Probabilistic Security Evaluation Software for Bulk Power System Considering Bus Arrangement

Hailei He, Jianbo Guo, Yunting Song and Dongxia Zhang

***Abstract*—more accurate algorithm based on analytical approach for probabilistic security evaluation is proposed in this paper. New software named PSD-PRE is developed using Visual FORTRAN and Visual C++. It achieves calling of PSD-BPA which is the basis of PSD-PRE for state evaluation. Trait of PSD-PRE is that it can evaluate bulk power system probabilistic security considering bus arrangement. It makes the calculation results more accurate. Accelerating algorithm is adopted to alleviate the calculation burden of PSD-PRE. Not only the single or double faults of line or transformer but also the multi-fault caused by protection failure to operate or rejection can be modeled to get the probabilistic security risk indices. PSD-PRE has been tested by IEEE-RTS79 test system. Simulation results show that PSD-PRE is valid, available and indices can be used as the basis of transmission network planning.**

***Index Terms*—Bulk power system, Bus arrangement, Security, Probabilistic evaluation, Analytical method.**

I. Introduction

In recent years, blackout occurs one by one in the world [1]. These events expose weakness of power grid. In order to prevent this kind blackout occurring, it's needs to insist overall reliability evaluation on transmission network planning, design and operation. With this starting point, reliability research is gradually developed from adequacy evaluation to probabilistic security evaluation [2]-[9]. Existing reliability assessment software like TPLAN, GATOR, CONFTRO etc. are adequacy evaluation software [10]. So, evaluating system probabilistic security needs to adopt the manual method which calculation burden is very heavy. In the power market environment, risk assessment as well as cost / benifit analysis has become the important basis for transmission network planning and operation. Its evaluation result must ensure precision.

Raise calculation precision will naturally increase calculation quantity. Calculation burden is heavy especially when power grid has large scale. Therefore it's very hard to evaluate bulk power system probabilistic security considering bus arrangement. General method that evaluation indices are lower than the actual indices is evaluating high voltage power grid only. There is another more precise method which divides bulk power system into two parts: high voltage power grid and bus arrangement; then evaluates each part. But this method still exist obvious error. When evaluating bus arrangement probabilistic security, it is normally assumed that outlet is completely reliability [11]. Actually, outlet is not completely security.

New probabilistic security evaluation software named PSD-PRE is developed in this paper. It can evaluate bulk power system probabilistic security considering bus arrangement. Like failures caused by protection failure to operate or rejection can be modeled to get precise probabilistic security indices. These indices can provide logical and precise gist for transmission network planning and analysis.

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II. General Function of Software

A. *Principle of Software Design*

PSD-PRE software is designed by following four steps:

(1) Calling of PSD-BPA

Power flow data file *.DAT and transient stability data file *.SWI of PSD-BPA can be used as original input file through calling of PSD-BPA.

(2) Deposit parameter of research system

Parameters of elements such as line, node, generator, and transformer etc. getting from power flow data file are stored to get fault set. Then, PSD-BPA power flow program is executed to get result files.

(3) Carry out transient stability evaluation

On the foundation of *.BSE file, transient stability program is carried out under different fault condition and corresponding *.out file is saved up.

(4) Probabilistic security evaluation

Transient stability result file is analyzed to get the result set of probabilistic security evaluation. Then, risk indices are got through probabilistic security evaluation.

PSD-PRE software design process is as shown in Fig.1:

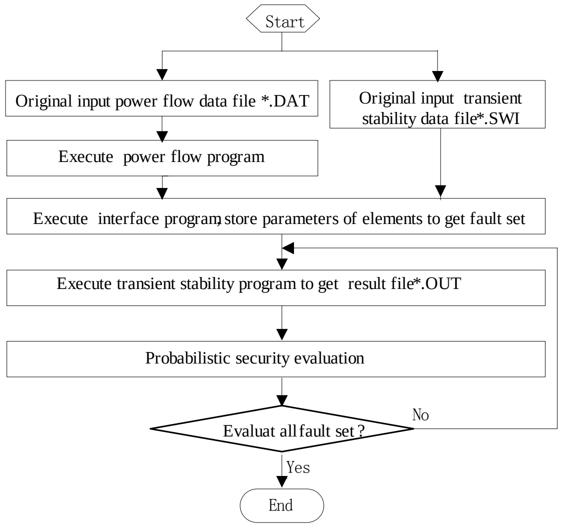

Fig.1 Flowchart of probabilistic security evaluation

B. Main Function of Software

Overall single element fault mode and part double elements fault mode are considered in risk assessment algorithm.

