Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 4682 – 4692

doi:10.3906/elk-1502-108

An interval-based contingency selection approach considering uncertainty

Chao XU[1], Wei GU[1,*], Lizi LUO[1], Jianguo YAO[2], Shengchun YANG[2], Ke WANG[2], Dan ZENG[2], Miao FAN[3]
[1]School of Electrical Engineering, Southeast University, Nanjing, P.R. China
[2]China Electric Power Research Institute, Nanjing, P.R. China
[3]Siemens Industry, Inc., Schenectady, NY, USA

Received: 14.02.2015 • **Accepted/Published Online:** 25.08.2015 • **Final Version:** 06.12.2016

Abstract: Static security assessment is affected by uncertainties of load flow distributions introduced by renewable sources. A fast contingency selection approach based on interval theory is proposed in this paper. Firstly, an interval line active flow calculation algorithm is developed to reduce conservation in application of interval mathematics in line flow calculation. Then a novel interval comparison method based on Bayesian probability theory is applied in interval index comparison to give the relative severity information of contingencies. Finally, an approximately consistent ranking method is utilized in contingency ranking to rank screened contingencies. Numerical studies on several IEEE standard test systems and two practical provincial power grids in China under different load and generation conditions have proved that the proposed approach is computationally light and highly accurate under different uncertainties.

Key words: Contingency selection, Bayesian probability theory, DC power flow, interval arithmetic, uncertainty

1. Introduction

With the desire for environmentally responsible energy use, renewable resources of electricity such as wind and solar power have increasingly contributed to the existing power grid. Since these resources are highly intermittent, variable, and difficult to forecast accurately, analysis and operation of a power system based on these resources are obviously affected [1].

In static security assessment (SSA), deterministic methods were developed to analyze and evaluate contingencies that should be secured against and to promote continuity of service without excessive cost [2]. Power flow analysis, when given a predetermined generation and load profile at a particular instant, laid the foundation of contingency analysis and is widely used by operators to take snapshots of system states and judge the level of static security [3]. When considering indeterminate generation and load profiles, system static states may vary among different levels such that the assessment of static security turns out to be uncertain [4].

Uncertain parameters in power system studies can be generally classified into two different categories: technical parameters and economic parameters. Various uncertainty handling methods were developed to deal with uncertain parameters [5]. In SSA under uncertainty, the main task is to deal with uncertain technical parameters such as the topological parameters and operational parameters. The power flow method is still regarded as the effective method in some problems such as unit commitment and SSA under uncertainties [6]. Previous approaches of assessing effects of uncertainties in power flow can be grouped into probabilistic

---

[*]Correspondence: wgu@seu.edu.cn

and fuzzy-set theoretical methods. In probabilistic power flow, uncertainties in load and power generation are modeled by random variables distributed according to probability density functions [7]. Power flow solutions are described by random variables with a certain probability distribution [8]. Both numerical and analytical methods have been proposed to address the probabilistic power flow problem [9]. In the fuzzy-set theoretical method [10], system parameters and variables are assumed to be imprecise but can be modeled using fuzzy sets. For example, with interval power flow [11], as a particular branch of fuzzy power flow, the method assumes that uncertain parameters usually have the property of being "unknown but bounded" and thus can be modeled by interval numbers [12]. All the above makes a great contribution to contingency analysis under uncertainty for static security assessment. In this research, an interval model is utilized mainly because renewable energy sources cannot be predicted precisely but within acceptable accuracy in a few hours before operation.

Few studies were found on static security assessment in the operational horizon considering system uncertainty. Most existing research has either concentrated on the economic implications of security for planning [13] or resorted to a statistical based method for risk analysis [14]. Reference [15] dealt with the assessment of the static and dynamic security of a real network considering a large set of uncertainties using a statistical method. The method was based on Monte Carlo samplings, dynamic simulations, and probability assessment. Reference [16] presented a probabilistic method of fast static security analysis for the planning of a power system containing wind power based on a sensitivity analysis and probabilistic load flow calculation. Reference [17] proposed a power flow approach based on affine arithmetic to quantify risks due to uncertainties and applied it to automatic contingency selection under uncertainties.

