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Iterative optimization of a bi-level formulation to identify severe contingencies in power transmission systems

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ABSTRACT

Recent large blackouts in power systems showed that common reliability criteria are not efficient anymore. Since cascading outages are the prevalent cause of more blackouts, and there is enormous interaction among different elements, determining the sequence of events before occurring blackouts is very challenging. Contingency screening methods are used to overcome some difficulties and identification of bottlenecks in power systems. However, risky contingencies are those with high probability, high consequences, or both. In this paper, a challenging work of seeking multiple events which potentially may result in cascades is addressed. Severe contingency identification, which is known as N-k problem in the literature, is difficult to deal with even for small values of k. A modified Binary Particle Swarm Optimization (BPSO), which proposed in this paper, could help power system planners and operators to upgrade the network resiliency by finding critical contingences that may initiate cascading outages. Severe contingencies are detected by computer simulations in the IEEE 39-bus test system and a real-sized network. The results are compared to the results of the IEEE 24-bus test system, which shows the method is more effective.

1. Introduction

Dependency of other infrastructures to power systems makes them more critical and important. There are great interdependences between power systems and other vital systems in our modern society. Power systems blackouts are very costly and involve considerable consequences to the society. Because of great outcomes of blackouts, the vulnerability assessment of power systems has been gotten an increasing interest. Complexity of power systems makes it impossible to completely eliminate blackouts but their average size and cost can be reduced [1]. However, it is possible to develop power systems in a way that pass severe events, even though needs more redundancy and it may not be an economic solution. Therefore, modeling interactions in power system to achieve operational resilience becomes extremely vital.

Natural and man-made events may cause catastrophes in power systems. Components failure may lead to a long-term electricity shortage. Loss of a component in a fault or maintenance normally occurs in power systems and it should be realized certainly. Therefore, most utilities are designing and operating their systems based on deterministic criteria called N-1. Some others in order to have more secure systems, prepare their systems for two contingencies. Recent blackouts have demonstrated that another type of events should be considered [2]. New studies of blackout time series have been shown that they are more likely than may be expected [3].

A variety of events can damage multiple components and cause cascading outages which are the most frequent reason for major blackouts in power systems [4]. Therefore, based on TOP standard of North American Electric Reliability Corporation (NERC) considering multiple contingencies is mandatory to assure preventing cascading outages occurrence [5]. There are numerous components in power systems. As a result of huge number of possible rare interactions and their complexity of these interactions, detecting multiple contingencies is very challenging [6]. There are more unlikely and unpredictable contingencies in which a power system is vastly vulnerable.

IEEE PES CAMS (Computer and Analytical Methods Subcommittee) has an illustrative review for cascading failures in [5] which defined it as a sequence of dependent failures that weaken the power system.

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Nomenclature

Sets

B	set of branches (transmission lines and power transformers)
G	set of generators
L	set of loads

Vectors

$\overline{T}$	loading of branches
$\overline{P_g}$	loading of branches
$\overline{P_d}$	nodal loading

Variables

v_j	binary variable for the state of branch j (1 for out of service branches)
b	number of branches
C_i	optimal load curtailed of the bus i in MW
CL	total optimal curtailed load of the system in MW
ϕ_{th}	threshold for total load shedding in MW, and
n	number of buses in the system
δ_i	voltage angle at bus i
x_j	reactance of a branch j
P_{id}	load of the bus i in MW
P_{gi}	optimal injection of generator in bus i in MW
T_j	flow of branch j after running optimal power flow
$c^t_{1,ij}$	uniform random values in [0 1] interval
$c^t_{2,ij}$	uniform random values in [0 1] interval
$d^t_{1,ij}$	cognition part
$d^t_{2,ij}$	social part

Constants:

$P_{gi,\min}$	lower limit of injection of generator at bus i in MW $P_{gi,\min}$
$P_{gi,\max}$	upper limit of injection of generator at bus i in MW
$T_{j,\max}$	emergency rating of branch j

Operators:

$+$	OR operator
$\otimes$	AND operator
$\oplus$	XOR operator

Sometimes a combination of independent failures may initiate cascading outages. For instance, two unrelated events on September 2003, in the Swedish/Danish system resulted in voltage collapse and separation of regions. These events were a substation equipment failure five minutes after the outage of a nuclear unit in southern Sweden, 300 km far from each other [7].

Risky contingencies are those with high probability, high consequences, or both. Some methods for first group as credible contingencies are presented in [8,9]. More attempts have been done to detect small set of multiple contingencies in the second group [10,11]. A variety of names have been used for the "N - k problem." The network interdiction, vulnerability analysis, and network inhibition although are used in the terminology [12].

Optimization procedures have been proposed in several papers to find severe contingencies. First, the problem formulated in [13] by Salmeron and his coworkers with network-interdiction model to find the optimal-attack in a max–min problem. Then a general bi-level formulation was presented in [14] in which the terrorist and the system operator goals may be modeled with different objective functions. Two bi-level programming approaches were presented and discussed in [15] and two methods were used to convert each formulation into an equivalent single-level mixed-integer linear programming problem. Nonlinear optimization was used in [16] for identifying the fewest possible transmission line outages resulting in system failures in which severity of failures determined by lost load. A combination of classical Deterministic Network Interdiction Problem (DNIP) and Multi-objective Optimization Evolutionary Algorithms (MOEA) for finding minimum contingencies with maximum load shedding was proposed in [17]. As a drawback, this model cannot include Ohm's and Kirchhoff's laws. A method using linear sensitivities in DC power flow was proposed in [18] to detect double contingencies. This method calculates Line Outage Distribution Factors (LODFs) which are used in two screening algorithms with complementary properties. The method is simple but its application is limited to double contingencies. The progressive entropy, which is a graphical index, using a training database for obtaining efficient decision trees in order to define multiple contingencies was proposed in [19] to group contingencies. Gaussian Mixture Method (GMM) was proposed in [20] for assessing risk of rare events and blackouts. This method considers the effects of cascading outages by using Monte Carlo Simulation (MCS) and can be used to study power-law distribution for the blackout size.

