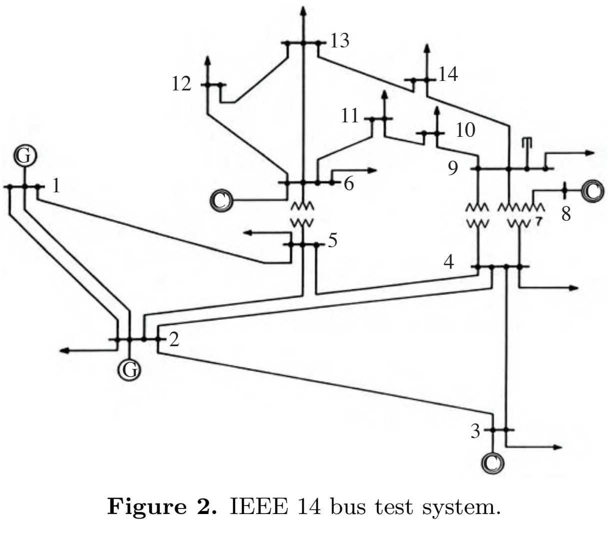

Figure 2. IEEE 14 bus test system.

It was supposed that the increasing or decreasing of the active power generation of all generators was limited to 20% of their current generation. In other words: $P_{Gi}^{\min} = 0.8 \times P_{Gi}^{0}$ and$P_{Gi}^{\max} = 1.2 \times P_{Gi}^{0}$. It was also supposed that $P_{Di}^{\min} = 0.5P_{Di}^{0}$ for all of the load buses. This equation means that load shedding in bus i could not be greater than 50% of the load demand in this bus.

Results were obtained in 2 different modes. In the first mode, it was supposed that all buses had equal importance factors, and in second mode, it was supposed that buses had different importance factors.

Table 1. Initial operating state of the system.

Bus No.	Voltage magnitude	Consumption power		Generation Power	
		MW	MVAr	MW	MVAr
1	1.06	0.00	0.00	232.32	-16.9
2	1.04	21.7	12.7	40.0	42.4
3	1.01	94.2	19.0	0.00	23.4
4	1.01	47.8	-3.9	0.00	0.00
5	1.02	7.6	1.6	0.00	0.00
6	1.07	11.2	7.5	0.00	12.2
7	1.06	0.00	0.00	0.00	0.00
8	1.09	0.00	0.00	0.00	17.4
9	1.05	29.5	16.6	0.00	0.00
10	1.05	9.0	5.8	0.00	0.00
11	1.05	3.5	1.8	0.00	0.00
12	1.05	6.1	1.6	0.00	0.00
13	1.05	13.5	5.8	0.00	0.00
14	1.03	14.9	5.0	0.00	0.00

5. Results and discussion

In this section, the previously mentioned 3 algorithms are applied to the test case and the obtained results are discussed in 2 contingency conditions. The first contingency is a single contingency and the second is a multiple contingency.

5.1. First contingency: line 1-2 outage

From power flow results at the precontingency operating condition, the maximum transmitted power flows in line 1-2 were equal to 157 MVA. Therefore, it seems that the removal of this line would be a critical contingency. Removing line 1-2 caused the overloadings of lines 1-5 and 4-5.

Table 2 shows the new system operating conditions after this contingency by means of the 3 proposed algorithms. Overloading of the mentioned lines was eliminated because of load shedding and generator rescheduling. The ↑ symbol indicates the increasing of the generator generation and ↓ indicates decreasing of the generator generation.

Table 2 shows that the generator at bus 1 decreased its generation to 110 MW. In fact, 110 MW is the maximum power that generator 1 could generate in this contingency. If the generation of generator 1 were more than 110 MW, then line 1-5 would overload as a result of power sent by means of the generator at bus 1 to the rest of the system only going through line 1-5.

Table 2. New operating state of system after first contingency by means of 3 algorithms (all buses have equal importance factors).

	Bus No.	LP algorithm	PSO algorithm	Proposed algorithm
Active power generation (MW)	1	110.00↓	110.00↓	110.00↓
	2	48.00↑	48.00↑	48.00↑
Reactive power of condensers (MVAr)	3	-	6.53↓	7.89↓
	6	-	8.32↓	7.53↓
	8	-	18.72↑	19.62↑
The percentage of load shedding (%)	1	0.00	0.00	0.00
	2	49.7	30.13	29.04
	3	40.7	49.99	49.99
	4	43.3	38.91	41.89
	5	26.8	0.06	0.03
	6	29.2	0.004	0.008
	7	0.00	0.00	0.00
	8	0.00	0.00	0.00
	9	39.6	48.29	45.90
	10	28.1	44.59	45.54
	11	25.9	30.00	31.74
	12	26.8	49.35	46.25
	13	30.9	46.75	45.92
	14	31.9	49.86	49.85
Calculation time (s)		0.25	6.32	1.03
Total shed power (MW)		101.00	108.31	108.61

When the generation of generator 1 was decreased, generator 2 increased its generation to provide the total power demand of the system. In addition, Table 2 shows that the LP algorithm cannot assign a value to the reactive power of the condensers. The percentage of load shedding for each bus is shown at the bottom of Table 2. The calculation time that was obtained by a Quad Core 2.5 GHz/6 M/4 G shows that the proposed algorithm is very fast in comparison with PSO.