In this paper, a new contingency selection approach based on interval theory for online static security assessment considering uncertainty is proposed. The rest of this paper is organized as follows: section 2 briefly introduces the application of interval mathematics in contingency selection and disadvantages. Section 3 proposes and describes in detail the fast contingency selection approach based on interval computation and comparison. In section 4, the proposed approach is tested on several IEEE standard test systems and two practical provincial power grids in China.

2. Application of interval arithmetic in contingency selection

Contingency selection is performed to analyze the effect of specified contingencies on a system security and to alert operators to the critical contingencies that violate limits or drive the system to instability or excessive frequency deviations. In SSA, contingency selection usually considers transmission line limit violations, transformer thermal overloads, and inadequate voltage levels at system buses. Given this information, system operators can judge the relative severity of each specified contingency and decide if preventive actions should be initiated to mitigate potential problems [18].

2.1. DC power flow in contingency selection

In contingency selection for transmission systems, DC power flow has gained widespread use mainly due to the weak coupling between real power and reactive power equations and its acceptable accuracy. The other reason is that, compared to voltage problem with its local nature, the solution to a real power problem is much more expensive [17]. Voltage phase angles and active power flow through branch $i-j$ are approximated as

$$P_{inj} = B \cdot \theta, P_{ij} = -B_{ij}\theta_{ij} = \frac{\theta_i - \theta_j}{x_{ij}}, \tag{1}$$

where P_{inj} is the bus injection power vector (for which the slack bus is not included), B is the system admittance matrix, and θ is the bus voltage phase angle vector. P_{ij} is the line active power flow (from bus i to bus j) and B_{ij} is the line admittance between bus i and bus $j.\theta_{ij}$ is the difference in the voltage phase angle between bus i and bus j, while x_{ij} is the line reactance between bus i and bus j.

Active power performance index (PI) is widely adopted. Severity of contingency is indicated by scalar PIs that measure system stress in terms of transmission line overloads. Real power PI is defined to quantify the extent of line overloads:

$$PI=\sum_{\alpha}\omega_p\left(\frac{P_l}{P_l^{\max}}\right)^2, \tag{2}$$

where ω_p is the line active power weighting factor and P_l is the line active power flow of line l. P_l^{max} is the transmission line flow capacity limit and α is the set of overload lines.

2.2. Interval arithmetic in contingency selection with DC power flow

Interval mathematics consists of methods for handling intervals that approximate uncertain data. Interval arithmetic (IA) operations are defined that the interval encloses all possible results. An interval number is a set [x] = $[\underline{x},\bar{x}]=\{\mathrm{x}\in\mathrm{R}|\underline{x}\le x\le\bar{x}\}$. Considering interval numbers [x] and [y], elementary operations are defined as Eqs. (3)–(6) in order to guarantee reliability [12].

$$[x]+[y]=\left[\underline{x}+\underline{y},\overline{x}+\overline{y}\right] \tag{3}$$

$$[x]-[y]=[\underline{x}-\overline{y}\overline{x}-\underline{y}], \tag{4}$$

$$[x]*[y]=[\min\left(\underline{x}*\underline{y},\underline{x}*\overline{y},\overline{x}*\underline{y},\overline{x}*\overline{y}\right)max\left(\underline{x}*\underline{y},\underline{x}*\overline{y},\overline{x}*\underline{y},\overline{x}*\overline{y}\right)] \tag{5}$$

$$[x]\,/\,[y]=[\underline{x},\overline{x}]*[1/\overline{y},1/\underline{y}], \tag{6}$$