Blackouts proceed in a stochastic manner [21] that is an intrinsic feature of evolutionary algorithms. A stochastic method for analyzing rare events proposed in [9]. Random Chemistry (RC) as a stochastic algorithm was proposed in [5] to find a set of simultaneous multiple contingencies which could initiate large cascading outages. Obtained results of this model are consistent with empirical data. Recently a procedure was proposed in [22] based on Genetic Algorithm (GA) optimization to improve the adequacy of power systems under contingences.

The results of severe contingency identification can be used to maximize the resiliency of the power system. Some works in the literature used distributed energy resources to strengthen the grid against intentional attacks [23,24]. In addition, they could be used to take into account risk of blackouts in planning studies and suppressing cascading blackouts [25,26].

In this paper we are exploring among multiple contingencies as initiating events in cascading outages. These contingencies happen in a short duration in which operators cannot perform corrective actions. Therefore, neglecting time between multiple contingencies is a valuable simplification which reduces search space [6] that means they occur simultaneously. The proposed procedure is suitable for transmission system planners to suggest expansion scenarios. On the other hand, union of the resultant contingencies up to a desired order would be used to complete the conventional credible set for detail analyses in security studies.

The contribution of this paper is to use a simple heuristic procedure for identifying multiple simultaneous failures in a bi-level optimization process such that it can be applied to real power systems. Also we proposed a modification in BPSO which improves the convergence speed of the algorithm. Inside the procedure, Linear Programming (LP) is used to minimize curtailed load of the contingencies in the lower level, whereas Binary Particle Swarm Optimization (BPSO) is used for minimizing the number of failed branches with desired consequences in the upper level. Trajectories in PSO algorithm are started from rare events with desired impacts and optimized heuristically.

It is worth noting that, the paper does not focus on the root causes of the branch outages. Different reasons of interruptions of the branches such as protection mal-operation, random failure of components (such as breaker stuck), terrorisms and etc. can be included in the model.

Reminder of this paper is organized as follows. Next section presents the optimization model, the properties of discrete version of PSO and used procedure. Numerical simulations for two cases of IEEE test systems and a real power grid, and some discussions on the results of the proposed approach are presented in section 3. Comparison of the results and the computational burden is performed in part 4. Conclusions are presented in section 5.

2. Optimization model

Transmission lines are over a large geographical area and physically unprotected. They have more vulnerability to natural disasters and thus larger failure rates. In the literature, great interest has been given to the transmission lines within all power system components. In the other hand, replacement or repair of power transformers is difficult and very time consuming which make them important. Therefore, we use "branches" including transmission lines and power transformers in our investigations.

2.1. Procedure

Suppose that we are looking for severe contingences, which have the desired number of branches k. The flowchart of detecting severe contingencies is shown in Fig. 1. The algorithm is started with an arbitrary ϕ_{th} as an input. The optimization procedure tries to find a contingency which results in a load shed more than ϕ_{th}. This optimization is done by BPSO, which will be described in more details in part 2.3. If the optimization procedure returned larger k than what is expected, ϕ_{th} is reduced drastically else increased slightly to $CL + \varepsilon$. Note that CL is the output of the optimization process which, is calculated by LP. While the returned number does not change, the process is repeated to guarantee detection of severe contingencies of order k. Good estimate of initial value of ϕ_{th} for N-k is found from curtailed load of severe contingencies in N-k-1.

The minimum load shed is required if the best remedial actions occur to prevent happening cascading outages in the grid. Consequently, each severe N-k-1 contingencies is terminated.

In contrast to common heuristic methods that assume cascading outages progress in a deterministic manner [21], proposed method proceeds stochastically. The only difference between this method and actual data is the reverse sequence of events. In other words, our method is going in opposite side of what happens really. Note that all simulations are in static manner.

2.2. Objective function

The objective function of the model is minimizing the number of disrupted transmission branches (upper level) while minimum curtailed load in the system is greater than a specified threshold (lower level), which should be optimized in two levels. The formulation of the problem is as follows according to [15]:

$$\min_{P_g, T, P_d} k = \sum_{j=1}^{b} v_j^*,\ v_j^* \in \{0,1\} \quad \forall j \in B \tag{1}$$

$$CL \in \arg\left\{ \sum_{i=1}^{n} C_i^*, \forall i \in L \right\} \tag{2}$$

Subject to:

$$CL = \sum_{i=1}^{n} C_i^* \geqslant \phi_{th}, \forall i \in L \tag{3}$$

$$T_j = \frac{v_j}{x_i}\left(\delta_i^{send} - \delta_i^{rec}\right), \forall i \in B : (\delta_{\min}, \delta_{\max}) \tag{4}$$