Single element fault modes are shown as follows: (1) Transmission line permanent short-circuit (including single phase to ground short-circuit, two-phase to ground short-circuit, phase to phase short-circuit, three-phase short-circuit); (2) Transmission line transient short-circuit; (3) Transmission line open circuit; (4) Short-circuit on bus-bar; (5) Short-circuit on transformer; (6) Fault of generator.

Double elements fault modes are shown as follows: (7) For dual circuit line, three-phase permanent short circuit on one circuit, and mal-operation of relay protection on the other; (8) Power transmission line short-circuit fault, one side switch failure to operate; (9) Short-circuit fault of bus, bus differential protection failure to operate; (10) Synonym phase fault of two circuits in dual circuit or multi-circuit on the same tower; (11) Simultaneous fault on any double circuits (including single phase to ground short-circuit, two-phase to ground short-circuit, phase to phase short-circuit, three-phase short-circuit).

As far as the calculation burden of analytical method is very heavy, accelerating algorithm is adopted to improve software efficiency. According to the severity degree of each fault, calculation order is determined. If system keep stability after calculating serious fault, next fault which severity degree lower than calculating fault do not need to calculate. According to fault above, fault 7-11 which relatively severity than other faults need to be calculated. Other faults calculation order is as follows:

Define Line fault: ①Three-phase short-circuit ②Three-phase open circuit ③Two-phase open circuit ④Single phase open circuit ⑤Two-phase to ground short-circuit ⑥Phase to phase short-circuit ⑦Single phase to ground short-circuit, auto-reclosing successful ⑧Single phase to ground short-circuit, auto-reclosing unsuccessful.

Severity degree of fault above is:

① { ② ③ ④
  { ⑤ ⑥ ⑦ ⑧

(1) if fault ① occur, system keep stability, faults behind ① are not calculated ; else fault ② and ⑤ need to be calculated; (2) if fault ② occur, system keep stability, faults behind ② are not calculated; else fault ③ needs to be calculated; (3) if fault ⑤ occur, system keep stability, faults behind ⑤ are not calculated; else fault ⑥ needs to be calculated. Other faults calculation order is similar to the above.

PSD-PRE software can realize four functions: (1) carry out deterministic analysis of single or multi-fault; (2) carry out entire system security evaluation, and give dynamic probabilistic risk indices; (3) optimization assessment of many planning schemes; (4) for single planning scheme, weak links can be discovered by analyzing dynamic probabilistic risk indices.

Function (1) and (2) can get through directly calculation by PSD-PRE software. Function (3) and (4) can be used to supervise transmission network planning.

C. Input Interface

If user wants to carry out deterministic analysis, button "deterministic fault analysis" is just needed to be clicked. Then, the interface as shown in Fig.2 is pop-up.

On this interface, the following steps must be complied. First, select path of power flow data file; second, select path of transient stability data file; third, select zone needing to be calculated.

At this time, if user clicks the button "calculation", software will calculate fault with default parameters.

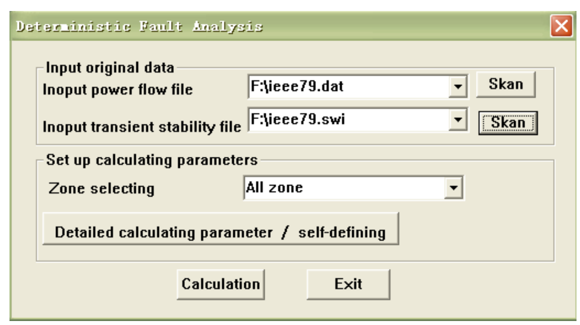

Fig.2 main interface of deterministic fault analysis

If user clicks the button "detailed calculating parameter / self-defining", another interface will be pop-up. This interface allows user to set up detailed calculating parameter, as shown in Fig.3.