The total load shed applied to the customers is shown in the last row of Table 2, with the same results for PSO and the proposed algorithm. Although the calculated time and total load shedding applied to buses in the LP method was better than those of PSO and the proposed method, it may violate some of the constraints.

Figures 3a and 3b show the plot of the global best particle and average of population as a function of generation in PSO and the proposed algorithm, respectively.

The dotted line shows the global best and the continuous line represents the average of the population. These show the convergence of the PSO algorithm and the proposed algorithm to the global optimum solution. As shown in Figure 3b, the proposed algorithm reaches the global optimum solution in fewer iterations.

In order to survey the effect of importance factors on the obtained solutions, the mentioned results were reobtained by considering the following equation:

$$\alpha_i = \begin{cases} 1 & i = 1, ..., 11 \\ 2 & i = 12, ..., 14 \end{cases} . \tag{16}$$

The results in this case are shown in Table 3. It can be deduced from Table 3 that, by increasing the importance of loads in bus numbers 12, 13, and 14 to twice their previous values, load shedding in these buses is decreased considerably.

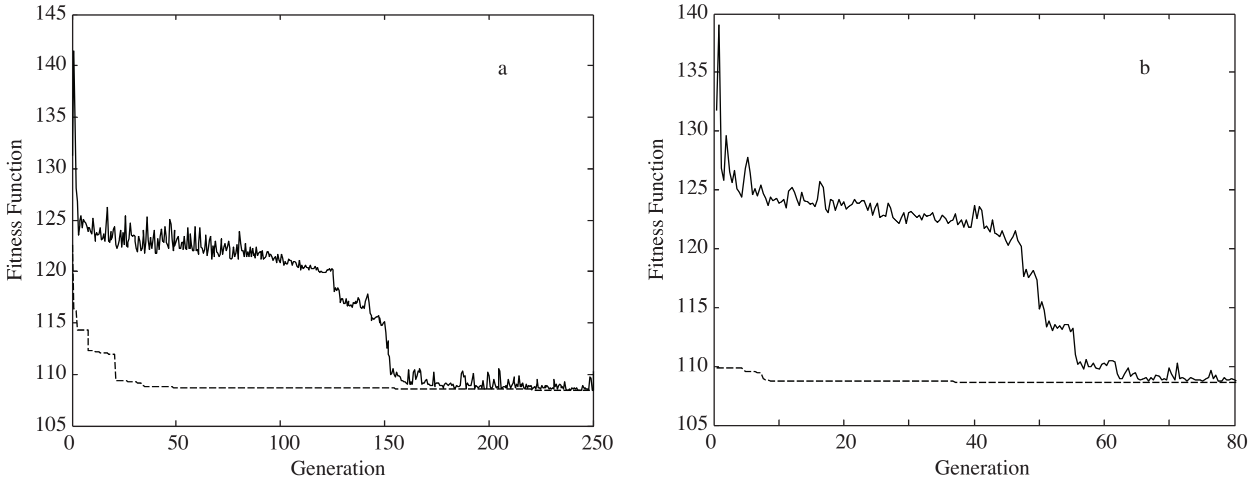

Figure 3. Plots of global best particle and population average as a function of generation for a) the PSO algorithm and b) the proposed algorithm.

Table 3. New operating state of system after first contingency by means of 3 algorithms (buses have different importance factors).

	Bus No.	LP algorithm	PSO algorithm	Proposed algorithm
Active power generation (MW)	1	106.73↓	109.97↓	109.98↓
	2	47.94↑	48.00↑	48.00↑
Reactive power of condensers (MVAr)	3	-	16.51↓	16.51↓
	6	-	15.20↑	15.20↑
	8	-	0.80↓	0.80↓
The percentage of load shedding (%)	1	0.00	0.00	0.00
	2	40.56	37.76	37.76
	3	49.70	46.82	46.82
	4	46.26	38.84	38.84
	5	32.38	40.10	40.10
	6	36.07	47.42	47.42
	7	0.00	0.00	0.00
	8	0.00	0.00	0.00
	9	43.69	48.58	48.58
	10	34.52	47.72	47.72
	11	28.72	38.93	38.93
	12	21.59	28.76	28.76
	13	9.23	40.16	40.16
	14	3.46	15.77	15.77
Calculation time (s)		0.25	5.67	1.00
Total shed power (MW)		104.00	108.74	108.74

5.2. Second contingency: line 1-5 and generator 2 outage

In order to reveal the performance of the mentioned algorithms, results were obtained by applying another contingency condition, the simultaneous outage of line 1-5 and the generator at bus 2. In this case, line 1-2 was overloaded. Table 4 shows the new operating condition in this contingency by means of the 3 mentioned algorithms.