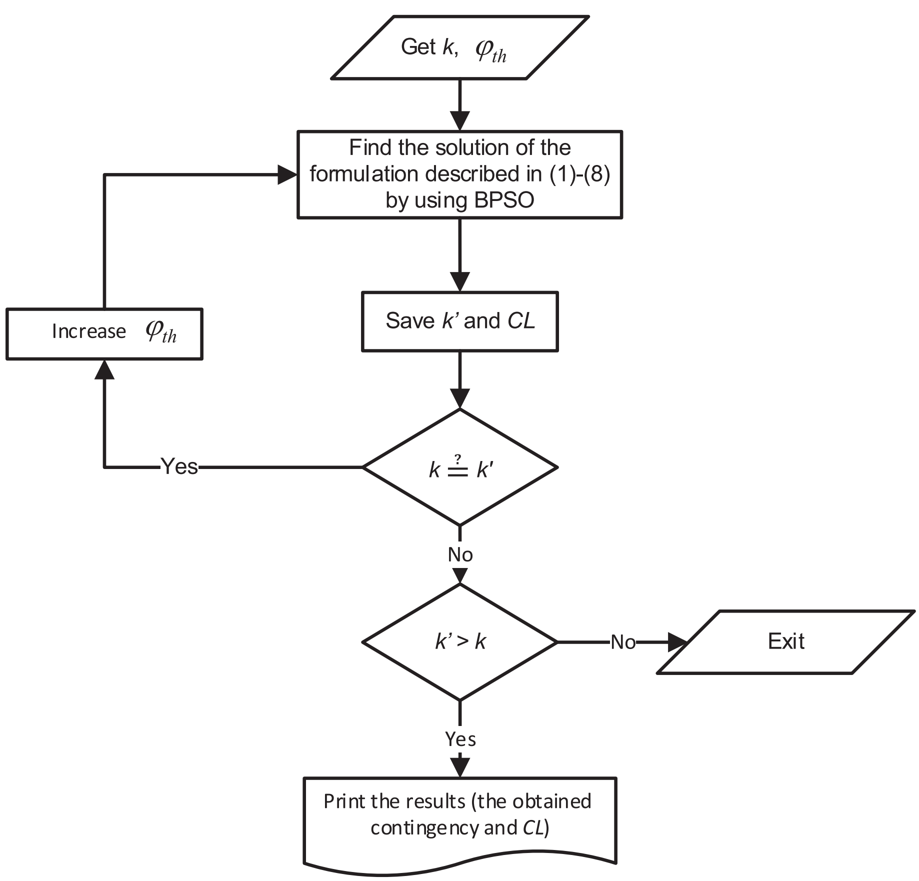


Fig. 1. Flowchart of the proposed method for finding severe contingencies.

$$\sum_{i=1}^{n} P_{gi} + \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} P_{di}, \forall i \in L \tag{5}$$

$$0 \leqslant C_i \leqslant P_{di}, \forall i \in L \tag{6}$$

$$P_{gi,\min} \leqslant P_{gi} \leqslant P_{gi,\max}, \forall i \in G \tag{7}$$

$$|T_j| \leqslant T_{j,\max}, \forall j \in B \tag{8}$$

In the above formulation, (1) denotes the upper-level objective function and (2) shows the lower-level objective function. The decision variable regarding the upper-level is v_j^* and the lower-level is C_i^*. In this paper the criterion for severity of a system failure is the amount of load shed. Indeed, response of operators to prevent blackouts is modeled as load shed and generation re-dispatch after the occurrence of the contingency. In other words, the decision variables which are controlled by the system operator are line power flows, generator power outputs, and nodal phase angles. Other system failure criterion would be the fraction of the disconnected buses in the largest island [5]. Different procedures may be used for calculating load shed as that described in [27]. In this paper after each contingency, LP minimize the amount of load shed in DC power flow described in (2) and (4)-(8). The result of the the linear optimization includes calculated results for control variables, such that all imposed constraints are fulfilled and the curtailed load is minimized. The algorithm will provide a solution where all generator injections and load demands are set to optimal values.

2.3. BPSOa

For the first time, PSO algorithm with good abilities in solving complex optimization problems was introduced by Kennedy and Eberhart [28]. PSO is an evolutionary method that has many advantages over the other optimization methods [29]. In this algorithm, a primary population each of them called a particle is produced, and the search space is explored for finding the global optimal point based on experience of each particle and its neighboring particles. Limited number of parameters of PSO and its ability to escape local optima make it simple and efficient method for identifying severe multiple contingencies. PSO was used in different fields of power studies such as optimal placement and sizing of capacitors in distribution systems, congestion management in power market, optimal PMU placement, optimal power flow, placement of distributed generation, and reactive power and voltage control [29,30].

Discrete version of PSO which is called Binary PSO (BPSO) was proposed in [31] for the optimization problems with binary variables (0 or 1). A modified version of BPSO based on Artificial Immune Systems (AIS) was presented in [32]. Searching ability, simplicity, and convergence speed of this technique was improved successfully.

Any particle is a string which represented by a vector with the length of b. Corresponding positions and velocities are vectors with the same size. In contrast to the old version, modified BPSO positions and velocities are binary. Velocity of each particle is the summation of ones in the velocity vector and should be smaller than V_{max} which controls the stability and convergence of the algorithm. When the particle velocity is greater than V_{max} some ones are changed to zeros randomly.

Suppose that $X_i^t = [x_{i1}^t \; x_{i2}^t \cdots x_{ib}^t]^T$ is the position vector with binary values for the particle i in the iteration t. So the related velocity vector is $V_i^t = [v_{i1}^t \; v_{i2}^t \cdots v_{ib}^t]^T$. In the every iteration, the vector of best experience for each particle, $PB_i^t = [pb_{i1}^t \; pb_{i2}^t \cdots pb_{ib}^t]^T$ and the vector of global best experience of total particles $GB^t = [gb_1^t \; gb_2^t \cdots gb_b^t]^T$ are updated by means of Eq. (1) which is the summation of the ones in position vector of particles. The procedure of BPSO used in this paper is as follows:

1) Initializing: Generate P initial particles for $t = 0$ with random binary position vector X_i^0 and velocity vector V_i^0. Each particle should have shed load greater than ϕ_{th}.