Application of interval mathematics in contingency selection is mainly focused on the use of interval arithmetic in interval DC power flow [19] and PI computation. The disadvantage of IA is that results are often conservative after steps of interval operations. For example, in line active power calculation, according to Eqs. (1) and (4), interval line flow can be computed as

$$[P_{ij}]=\frac{[\theta_i]-[\theta_j]}{x_{ij}}=\frac{[\underline{\theta_i}-\overline{\theta_j},\overline{\theta_i}-\underline{\theta_j}]}{x_{ij}} \tag{7}$$

The traditional method treats phase angles of adjacent buses as independent interval variables and thus interval operation was directly applied in the interval line flow calculation. Lack of consideration of correlation in phase angles derived from independent bus power injections expands the width of intervals of line flow. In fact, phase angles of two neighbor buses are rarely at their opposite bounds simultaneously; they are all determined by nodal power injections so that it is not appropriate to treat them as independent interval variables. Since interval line flow results play a vital role in contingency screening, the expansion leads to more conservative results and thus clearly affects contingency screening and ranking.

3. Fast contingency selection based on interval theory

Contingency selection under various conditions, especially under uncertainty, is much more complicated and time consuming. An important factor that limits the speed is the enormous number of contingency scenarios resulting from uncertain nodal injections and it is impossible to investigate all hypothetical states. The contingencies should be properly and quickly screened and ranked to obtain credible results.

In this study, postcontingency states are characterized by interval values and interval PI is utilized for contingency screening and ranking. An interval line power flow calculation method combining power transfer distribution factor and interval arithmetic is firstly proposed for postcontingency state assessment. An interval-number comparison method based on Bayesian probability theory is then applied in the interval index comparison. Finally, an approximate consistent ranking method is employed in contingency ranking.

3.1. Interval line flow calculation method for fast contingency selection

In this paper, a novel direct method to obtain specific interval line flow is proposed. Unlike previous work, this method deals with interval bus injections rather than interval phase angles. By introducing interval arithmetic and power transfer distribution factor into the calculation, suitable results are obtained for further interval PI computations.

Considering a system with n buses and m branches, interval line flow can be calculated according to [20]

$$[P_l] = X_m^{-1} M^T [\theta], \tag{8}$$

where $[P_l]$ is interval line flow and $[\theta]$ is interval phase angle, $\boldsymbol{X}_m$ is an m-dimensional diagonal matrix of line reactance, and M is an incidence matrix of buses and branches.

According to (1), line flow can be further derived as

$$[P_l] = X_m^{-1} M^T X [P_{inj}] = PTDF \cdot [P_{inj}], \tag{9}$$

where $\boldsymbol{X}$ is the nodal impedance matrix, $[P_{inj}]$ is the interval node injection power, and $PTDF$ is power transfer distribution factor.

Eq. (9) fundamentally expresses the connection between interval line flow and independent interval nodal injections. Interval line flow is directly obtained from interval power injections so that no more interval computation is introduced. Furthermore, interval bus injections are handled independently of each other and no additional conservation in computation of correlative phase angles is introduced. Improvement in the solution of line flow makes a considerable contribution to the PI calculation for contingency screening and ranking.

Interval PI in (2) can be obtained based on interval line flow results

$$[PI] = \sum_{\alpha} \omega_p \left(\frac{[P_l]}{P_l^{\max}}\right)^2, \tag{10}$$

where $[P_l]$ and $[PI]$ are the interval forms of the interval line active power flow and PI.

3.2. Contingency selection based on interval comparison and ranking

The purpose of contingency selection is to screen and rank severe contingencies to avoid exhaustive studies. In interval contingency analysis, the infimum and supremum of interval line flow that exceeds the branch power limit were regarded as power violations. Contingency screening is done above through postcontingency analysis and evaluation; the rest turns out to be comparing interval indices and ranking screened contingencies.