First, user sets up fault type; second, fault cut time including single-phase auto-reclosing time; fault cut time; bus unites element cut time; bus switch cut time; back up protection cut time; cut time of bus failure, breaker failure to operate; last, set voltage grade: 110 kV, 220 kV, 330 kV, 500 kV, 750 kV. Click the button "calculation" after setting up all parameters, then, PSD-PRE will calculate fault of selecting zone.

If user wants to carry out probabilistic security evaluation, clicking the button "probabilistic security evaluation" is just needed. Then, the interface as shown in Fig.4 is pop-up.

On this interface, the following steps must be complied. First, select path of power flow data file; second, select path of transient stability data file; third, select zone that needs to be calculated; then, set up fault type, fault cut time, and voltage class; last, click the button "calculation". PSD-PRE will calculate fault of selecting zone and give probabilistic security risk indices.

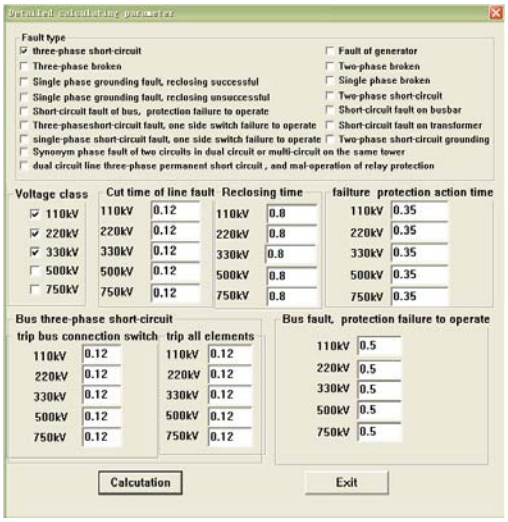

Fig.3 main interface of deterministic fault detailed parameter

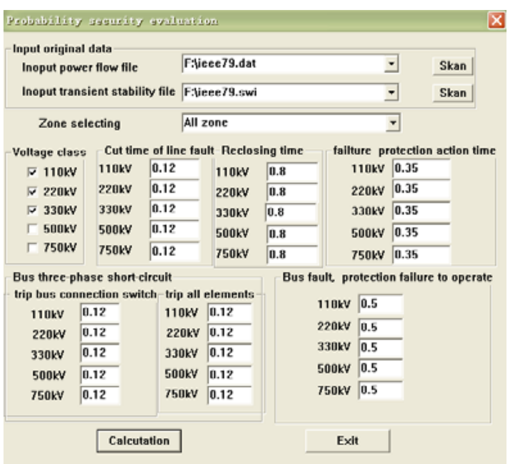

Fig.4 main interface of probabilistic security evaluation

D. Output of Software

Judgment system stability is a very important step in probabilistic security evaluation. PSD-PRE defines system stability as biggest swing angle among unit no more than 300, bus-bar voltage no lower than 0.75p.u and duration no more than 1 sec.

When carrying out deterministic analysis, PSD-PRE exports result of text form. This result includes: ① the stability condition of system under different fault situation; ② minimum voltage and duration of node; ③ biggest swing angle among unit.

When carrying out probabilistic security evaluation, PRE software not only exports the indices above, but also exports system probabilistic risk indices.

III. Risk Indices

When PSD-PRE evaluate bulk power system probabilistic security, risk indices are as shown in 1-13, where 1-6 are basic indices which describe the system probabilistic security level;7-10 are dynamic load curtail indices.

For a system containing J elements, M kind of load scenarios, the probabilistic index of system lose of transient stability (LOTS) is P_{LOTS} :

$$P_{LOTS} = \sum_{k \in US} p_k \tag{1}$$

where *US* is set of system lose transient stability, P_k is the probability of system in scenarios k..