2) Updating: For $j = 1,2,\ldots,b$ in the each iteration, the velocities and positions are calculated by [33]:

$$d_{1,ij}^t = pb_{ij}^t \oplus x_{ij}^t \tag{9}$$

$$d_{2,ij}^t = gb_j^t \oplus x_{ij}^t \tag{10}$$

$$v_{ij}^{t+1} = v_{ij}^t + c_{1,ij}^t \otimes d_{1,ij}^t + c_{2,ij}^t \otimes d_{2,ij}^t \tag{11}$$

$$x_{ij}^{t+1} = v_{ij}^{t+1} + x_{ij}^t \tag{12}$$

3) Particle best detection: New position of each particle (X_i^t) is saved as the best experience of that particle (PB_i^t) if its ones is smaller than PB_i^{t-1} and curtailed load is greater than C_{th}. If PB_i^t is updated, DC OPF will be run. The new position of a particle is discarded if it does not satisfy the Eq. (2).

4) Global best detection: The particle with the minimum ones among all PB_i^t is chosen and stored as global best GB^t.

5) Repeating: Steps 2–5 are redone up to desired number of iterations.

3. Case studies

To investigate and verify the proposed method, it is applied to the IEEE 39-bus test system and the real power system of EirGrid in Ireland with 100 iterations by 10, 50, and 100 particles respectively. Identified severe contingencies up to order $k = 8$ are presented and discussed in this section.

3.1. The IEEE 39-bus

First, the 345 kV test system of New England is used for validating the performance of the proposed method. It has 20 load points of total 6150 MW with 10 generators, 12 transformers, and 34 transmission lines [34]. Ampacity of all branches are set to 1 kA. The single-line diagram of this system is shown in Fig. 2 [35].

Severe outage of double branches has 320 MW load curtailed which happens in the outage of lines 14–15 and 15–16. Therefore, initial value of ϕ_{th} for triple outage of branches should be larger than that. Table 1 shows the steps of detecting severe N-3 contingencies. This table shows that there are two severe N-3 contingencies with exactly similar curtailed loads derived in separate simulations. As can be seen, after two

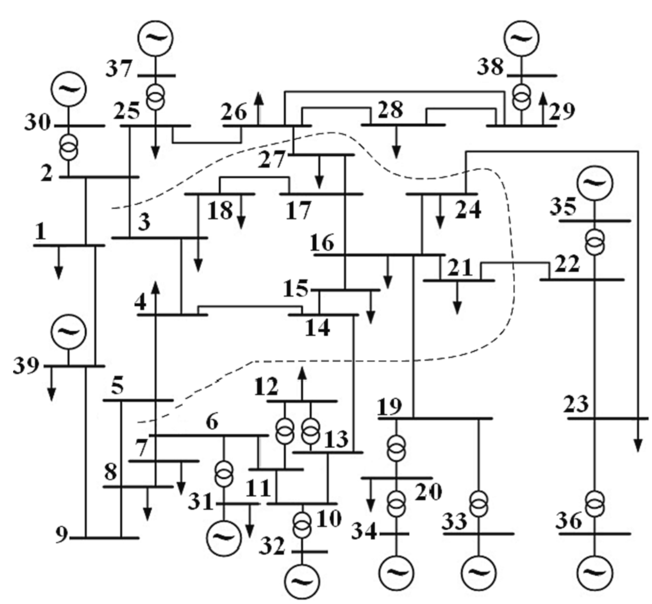


Fig. 2. Single-line diagram of the IEEE 39-bus test system [35].

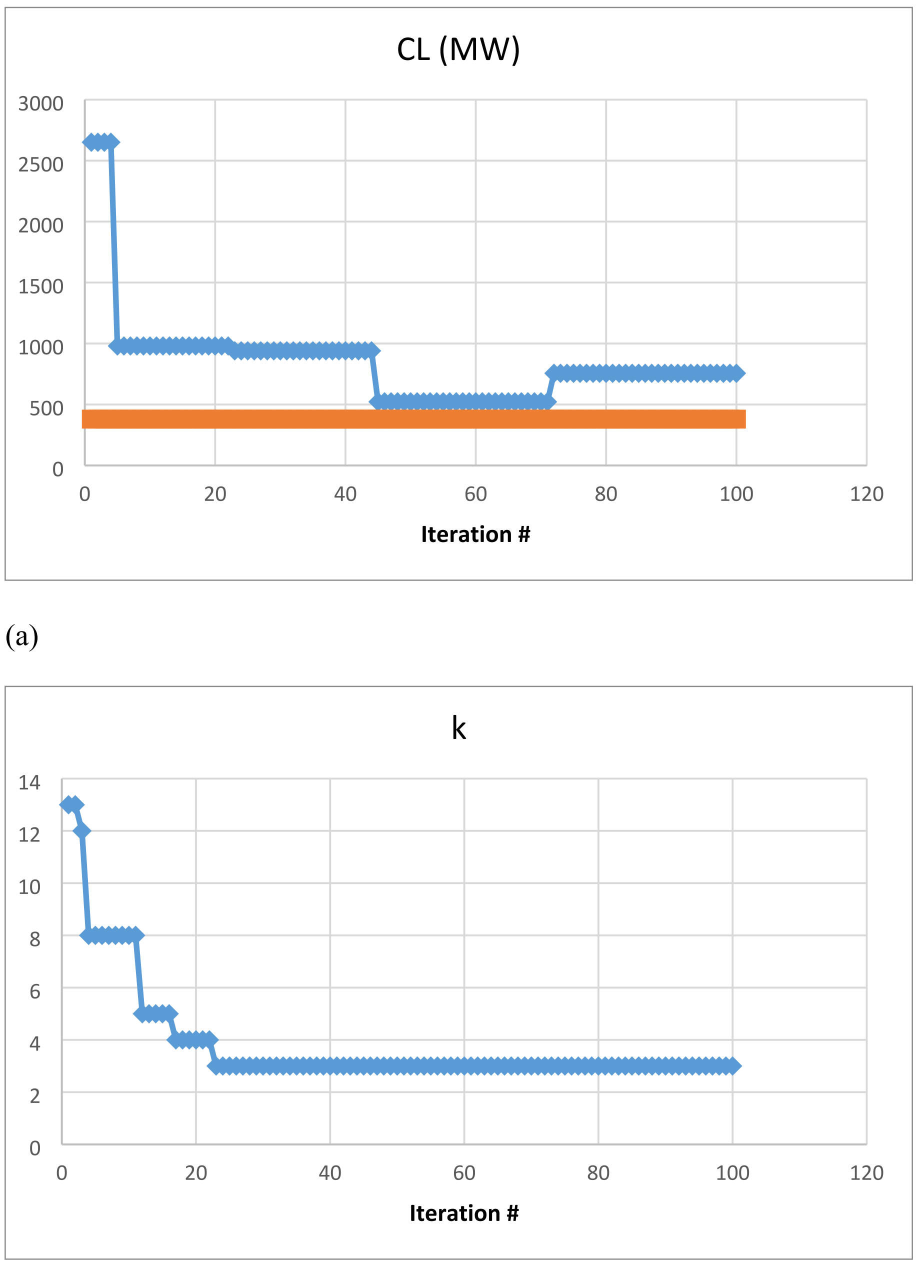
Table 1
Severe N-3 contingency of the proposed method in the IEEE 39-bus.