3.2.1. Contingency comparison based on interval method

Few studies have been conducted on the ranking of interval PIs for contingency selection. Previous work mainly involved interval number comparison. The pairwise relationship of two interval numbers based on typical values such as midpoint is usually applied, thus lacking suitability. In this paper, interval contingency index is compared based on interval and probability theory. To evaluate relative severity, a complementary judgment matrix is generated through pairwise comparison of screened interval indices.

Interval number is the α-cut representation of fuzzy numbers. According to the Bayesian principle of insufficient reason and interval modeling of nodal injections, interval numbers can be assumed uniformly distributed within ranges [21]. As shown in the Figure, only three cases of locations need to be considered: separation, overlapping, and inclusion. Comparison of two interval PIs is considered as comparison of two random variables a and b distributed in independent intervals $A = [a_L, a_U]$ and $B = [b_L, b_U]$.

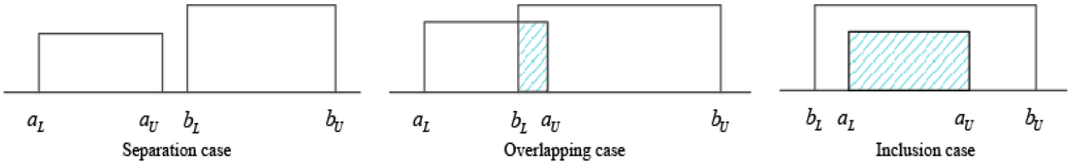

Figure. Spatial location relations of interval numbers.

The comparison method based on a probabilistic approach is expressed by composite probability:

$$P(B \geq A) = \sum_{k=1}^{n} P(H_k) P(B \geq A/H_k), \tag{11}$$

where $P(H_k)$ is the probability of occurrence of event H_k and $P(B \geq A/H_k)$ is the conditional probability that $B \geq A$ given H_k. H_k denotes events representing all cases of random values a and b falling into subintervals A_i and B_j. A_i and B_j are subintervals formed by the boundaries of compared intervals A and B such that $A = \cup_i A_i$ and $B = \cup_j B_j$. $P(H_k)$ is obtained geometrically when interval values are distributed as previous descriptions and belonging to three independent categories. Take the overlapping case for example; other cases are similar. There is a set of four events in this case:

$$H_1: \; a \in [a_L, b_L] \wedge b \in [b_L, a_U], \quad H_2: \; a \in [a_L, b_L] \wedge b \in [a_U, b_U],$$

$$H_3: \; a \in [b_L, a_U] \wedge b \in [b_L, a_U], \quad H_4: \; a \in [b_L, a_U] \wedge b \in [a_U, b_U].$$

Probabilities of each event are

$$P(H_1) = \frac{b_L - a_L}{a_U - a_L} \frac{a_U - b_L}{b_U - b_L}, \quad P(H_2) = \frac{b_L - a_L}{a_U - a_L} \frac{b_U - a_U}{b_U - b_L},$$

$$P(H_3) = \frac{a_U - b_L}{a_U - a_L} \frac{a_U - b_L}{b_U - b_L}, \quad P(H_4) = \frac{a_U - b_L}{a_U - a_L} \frac{b_U - a_U}{b_U - b_L} \tag{12}$$

Events H_1, H_2, and H_4 can be regarded as evidence of $B \geq A$ and thus conditional probabilities of each event can be derived as

$$P(B \geq A/H_1) = P(B \geq A/H_2) = P(B \geq A/H_4) = 1. \tag{13}$$

Event $b = a$ contained in the event $B \geq A$ has small probability when selecting numbers from two intervals as it would be rare that a and b are equal by coincidence. When considering event H_3, which is evidence of events $a \in [b_L, a_U]$ and $b \in [b_L, a_U]$, it may hold that both $B \geq A$ and $B \leq A$. It is assumed that there are equal chances for the two results when event H_3 occurs:

$$P(B \geq A) = P(B < A) = 0.5. \tag{14}$$

From (12) and (14), we obtained

$$P(B \geq A) = 1 - \frac{1}{2}\frac{(a_U - b_L)^2}{(a_U - a_L)(b_U - b_L)}. \tag{15}$$

Severities of consequences of the postcontingency system under uncertainty based on the interval method are described by interval PIs. Comparison and ranking of severities of screened contingencies become sequencing interval indices.