If faults 1-6 occur, the probability index of loss of system transient stability is "(2)":

$$P_k = \sum_{m=1}^{M} p_m^0 \sum_{j=1}^{J} \sum_{i=1}^{I} p_j^S \times p_{ji} \times F \tag{2}$$

where $k = 1, 2 \ldots 6$; p_m^0 is the probability of scenarios m in all scenario; I is the number of total fault type; p_{ji} is the probability of fault i occurs at element j; F is the value of the system testing function which value is 1 as system lose transient stability, else is 0: p_j is the normal operation probability of element j; p_j^s is the probability of system state as element j fault which can be calculated as $p_j^S = \prod p_1 \times p_2 \times \ldots \times (1 - p_j) \times \ldots \times p_J$;

If fault 7 occurs, the probability index of loss of system transient stability is "(3)":

$$P_7 = \sum_{m=1}^{M} p_m^0 \sum_{j=1}^{J} \sum_{i=1}^{I} p_{rf} \times p_j^S \times p_{ji} \times F \tag{3}$$

where p_{rf} is the probability of line protection equipment unwanted operation;

If fault 8 occurs, the probability index of loss of system transient stability is "(4)":

$$P_8 = \sum_{m=1}^{M} p_m^0 \sum_{j=1}^{J} \sum_{i=1}^{I} p_{cr} \times p_j^s \times p_{ji} \times F \tag{4}$$

where p_{cr} is the probability of breaker failure to operate;

If occur fault 9, the probability index of loss of system transient stability is "(5)":

$$P_9 = \sum_{m=1}^{M} p_m^0 \sum_{j=1}^{J} \sum_{i=1}^{I} p_{bdrpr} \times p_j^s \times p_{ji} \times F \tag{5}$$

where p_{bdrpr} is the probability of bus breaker failure to operate;

The probability index of loss of system transient stability with double elements fault is "(6)":

$$P_k = \sum_{m=1}^{M} p_m^0 \sum_{j=1}^{J} \sum_{i=1}^{I} p_j^S \times p_{ji} \times F \tag{6}$$

where $k = 10, 11$, p_j^s is the probability index of system state with double elements fault..

The basic definition for electric power system risk is: "to give comprehensive measurement for possibility and severity of uncertainty factors facing by the electric power system"

[12], the risk index based on fault enumeration method can be described by "(7)":

$$Risk(X_f) = \sum_i P_r(E_i) \cdot Sev(E_i, X_f) \quad (7)$$

where $P_r(E_i)$ is the happening probability of each system state $X_i \in \Omega$, $Sev(E_i, X_f)$ is the index function obtained by calculation, and it denotes the reliability index like probability, power or time.

Security risk indices are divided into node indices and system indices. For fault i occur at element j in the scenario m, n elements need to curtail load.

Then node indices are shown as follows:

Probability of Node Dynamic Load Curtailments (PNDLC):

$$P_{xPNDLC} = \sum_{j=0}^{J} P_j^S \times p_{ji} \times F_x \quad (8)$$

where $x = 1, 2, \ldots n$; F_x is the node testing function which value is 1 when element x needs to curtail load, else is 0;

Node Expected Power Not Supplied (NEPNS):

$$P_{xNEPNS} = \sum_{j=0}^{J} P_j^S \times p_{ji} \times F_x \times \Delta p_j / P_{xPNDLC} \quad (9)$$

Expected Energy of Node Not Supplied (EENNS):

$$P_{xEENNS} = P_{xNEDLC} \times \Delta T_j$$
$$= \sum_{j=0}^{J} P_j^S \times p_{ji} \times F_x \times \Delta p_j \times \Delta T_j / P_{xPNDLC} \quad (10)$$

where ΔT_j is the repair time of element j.

System indices can get according to node indices:

Probability of Dynamic Load Curtailments (PDLC):

$$P_{PDLC} = \sum_{j=0}^{J} P_j^S \times p_{ji} \times F_j \quad (11)$$

where F_j is the system testing function which value is 1 when system exists curtailing load under the condition of element j fault, else is 0.

Expected Dynamic Power Not Supplied (EDPNS):

$$P_{EPNS} = \sum_{x=0}^{N} p_{xNEPNS} / P_{PDLC} \quad (12)$$

Expected Dynamic Energy Not Supplied (EDENS);

$$P_{EENS} = \sum_{x=0}^{N} p_{xEENNS} / P_{PDLC} \quad (13)$$

IV. Theory of Evaluate Probabilistic Security Considering Bus Arrangement

On the single-line diagram of bulk power system, station and substation are usually described by single bus. But the actual bus arrangement is very complex. The single-line diagram and detailed bus arrangement for bus-bar 1 of IEEE-RTS79 are as shown in Fig.5.