Simulation #	Run #	Contingences	*k*	ϕ_{th}(MW)	*CL* (MW)
1	1	5–8, 7–8, 9–39	3	450	522
1	2	5–8, 6–7, 9–39	3	525	755.8
2	1	5–6, 4–14, 5–6	3	350	352.6
2	2	5–8, 6–7, 8–9	3	380	755.8

trials, the severe contingency is obtained in both simulations. Maximum value of curtailed load in N-3 contingencies is 755.8 MW.

Complete contingency analysis up to order k, for a system with n branches contains $O(n^k)$ contingencies which is computationally very expensive and time consuming. As we assess transmission system, generating units are considered fully reliable. In this small test system, there are 37 branches. Thus, to verify the obtained results by the proposed method, contingency analysis of this system up to order 3, composed of 37 + 666 + 7770 = 8473 contingencies, were performed using DC OPF model. According to these calculations, the same severe contingencies reported in Table 1 were obtained.

To show the performance of BPSO in a given simulation, the attained results for the last row of Table 1 are depicted in Fig. 3. On the top, the curtailed load is represented against the iteration number in blue. Moreover, ϕ_{th} (380 MW) is plotted in orange. As can be seen, the algorithm does not allow the curtailed load to be smaller the threshold. Furthermore, the blue diagram does not follow a smooth decline. On the button the number of branches in the achieved contingency vs the iteration number is illustrated. Contrary to the other diagram, here, the number of outaged branches in the severe contingency is decreasing and



(a)

(b)

Fig. 3. The results for the BPSO simulation; (a) the curtailed load vs the iteration number (b) the number of branches in the achieved contingency vs the iteration number.

finally settles on the final value which is the result of the optimization algorithm.

It should be noted that the minimum load shed indicated in Table 1 is required if the best remedial actions take place to suppress cascading outages in the network. Therefore, each severe N-3 contingencies is terminated. Suppose that following the severe contingency identified in the first simulation, remedial actions are not performed properly. DC power flow of the network can be used to trace what happens. The sequence of events is described in Table 2. The values in the parenthesis show the loading of related branches in the second and third sequence. In the last stage, there is not any overload in the network and the cascade is terminated naturally. So, the total load shed is 1064.4 MW. Note that if we use AC power flow, more lines are tripped and the consequent lost load is superior.

The same process was made for N-4 contingencies by the proposed method. Initial ϕ_{th} for the first run is 850 MW. The results are presented in Table 3. Final value of ϕ_{th} is 940 MW that results in 980.0 MW curtailed load for the severe N-4 contingency.

Other severe N-k contingencies for $k \geq 5$ k $\geq$ 5 which are obtained by the proposed method are presented in Table 4.

In occurrence of each contingency in Table 4 the AC load flow cannot be converged. For example, $k = 5$ affects a large section in the center of the network with no generation unit and the total load of 2492.6 MW depicted by dashed curve in Fig. 2. By this contingency, this region can be supplied by the only remaining lines of 2–3 and 5–6 with a total capacity of 1173 MW that is impossible and a chain of cascade failures will be maintained. Unless, according to the results obtained by the proposed method, the optimal remedial action takes place and the minimum amount of 1529 MW load be shedded. Table 5 shows the details of the required shed loads in this case. It is worth noting that in the lower level (for each contingency) the minimum curtailed load is calculated as described in equations (2), and (4)-(8). Table 5 is the result of that for the sever N-5. In this paper after each contingency, a linear programming is used to minimize the amount of load shed in DC power flow.All the loads except Load 16 are totally curtailed and 43.7 percent of Load 16 is shedded.