3.2.2. Contingency ranking based on an approximate consistent ranking method

An approximately consistent ranking method based on fuzzy mathematics according to the information matrix is then presented in this section to rank screened contingencies. By applying results of paired comparison of interval indices of each screened contingency, a comparative information matrix is established. The matrix (denoted C) is an N-dimensional square fuzzy judgment matrix. Elements of C (denoted $c_{ij}; i = 1, 2, \ldots, n; j = 1, 2, \ldots n$) are the extent index of contingency i is greater than contingency j and is obtained according to the above section.

Interval contingency ranking is an application of a multiple-attribute decision-making problem. Attribute set $X = (x_1, x_2, x_3, \ldots, x_n)$ is regarded as a decision factor set and fuzzy binary relation of X is recorded in fuzzy judgment matrix $R = (r_{ij})_{n\times n}$. Matrix R indicates relatively important relationships among attributes. In dualistic decision-making theory, dualistic relation is expressed by fuzzy judgment matrix (denoted C in above description) in which constraints $0 \leq c_{ij} \leq 1$ and $c_{ij} + c_{ji} = 1$ should be guaranteed.

In the definition, matrix C is referred to as perfectly consistent complementary if $c_{ik}c_{ki}c_{ji} = c_{ki}c_{jk}c_{ij}$. To generate the unique ranking vector considering lack of perfect consistency, this paper applies an arithmetic derived from the definition of perfect consistency based on normalizing rank aggregation [22]. It has two primary steps.

Step 1: regenerate a new matrix $R = (r_{ij})_{n\times n}$ based on judgment matrix C. Grand totals are calculated for rows of the former matrix $C = (C_{ij})_{n\times n}$ according to (16):

$$r_i = \sum_{k=1}^{n} c_{ik}, i = 1, 2, \cdots, n r_{ij} = \frac{r_i - r_j}{2(n-1)} + 0.5. \tag{16}$$

Step 2: obtain a ranking vector based on normalizing rank aggregation method according to Eq. (17)

$$w_i = \sum_{j=1}^{n} r_{ij} / \sum_{i=1}^{n}\sum_{j=1}^{n} r_{ij}. \tag{17}$$

The algorithm for ranking vector formulation derived from the fuzzy complementary judgment matrix is applied in contingency comparison and ranking. This method not only makes use of characteristics of the comparison matrix but also consumes less computational resources. Screened contingencies are ranked according to elements of the vector.

4. Simulation results

The proposed work aims to develop an online contingency selection approach considering load and generation uncertainty. To demonstrate the effectiveness of the approach, studies are conducted on several IEEE benchmark systems and two practical provincial power grids in China, namely Ningxia 151-bus and Jiangsu 1079-bus systems. Some detailed results are omitted due to space limitations. Results obtained with the proposed method are compared with those obtained from Monte Carlo simulations in terms of computational accuracy (capture rate), ranking order, and computational cost. All simulations are conducted with MATPOWER 4.0 and several interacting software packages developed for interval arithmetic.

4.1. Capture rate of the proposed method

Branch outages of the IEEE 30-bus system are studied for a detailed illustration of capture rate statistics and statistical information is presented in Table 1. Results of the interval method compared to Monte Carlo simulations (regarded as the “exact” results) are presented. In Table 1, F–T refers to the transmission line between “From” and “To” buses selected. MC refers to the violation check result of numbers of line flow violations in the Monte Carlo flow test (in each outage, sample size = 10^5). IM refers to violation check results of the proposed interval method. CR refers to capture rate calculation results (in percentage). FA refers to number of false alarms. In addition, “*” indicates no violation and thus CR could not be computed and “–” indicates no false alarms.