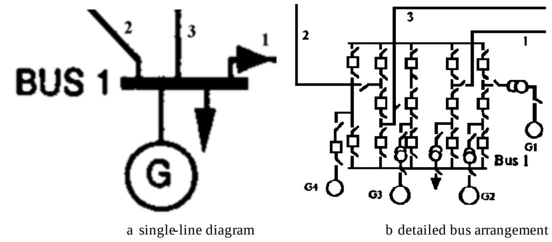

Fig.5 diagrammatic sketch for bus-bar of IEEE-RTS79

Seen from Fig.5, diversity between them is obvious. It is not appropriate to use one single bus-bar denoting the detailed bus arrangement. There are two reasons: equivalent bus-bar is very easy confused with the actual bus-bar; different bus arrangements have different influence on system stability.

Seen from three representative bus arrangement structures in Fig.6, internal elements (major as circuit breaker and bus) fault causes different feeder outage. For single bus-bar structure, all feeders connect on bus-bar. If this bus-bar faults, all feeders will be outage. Probability of power plant blackout is very great. So the probability index of loss of system transient stability must include the probability index of this fault.

For double bus-bar or single bus-bar subsection, part feeders connect on one bus-bar and others connect on the other bus-bar. Like single bus-bar structure, outage probability of feeders connected on same section is much great, but outage probability of feeders connected on different section is very small. For 3/2 arrangement, the situation is completely different. If circuit breaker and protection system operate naturally, bus-bar fault will cause no feeder outage. For example, bus-bar W1 fault, all feeders can operate through bus-bar W2. For power transmission line short-circuit fault, one side switch failure to operate or short-circuit fault of bus, bus differential protection failure to operate, the same fault cause different result under different bus arrangement. For example, on 3/2 arrangement, line F5 short-circuit fault, one side switch failure to operate; if switch QF1 fails to operate and QF2 is tripped off successfully, line F1 can still operate through bus-bar W2; if switch QF2 fail to operate, then switch QF1 and QF3 need to trip off, line F1 can't operate.

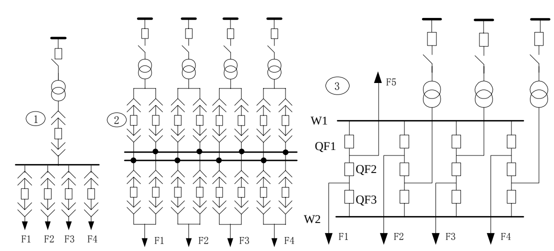

Fig.6 diagrammatic sketch of typical bus arrangement

Theory of evaluating probabilistic security considering bus arrangement is as shown below.

When short-circuit fault occur on bus-bar, the bus-bar arrangement is considered to analysis outage result and get probabilistic risk indices. As PSD-PRE achieves calling of PSD-BPA power flow and transient stability program, evaluating probabilistic security for bulk power system can be realized by following steps. First, modify power flow data *.DAT file. According to actual bus arrangement, separate corresponding bus-bar node into two or more new nodes which connect by little switch lines; then, connect the feeders to the right bus node. At last, modify transient stability data file. The old node of *.SWI file must be replace by the corresponding new node as define in *.DAT file.

V. Case Study

A. Test system

The single line diagram of IEEE-RTS 79 is as shown in Fig.7. It has 24 nodes, 34 lines, 32 generators. The total system load is 2850 MW and the installed generation capacity is 3405 MW. The bus arrangement are all most 3/2 arrangement or polygon arrangement, so bus fault will cause no feeder outage.