3.2. The EirGrid

The EirGrid is a state-owned commercial company as independent electricity Transmission System Operator (TSO) and Market Operator (MO) in Ireland. Its power system has 7652 MW of installed capacity and a 4951 MW summer peak demand. It includes 203 load points, 131 synchronous machines, 352 transformers, 398 transmission lines, and 619 buses in different voltage levels from 0.66 kV to 380 kV. Similar to the studies conducted for the test case, severe contingencies up to $k = 8$ are derived for EirGrid power system. The results are presented in Table 6. In addition, CPU time of calculating each contingency is included for a computer with Dual Core CPU at 2.6 MHz, and 2 GB of RAM. Note that this time is for terminating 10 iterations, but the algorithm reaches the optima earlier.

To the best of our experience, contingencies in MV and LV branches have lower and closer level of lost load and have fewer consequences when occurred and more dangerous contingencies are occurred in the higher voltage levels of the grid. As can be seen in Table 6, all contingencies up to $k = 8$ contain components in higher voltage levels namely 110 and 220 kV. Therefore, considering all voltage levels in identifying severe contingencies just enlarges the search space and increases the CPU time without significant effect on the optima.

Table 2
Sequence of cascading loading after each severe N-3 without appropriate remedial actions.

Seq. #	Out of service lines	*CL* (MW)
1	5–8, 6–7, 9–39	0
2	21–22(101.9%)	0
3	23–24(161.1%), 16–24(109.4%), 22–23(108.8%)	1064.4

Table 3
Severe N-4 in the IEEE 39-bus test system by the proposed method.

Run #	Contingencies	k	ϕ_{th}(MW)	*CL* (MW)
1	13–14, 16–19, 21–22, 26–27	4	850	931.4
2	2–3, 4–14, 4–5, 17–18	4	940	980.0

Table 4
Severe contingencies in the IEEE 39-bus obtained by the proposed method.

Contingencies	k	ϕ_{th}(MW)	*CL* (MW)
13–14, 16–19, 21–22, 23–24, 26–27	5	1300	1529.0
2–3, 4–5, 13–14, 16–19, 23–24, 26–27	6	1880	1895.0
2–3, 4–5, 13–14, 16–19, 21–22, 23–24, 26–27	7	2400	2420.0
2–3, 5–6, 6–7, 8–9, 16–19, 21–22, 23–24, 26–27	8	2651	2650.8

Table 5
The affected loads in 39-bus test system in severe N-5.

Load #	3	16	18	21	24	27
Load shed (%)	100	56.3	100	100	100	100
P_{di}(MW)	322	329	158	274	308.6	281

Table 6
Severe contingencies in the EirGrid obtained by the proposed method.

Contingencies	k	ϕ_{th}(MW)	*CL* (MW)	CPU time(s)
1741–1801, 2021–3081	2	80	88.64	952.1
3201–14619, 3281–5381, 4941–31019	3	120	126.64	927.5
1361–2161, 3201–14619, 3281–5381, 4941–31019	4	200	218.29	1002.4
1361–2001, 3201–14619, 3281–5381, 4941–31019, 5001–50019	5	250	255.18	940.5
1361–2001, 2041–4621, 3201–14619, 3281–5381, 3851–4621, 4941_31019	6	310	314.64	988.1
1361–2001, 1741–1801, 2021–3081, 3201–14619, 3281–5381, 3321–4221, 4941–31019	7	330	347.78	951.0
1221–4481, 1721–14619, 2002–3202, 2141–3201, 2202–3342, 2742–3642, 3281–5381, 4941–31019	8	390	428.80	864.7

4. Comparison with other methods

By the aforementioned computer, the CPU time for the 39-bus test system CPU time t_s is about 0.2 s. Therefore, upper limit of computation time is about 20 s for 10 particles and 10 iterations. We experienced that increasing the initial population is more efficient than increasing the number of iterations and also the number of initial particles is better to be proportionally increased by the larger number of system branches. We used 10 and 50 initial particles for the 39-bus and 118-bus systems respectively. Despite of stochastic nature of the proposed method, the optima is usually obtained before 10 iterations in a short CPU time with approximately the same duration for all orders. To show this, we repeated identification of the severe N-3 contingency of 39-bus system for 100 epochs. On average, BPSO found the optima after 3.62 iterations with standard deviation of 2.034 typically takes 13.06 s.

The effectiveness of the proposed method is compared with published results in [14], and [15] in Table 7. It can be learned that the proposed method has the ability to find all severe contingencies, whereas the other methods sometimes cannot do. For instance, in severe N-3, regarding small CPU time, [15] has not found the optima, and for severe N-4, both [14] and [15] have not obtained the target. The

Table 7
Severe contingencies in the IEEE 24-bus test system by different methods.

Ref.	Contingencies	*k*	*CL* (MW)	CPU Time (s)
This paper	16–19, 20-23A, 20-23B	3	309	8.98
[14]	16–19, 20-23A, 20-23B	3	309	2445.7
[15] [a]	15-21A, 15-21B, 16–17	3	266.2	1.7
This paper	12–23,13–23,14–16,15–24	4	491	10.1
[14]	3–24,9–12,11–13,14–16	4	442	1284
[15]	10–12,11–13,14–16,15–24	4	426	0.18
This paper	11–13,12–13,12–23, 14–16,15–24	5	842	9.61
[14]	11–13,12–13,12–23, 14–16,15–24	5	842	1786
[15]	11–13,12–13,12–23, 14–16,15–24	5	842	0.21
This paper	7–8,11–13,12–13,12–23, 14–16,15–24	6	1017	10.07
[14]	7–8,11–13,12–13,12–23, 14–16,15–24	6	1017	380.9
[15]	3–24,7–8,11–13,12–13, 12–23,14–16	6	1017	0.05
[36]	7–8,11–13,12–13,12–23,20-23A, 20-23B	6	775	1201.8

[a] Using duality-based approach.

proposed method spends nearly the same CPU time for all contingencies (about 9 s for IEEE 24-bus). Presented results in Table 6 for [15] are based on duality-based approach while the other method which is based on Karush–Kuhn–Tucker approach needs more CPU times. It is worth noting that we have performed all modifications considered in [14].