Table 1. Simulation results for the IEEE 30-bus test system.

Contingency	Line limit violations (Tolerance 10%)				Line limit violations (Tolerance 15%)				Line limit violations (Tolerance 20%)			
F–T	MC	IM	FA	CR	MC	IM	FA	CR	MC	IM	FA	CR
6–8	1	1	0	100	1	2	1	100	2	2	0	100
12–13	0	0	0	*	1	1	0	100	1	3	2	100
12–16	0	0	0	*	0	1	1	-	1	1	0	100
16–17	0	0	0	*	0	0	0	*	0	2	2	-
10–20	1	1	0	100	1	1	0	100	1	2	1	100
21–22	0	0	0	*	0	1	1	-	1	1	0	100
15–23	1	1	0	100	1	2	1	100	2	3	1	100
22–24	0	0	0	*	0	1	1	-	1	1	0	100
23–24	1	1	0	100	1	2	1	100	1	3	2	100
28–27	1	1	0	100	2	3	1	100	3	4	1	100
8–28	1	1	0	100	1	1	0	100	1	1	0	100
6–28	0	0	*	*	0	1	1	-	1	1	0	100
Numbers of contingencies in sets under different uncertainties												
STATS	6	6	0		7	11	4		11	12	1	

Outages that may cause line flow violations are screened and listed in column “Contingency”. The STATS row is the statistical result of the number of contingencies in contingency sets under different tolerances of uncertainty to be validated. The data show that when the uncertainty tolerance of nodal injections is relatively small (10%), violations captured by the interval method are the same as the Monte Carlo test and result in the same number of contingencies in the contingency set. CR is 100% and there are no false alarms. When tolerance becomes larger (15% to 20%), though CRs are still 100%, all violations are still captured and the number of false alarms increases a little due to the conservation nature of the interval algorithm. In the authors' opinion, the most important point of contingency screening is to guarantee no contingency is left and thus the conservative result still has reference value. The proposed interval method has high precision if tolerances of uncertainty are within acceptable ranges. When tolerance increases, conservation is brought into contingency screening and thus a few false alarms occur.

A similar test is conducted on the Ningxia 151-bus system with 56 generators and 252 branches. In this system, output powers of 11 generators and 12 loads are uncertain, representing renewable energy and imprecise load forecast. In addition, 10%, 15%, and 20% tolerances are selected and 4, 8, and 17 contingencies are screened with 5, 12, and 19 violations captured separately. In this case, contingency screening results of the interval method perfectly match the Monte Carlo simulations mainly due to the medium load levels of the power grid.

4.2. Contingency ranking with the proposed interval method

A ranking list of screened contingencies is necessary for further validation of static security. Tests are done in the Ningxia 151-bus and Jiangsu 1079-bus systems under different tolerances of uncertainty to illustrate the efficiency of the proposed method. Detailed results of the Jiangsu 1079-bus system are listed in Table 2. Contingencies are compared and ranked according to their severities using the interval index value computed using (10) and the ordering vector is calculated according to (17). This system contains 153 generators and 1870 transmission lines. Twenty-one buses connected with renewable energy and 427 loads are thought to be uncertain. The top 20 contingencies are listed in detail.

In the table, the STATS row shows that the number of screened contingencies grows with an increase in tolerance. Ranking order by the proposed method is similar to that of the Monte Carlo simulation with only a few order changes and no more than 3 false alarms. This result shows the good robustness of the proposed approach in contingency ranking.

4.3. Computational cost of the proposed method

The computational efficiency of contingency selection is investigated. The computational time required for contingency selection is tested on a desktop with a Core i5 CPU and 4 GB RAM. Table 3 illustrates computation time required for conducting contingency selection in different test systems. It can be seen that the proposed approach is much faster than the Monte Carlo method and computational time cost increases slowly with system size.