The difference between the solutions obtained by the LP and PSO methods for calculation time and energy not supplied can be explained by the fact that in the PSO algorithm, the network is modeled accurately and additional constraints are considered, whereas these constraints are neglected in the LP method.

Table 4. New operating state of system after second contingency by means of 3 algorithms (all buses have equal importance factors).

	Bus No.	LP algorithm	PSO algorithm	Proposed algorithm
Active power generation (MW)	1	220.00↓	220.00↓	220.00↓
	2	0.00↓	0.00↓	0.00↓
Reactive power of condensers (MVAr)	3	-	22.02↓	24.05↑
	6	-	6.53↓	9.17↓
	8	-	23.99↑	24.00↑
The percentage of load shedding (%)	1	0.00	0.00	0.00
	2	16.51	0.00	0.12
	3	11.63	21.89	20.29
	4	11.02	6.76	5.82
	5	21.15	23.26	24.54
	6	21.67	0.30	4.06
	7	0.00	0.00	0.00
	8	0.00	0.00	0.00
	9	16.37	26.67	28.87
	10	22.38	49.44	50.21
	11	23.98	47.12	49.00
	12	23.26	7.62	10.25
	13	21.19	49.61	45.24
	14	20.87	47.48	48.95
Calculation time (s)		0.25	7.96	1.24
Total shed power (MW)		39.00	53.92	53.07

Figures 4a and 4b show the plot of the global best particle and average of population as a function of generation in the PSO algorithm and proposed algorithm, respectively. They also illustrate the convergence of the PSO algorithm and proposed algorithm to the global optimum solution. As shown in Figure 4b, the proposed algorithm reaches the global optimum solution in fewer iterations.

It is clear from Tables 2 and 4 that the proposed algorithm has the advantages of the LP method, i.e. faster solutions than PSO and the considering of all necessary constraints.

In addition, in order to survey the effect of load importance factors on obtained solutions in the second contingency, results were reobtained by considering the following values:

$$\alpha_i = \begin{cases} 1 & i = 1, ..., 11 \\ 2 & i = 12, ..., 14 \end{cases} . \tag{17}$$

Results are shown in Table 5. It is clear from Table 5 that by increasing importance factors of loads in bus numbers 12, 13, and 14 to twice their previous values, load shedding in these buses was decreased considerably.

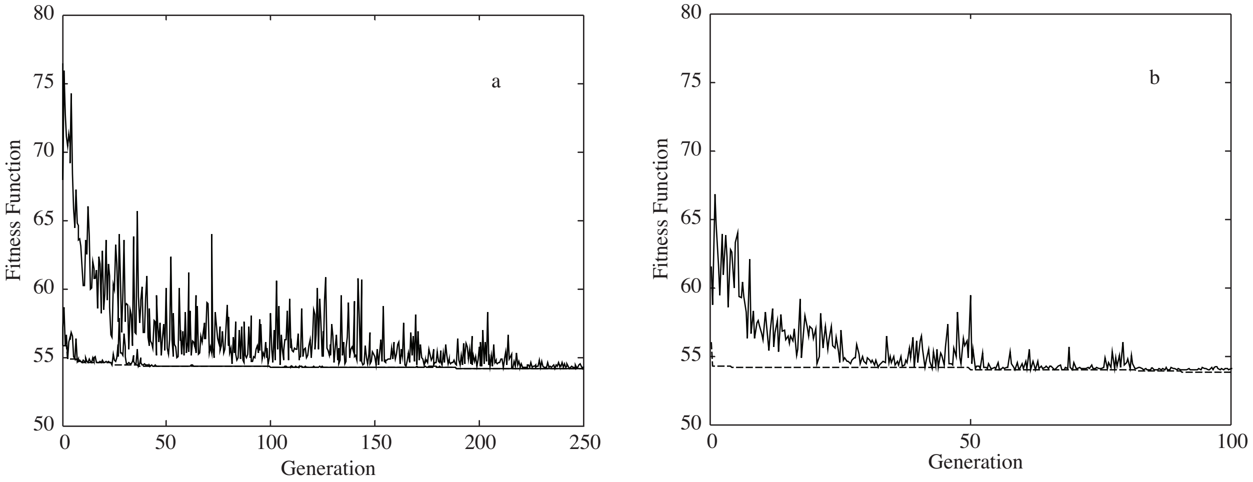

Figure 4. Plots of global best particle and population average as a function of generation for a) the PSO algorithm and b) the proposed algorithm.