Although computational burden is not a primary concern in this category of planning problems but the proposed approach is computationally much more effective than Genetic Algorithm proposed in [30], especially for a large power system.

5. Conclusions

Recent blackouts in power systems actuated regulatory corporations to force utilities for considering multiple contingencies in their operation and planning procedures. Because of the huge number of contingencies in the power system, it is impractical to analyze all of them by traditional methods. The BPSO exploited in this paper with small number of parameters, is efficient for determining severe multiple contingencies which can be used for further investigations such as security analysis or suggesting new transmission expansion plans. Simulation time in the proposed method is independent of the contingency order and severe contingencies of higher orders can be simply identified by this method.

The optimization procedure used in this paper is a bi-level programming in which the number of out of service branches should be minimized while the curtailed load as the consequence must be larger than a pre-defined value. Curtailed load in each contingency is minimized using DC optimal power flow which is solved by Linear Programming. A suitable estimate of minimum load shedding speeds up the identification of severe contingencies properly. However, 2–5 epochs are usually sufficient to find severe contingency of each order.

In this paper, we assumed that multiple contingences as initiating events of cascading outages occur simultaneously because they happen in a short duration in which operators cannot execute corrective actions. Severe contingencies up to order 8 were derived for the IEEE 39-bus test system and the large sized real power grid of EirGrid.

Our experiences revealed that severe and more dangerous contingencies contain components at higher voltage levels. Therefore, considering components of low voltage levels just enlarges the search space and increases the CPU time to find the optima.

Vast executed experiments showed that BPSO can find better solutions in severe contingency analysis, but its speed is not yet so high that to be applicable to real time assessments. However, it can be used as a valuable tool in mid-term or long-term studies in large-scale power systems.

CRediT authorship contribution statement

Abbas Zare Ghaleh Seyyedi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Supervision, Visualization, Writing - original draft, Writing - review & editing. **Mohammad Javad Armand:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Saeid Shahmoradi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Sara Mahmoudi Rashid:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Ehsan Akbari:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft. **Ali Jawad Kadhim Al-Hassanawy:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hines P, Balasubramaniam K, Sanchez EC. Cascading failures in power grids. IEEE Potentials Sep. 2009;28(5):24–30. https://doi.org/10.1109/MPOT.2009.933498.
[2] Karimi E, Ebrahimi A, Mahmud Fotuhi-firuzabad. Exploring self-organized criticality conditions in iran bulk power system with disturbance times series. Sci Iran 2014;21(6):2264–72.
[3] Carreras BA, Newman DE, Dobson I, Poole AB. Evidence for self-organized criticality in a time series of electric power system blackouts. IEEE Trans Circuits Syst I Regul Pap Sep. 2004;51(9):1733–40. https://doi.org/10.1109/TCSI.2004.834513.
[4] Andersson G, Donalek P, Farmer R, Hatziargyriou N, Kamwa I, Kundur P, et al. Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance. IEEE Trans Power Syst 2005;20(4):1922–8.
[5] Eppstein MJ, Hines PDH. A 'Random Chemistry' algorithm for identifying collections of multiple contingencies that initiate cascading failure. IEEE Trans Power Syst Aug. 2012;27(3):1698–705. https://doi.org/10.1109/TPWRS.2012.2183624.
[6] Baldick R. et al., Initial review of methods for cascading failure analysis in electric power transmission systems IEEE PES CAMS task force on understanding, prediction, mitigation and restoration of cascading failures. In: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, Jul. 2008, pp. 1–8, doi: https://doi.org/10.1109/PES.2008.4596430.
[7] Pourbeik P, Kundur PS, Taylor CW. The anatomy of a power grid blackout - Root causes and dynamics of recent major blackouts. IEEE Power Energy Mag Sep. 2006;4(5):22–9. https://doi.org/10.1109/MPAE.2006.1687814.
[8] Kirschen DS, Jayaweera D, Nedic DP, Allan RN. A Probabilistic Indicator of System Stress. IEEE Trans Power Syst Aug. 2004;19(3):1650–7. https://doi.org/10.1109/TPWRS.2004.831665.
[9] Chen Q, McCalley JD. Identifying High Risk N-k Contingencies for Online Security Assessment. IEEE Trans Power Syst May 2005;20(2):823–34. https://doi.org/10.1109/TPWRS.2005.846065.
[10] Bagheri A, Zhao C. Distributionally Robust Reliability Assessment for Transmission System Hardening Plan Under $N-k$ Security Criterion. IEEE Trans Reliab Jun. 2019;68(2):653–62. https://doi.org/10.1109/TR.2019.2893138.
[11] Jia Y, Xu Z, Lai LL, Wong KP. Risk-Based Power System Security Analysis Considering Cascading Outages. IEEE Trans Ind Informatics Apr. 2016;12(2):872–82. https://doi.org/10.1109/TII.2015.2499718.
[12] Bienstock D, Verma A. The N-K Problem in Power Grids: New Models, Formulations and Numerical Experiments (extended version). Dec. 2009, [Online]. Available: http://arxiv.org/abs/0912.5233.
[13] Salmeron J, Wood K, Baldick R. Analysis of electric grid security under terrorist threat. IEEE Trans Power Syst May 2004;19(2):905–12. https://doi.org/10.1109/TPWRS.2004.825888.
[14] Arroyo JM, Galiana FD. On the solution of the bilevel programming formulation of the terrorist threat problem. IEEE Trans Power Syst May 2005;20(2):789–97. https://doi.org/10.1109/TPWRS.2005.846198.
[15] Arroyo JM. Bilevel programming applied to power system vulnerability analysis under multiple contingencies. IET Gener Transm Distrib 2010;4(2):178. https://doi.org/10.1049/iet-gtd.2009.0098.
[16] Donde V, Lopez V, Lesieutre B, Pinar A, Chao Yang, Meza J. Severe multiple contingency screening in electric power systems. IEEE Trans Power Syst 2008;23(2):406–17.
[17] Rocco CM, Ramirez-Marquez JE, Salazar DE, Yajure C. Assessing the vulnerability of a power system through a multiple objective contingency screening approach.