5. Conclusion

This paper contributes a fast contingency selection approach for assessing the security of a power system against line outages under uncertainties of load and generated power. An interval calculation and comparison technique based on combined interval and probabilistic theory was employed to screen and rank contingencies under different tolerances of uncertainty.

The proposed approach reduces conservation in line flow calculation by reducing interval computation and considering the correlation of phase angles. Capture rate results show that the approach has high precision in contingency screening when uncertainty tolerances are within acceptable ranges. When dealing with large

Table 2. Contingency ranking list under different uncertainty tolerances for the Jiangsu 1079-bus system.

Ranking order	5% tolerance		10% tolerance		15% tolerance	
	IM	MC	IM	MC	IM	MC
1	7130–130	119–120	7130–130	7130–130	7130–130	7130–130
2	119–120	7130–130	119–120	119–120	119–120	119–120
3	234–236	234–236	234–236	234–236	234–236	234–236
4	190–231	190–231	190–231	190–231	190–231	190–231
5	231–232	231–232	231–232	231–232	231–232	231–232
6	231–237	231–237	231–237	231–237	231–237	231–237
7	241–237	241–237	241–237	241–237	133–171	241–237
8	221–223	221–223	221–223	221–223	241–237	221–223
9	238–239	238–239	238–239	238–239	7139–139	238–239
10	191–192	133–171	191–192	133–171	221–223	133–171
11	133–171	191–192	133–171	191–192	238–239	191–192
12	7139–139	7139–139	7139–139	7139–139	191–192	7139–139
13	125–126	125–126	125–126	125–126	133–137	125–126
14	214–215	214–215	214–215	214–215	125–126	214–215
15	220–238	220–238	220–238	220–238	214–215	220–238
16	2–8	225–191	2–8	225–191	220–238	225–191
17	225–191	2–8	225–191	2–8	225–191	2–8
18	136–152	136–152	133–137	136–152	2–8	133–137
19	62–64	62–64	136–152	63–64	136–152	136–152
20	63–64	63–64	62–64	62–64	59–61	63–64
	Contingency sets under different uncertainty					
STATS	60	60	64	62	71	68

Table 3. Computational time required for each test system.

Test systems	Time required for contingency selection (s)						
	IEEE 9-bus	IEEE 30-bus	IEEE 57-bus	IEEE 118-bus	Ningxia 151-bus	IEEE 300-bus	Jiangsu 1079-bus
Proposed method	0.079	0.640	2.431	7.903	13.769	22.437	374.241
MC	5.839	39.081	100.996	430.012	938.176	3602.77	>7 h

systems, it is still reliable because no violation is missed although a few false alarms occur. In contingency ranking, it gives ranking orders similar to those obtained by the Monte Carlo test under different tolerances of uncertainty. The approach is designed to simulate the boundary of system states based on interval theory so that numerous sampling calculations can be reduced. The acceptable accuracy and significantly reduced computation time indicate that the approach has broad prospects in online application.

Acknowledgments

This work was supported by the National High Technology Research and Development Program of China (863 Program Grant 2012AA050210), the National Science Foundation of China (51277027), the State Grid Corporation of China (dz71-13-036), and the Natural Science Foundation of Jiangsu Province of China (SBK201122387).

References

[1] Bessa RJ, Matos MA, Costa IC, Bremermann L, Franchin IG, Pestana R, Machado N, Waldl HP, Wichmann C. Reserve setting and steady-state security assessment using wind power uncertainty forecast: a case study. IEEE T Sustain Energy 2012; 3: 827-836.

[2] Paul JP, Bell KRW. A flexible and comprehensive approach to the assessment of large-scale power system security under uncertainty. Int J Electr Power Energy Syst 2004; 26: 265-272.

[3] Chauhan S. Fast real power contingency ranking using counter propagation network: feature selection by neuro-fuzzy model. Electric Power Syst Res 2005; 73: 343-352.