Table 5. New operating state of system after second contingency by means of 3 algorithms (buses have different importance factors).

	Bus No.	LP algorithm	PSO algorithm	Proposed algorithm
Active power generation (MW)	1	220.00↓	219.99↓	220.00↓
	2	0.00↓	0.00↓	0.00↓
Reactive power of condensers (MVAr)	3	-	20.22↓	19.24↓
	6	-	14.31↑	12.65↑
	8	-	19.53↑	21.25↑
The percentage of load shedding (%)	1	0.00	0.00	0.00
	2	20.44	0.28	0.28
	3	12.03	22.74	23.15
	4	17.71	11.19	11.61
	5	23.41	16.24	16.25
	6	23.57	38.48	38.50
	7	0.00	0.00	0.00
	8	0.00	0.00	0.00
	9	22.45	35.5	35.47
	10	23.84	45.43	45.52
	11	24.55	18.98	15.39
	12	12.69	0.58	0.55
	13	2.33	10.05	6.37
	14	2.33	33.64	33.80
Calculation time (s)		0.23	7.43	1.24
Total shed power (MW)		39.72	54.20	54.18

Table 6 indicates the advantages and disadvantages of the 3 algorithms in a general comparison.

Table 6. Comparison of advantages and disadvantages of 3 algorithms.

	LP	PSO	Proposed algorithm
Calculation time	Low	Almost high	Almost low
Consideration of voltage constraints	-	√	√
Consideration of generators' reactive power constraints	-	√	√
Loss considerations	-	√	√
Total shed power	Lowest	Low	Low

Table 7 presents a comparison of the proposed method and the evaluated algorithm in reference [8] during the second contingency. It was supposed that all buses had equal importance factors.

The results show that the PSO algorithm has a superior ability of finding the global optimum solution in comparison with GA. Both of these algorithms are slow and cannot be applied to the system after contingencies simultaneously. The proposed method of sequential use of LP and PSO can overcome the convergence speed problem and present reliable solutions.

Table 7. Comparison of proposed algorithms and algorithm evaluated in reference [8] during second contingency (all buses have equal importance factors).

	Ref. [8] evaluated algorithm	LP	PSO	Proposed algorithm
Calculation time (s)	12.3	1.24	7.96	0.25
Total load shedding (MW)	57.42	53.07	53.92	39.00

6. Conclusion

Three algorithms, including linear programming (LP), particle swarm optimization (PSO), and a new method based on sequential use of LP and PSO, were used to minimize the load shedding in contingency conditions. Generation rescheduling was used to decrease load shedding, as well. It was shown that the LP method is a fast algorithm but cannot be used in nonlinear problems, so its results are not useable in practical applications. On the other hand, PSO can be used as a practical method to solve the mentioned problem, but it needs a longer solution time than LP. In addition, it was shown that the proposed method is a fast method that considers constraints of the power system. The 3 proposed algorithms were compared with the algorithm used in reference [8]. It is obvious that the PSO algorithm is faster and more powerful than GA, but it is not yet appropriate for online and fast calculations. Sequential use of LP and PSO can present fast and reliable solutions. It is expected that the final calculation time will be decreased much more by use of faster computers.

Nomenclature

N_{BUS}	number of buses
N_G	number of generators
$UN(i)$	set of buses connected to bus i
0	normal state index (superscript)
p	contingency state index (superscript)
i	bus index (subscript)
α_i	importance factor of loads
P_{Di}^0	load active power demand in normal state

P_{Di}^{p}	load active power demand in contingency state
P_{Gi}^{0}	active power generation in normal state
P_{Gi}^{p}	active power generation in contingency state
P_{L}^{p}	active power losses in contingency state
Q_{Di}^{0}	load reactive power demand in normal state
Q_{Di}^{p}	load reactive power demand in contingency state
Q_{Gi}^{0}	reactive power generation in normal state
Q_{Gi}^{p}	reactive power generation in contingency state
Q_{L}^{p}	reactive power losses in contingency state
$P_{Gi}^{\min}$	minimum active power generation
$P_{Gi}^{\max}$	maximum active power generation
$Q_{Gi}^{\min}$	minimum reactive power generation
$Q_{Gi}^{\max}$	maximum reactive power generation
$P_{Di}^{\min}$	minimum amount of load that must be supplied
S_{ij}	apparent power flow from bus i to j
$S_{ij}^{\max}$	apparent power limit of line between buses i and j
P_{ij}	active power flow from bus i to j
$P_{ij}^{\max}$	active power limit of line between buses i and j
$V_{i}^{\min}$	voltage lower limit
V_{i}	bus voltage in contingency state
$V_{i}^{\max}$	voltage upper limit
θ_{i}	voltage angle in bus i

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