IEEE Trans Reliab 2011;60(2):394–403. https://doi.org/10.1109/TR.2011.2135490.
[18] Davis CM, Overbye TJ. Multiple Element Contingency Screening. IEEE Trans Power Syst Aug. 2011;26(3):1294–301. https://doi.org/10.1109/TPWRS.2010.2087366.
[19] Krishnan V, McCalley JD. Progressive entropy based contingency grouping for deriving decision trees for multiple contingencies. Int J Electr Power Energy Syst Feb. 2013;45(1):35–41. https://doi.org/10.1016/j.ijepes.2012.08.078.
[20] Alizadeh Mousavi O, Cherkaoui R, Bozorg M. Blackouts risk evaluation by Monte Carlo Simulation regarding cascading outages and system frequency deviation. Electr Power Syst Res 2012;89:157–64.
[21] Vaiman, et al. Risk assessment of cascading outages: methodologies and challenges. IEEE Trans Power Syst May 2012;27(2):631–41. https://doi.org/10.1109/TPWRS.2011.2177868.
[22] Gatta FM, Geri A, Lauria S, Maccioni M. Improving high-voltage transmission system adequacy under contingency by genetic algorithms. Electr Power Syst Res Jan. 2009;79(1):201–9. https://doi.org/10.1016/j.epsr.2008.05.013.
[23] Mosquera Palacios DJ, Trujillo ER, López-Lezama JM. Vulnerability analysis to maximize the resilience of power systems considering demand response and distributed generation. Electronics Jun. 2021;10(12):1498.
[24] López Lezama JM, Restrepo Cuestas BJ, Hernández Valencia JP. A bilevel attacker-defender model for enhancing power systems resilience with distributed generation. Sci tech Dec. 2020;25(4):540–7.
[25] Karimi E, Ebrahimi A. Inclusion of blackouts risk in probabilistic transmission expansion planning by a multi-objective framework. IEEE Trans Power Syst Sep. 2015;30(5):2810–7. https://doi.org/10.1109/TPWRS.2014.2370065.
[26] Karimi E, Ebrahimi A. Considering risk of cascading line outages in transmission expansion planning by benefit/cost analysis. Int J Electr Power Energy Syst Jun. 2016;78:480–8. https://doi.org/10.1016/j.ijepes.2015.11.101.
[27] Rios MA, Kirschen DS, Jayaweera D, Nedic DP, Allan RN. Value of security: modeling time-dependent phenomena and weather conditions. IEEE Trans Power Syst Aug. 2002;17(3):543–8. https://doi.org/10.1109/TPWRS.2002.800872.
[28] Kennedy J, Eberhart R. Particle swarm optimization. In: Proceedings of ICNN'95 - International Conference on Neural Networks, vol. 4, pp. 1942–1948, doi: https://doi.org/10.1109/ICNN.1995.488968.
[29] AlRashidi MR, El-Hawary ME. A survey of particle swarm optimization applications in electric power systems. IEEE Trans Evol Comput Aug. 2009;13(4):913–8. https://doi.org/10.1109/TEVC.2006.880326.
[30] del Valle Y, Venayagamoorthy GK, Mohagheghi S, Hernandez J-C, Harley RG. Particle swarm optimization: basic concepts, variants and applications in power systems. IEEE Trans Evol Comput Apr. 2008;12(2):171–95. https://doi.org/10.1109/TEVC.2007.896686.
[31] Kennedy J, Eberhart RC. A discrete binary version of the particle swarm algorithm. In: 1997 IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation, vol. 5, pp. 4104–4108, doi: https://doi.org/10.1109/ICSMC.1997.637339.
[32] Mojtaba Ahmadieh Khanesar, Mohammad Teshnehlab, Mahdi Aliyari Shoorehdeli. A novel binary particle swarm optimization. In: 2007 Mediterranean Conference on Control & Automation, Jun. 2007, pp. 1–6, doi: https://doi.org/10.1109/MED.2007.4433821.
[33] Hajian M, Ranjbar AM, Amraee T, Mozafari B. Optimal placement of PMUs to maintain network observability using a modified BPSO algorithm. Int J Electr Power Energy Syst Jan. 2011;33(1):28–34. https://doi.org/10.1016/j.ijepes.2010.08.007.
[34] "39-bus." http://khorshid.ut.ac.ir/~h.ahmmadi/download_files/case39.m.
[35] Khodabakhshian A, Hemmati R. Multi-machine power system stabilizer design by using cultural algorithms. Int J Electr Power Energy Syst Jan. 2013;44(1):571–80. https://doi.org/10.1016/j.ijepes.2012.07.049.
[36] Arroyo JM, Fernández FJ. Application of a genetic algorithm to n-K power system security assessment. Int J Electr Power Energy Syst Jul. 2013;49:114–21. https://doi.org/10.1016/j.ijepes.2012.12.011.