[4] Henry S, Pompée J, Devatine L, Bulot M, Bell, K. New trends for the assessment of power system security under uncertainty. In: IEEE PES Power Systems Conference and Exposition; 10–13 Oct 2004; New York, NY, USA: IEEE. pp. 1380-1385.

[5] Soroudi A, Amraee T. Decision making under uncertainty in energy systems: state of the art. Renew Sustain Energy Rev 2013; 28: 376-384.

[6] Ruiz PA, Brick Phil, Zak E, Cheung KW, Sauer PW. Uncertainty management in the unit commitment problem. IEEE T Power Syst 2009; 24: 642-651.

[7] Fan M, Vittal V, Heydt GT, Ayyanar R. Probabilistic power flow studies for transmission systems with photovoltaic generation using cumulants. IEEE T Power Syst 2012; 27: 2251-2261.

[8] Villanueva D, Feijoo AE, Pazos JL. An analytical method to solve the probabilistic load flow considering load demand correlation using the DC load flow. Electric Power Syst Res 2014; 110: 1-8.

[9] Fan M, Vittal V, Heydt GT, Ayyanar R. Probabilistic power flow analysis with generation dispatch including photovoltaic resources. IEEE T Power Syst 2013; 28: 1797-1805.

[10] Heleno M, Sumaili J, Meirinhos J, da Rosa MA. A linearized approach to the symmetric fuzzy power flow for the application to real systems. Int J Electr Power Energy Syst 2014; 54: 610-618.

[11] Pereira LES, da Costa VM, Rosa ALS. Interval arithmetic in current injection power flow analysis. Int J Electr Power Energy Syst 2012; 43: 1106-1113.

[12] Moore RE. Methods and Applications of Interval Analysis, Philadelphia, PA, USA: SIAM Publications, 1979.

[13] Grijalva S, Dahman SR, Patten KJ, Visnesky AM. Large-scale integration of wind generation including network temporal security analysis. IEEE T Energy Convers 2007; 22: 181-188.

[14] Papaefthymiou G, Verboomen J, Schavemaker PH, van der Sluis, L. Impact of stochastic generation in power systems contingency analysis. In: International Conference on Probabilistic Methods Applied to Power Systems; 11–15 June 2006 KTH, Stockholm, Sweden: IEEE. pp. 142-147.

[15] Henry S, Pompee J, Bulot M, Bell K. Applications of statistical assessment of power system security under uncertainty. In: International Conference on Probabilistic Methods Applied to Power Systems; 12–16 September 2004; Iowa State Univ, Ames, IA, USA: IEEE. pp 914-919.

[16] Jiang P, Yang S, Huo Y. Static security analysis of power systems considering randomness of wind farm output. Automation of Electric Power Systems 2013; 37: 35-40.

[17] Wang S, Han L, Zhang P. Affine arithmetic-based DC power flow for automatic contingency selection with consideration of load and generation uncertainties. Electr Pow Compo Sys 2014; 42: 852-860.

[18] Sunitha R, Kumar RS, Mathew AT. Online static security assessment module using artificial neural networks. IEEE T Power Syst 2013; 28: 4328-4335.

[19] Wang Z, Alvarado FL. Interval arithmetic in power flow analysis. IEEE T Power Syst 1992; 7: 1341-1349.

[20] Kumar A, Kumar J. ATC determination with FACTS devices using PTDFs approach for multi-transactions in competitive electricity markets. Int J Electr Power Energy Syst 2013; 44: 308-317.

[21] Sevastianov P. Numerical methods for interval and fuzzy number comparison based on the probabilistic approach and Dempster-Shafer theory. Information Science 2007; 77: 4645-4661.

[22] Xu ZS, Wei CP. A consistency improving method in the analytic hierarchy process. European Journal of Operational Research 1999; 116: 443-449.