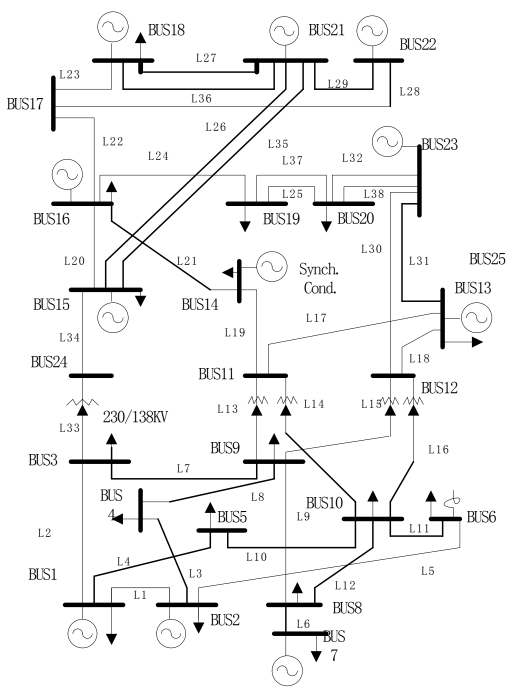

Fig.4 IEEE-RTS diagram

B. Basic Data for Probabilistic Security Evaluation

The basic data for probabilistic security evaluation are as shown in Tables I-III.

TABLE I
The average value of different fault types over the country during 2000-2004

Fault types	Proportion (%)
Single phase to ground short-circuit	88.94
Two-phase to ground short-circuit	4.348
Phase to phase short-circuit	2.986
Three-phase short-circuit	1.038
Open circuit	0.876
Others	1.808

TABLE II
The average value of probabilistic indices in national-wide 220kV component during 2000-2004

Lines	Success rate of reclosing (%)	77.07
Bus-bar protection	failure to operate (%)	2.7
Relay protection device	Incorrect operation rate (%)	0.868

TABLE III
Transmission line reliability data of IEEE RTS 79

line	Failure rate (occs./year)	repair time/h	line	Failure rate (occs./year)	repair time/h
1-2	0.24	16	11-13	0.4	11
1-3	0.51	10	11-14	0.39	11
1-5	0.33	10	12-13	0.4	11
2-4	0.39	10	12-23	0.52	11
2-6	0.48	10	13-23	0.49	11
3-9	0.38	10	14-16	0.38	11
3-24	0.02	768	15-16	0.33	11
4-9	0.36	10	15-21	0.41	11
5-10	0.34	10	15-24	0.41	11
6-10	0.33	35	16-17	0.35	11
7-8	0.3	10	16-19	0.34	11
8-9	0.44	10	17-18	0.32	11
8-10	0.44	10	17-22	0.54	11
9-11	0.02	768	18-21	0.35	11
9-12	0.02	768	19-20	0.38	11
10-11	0.02	768	20-23	0.34	11
10-12	0.02	768	21-22	0.45	11

C. Results Analysis

With PSD-PRE software, 24 short-circuit on bus-bar and 24 short-circuit fault of bus, bus differential protection failure to operate, 29 line three-phase short-circuit failure, single-phase protection equipment unwanted operation, 29 line short-circuit fault, one side switch failure to operate etc. 576 fault patterns have been calculated. Following with the application of accelerating method used in PSD-PRE, total calculation quantity has reduced by 69.2% as probabilistic security evaluation decreased 1297 times. At the same time, evaluating one system probabilistic security artificially is larger than 90 seconds, but PRE takes no more than 30 seconds. Thus calculation time is greatly reduced and efficiency is greatly enhanced by PSD-PRE software.

According to above fault result and risk assessment algorithm, the probabilistic indices with and without considering bus arrangement of IEEE RTS 79 are as shown in Table IV and the node indices are as shown in Tables V-VI.

TABLE IV
System probabilitic indices of IEEE RTS 79

System risk indices	Without considering bus arrangement	Considering bus arrangement	Error proportion (%)
LOTS	0.0000583	0.000041	42.2
PDLC	0.0001682	0.0001659	1.37
EDPNS	403.8885 *Mw*	403.0493 *Mw*	0.21
EDENS	5340.948 *Mwh*	5329.2884 *Mw·h*	0. 22

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TABLE V
NODE PROBABILISTIC INDICES OF IEEE RTS 79 WITHOUT CONSIDERING BUS ARRANGEMENT

Node	EENNS(*Mwh*)	NEDLC(*Mw*)	PNDLC
10	568.2453	32.89478	8.017538E-05
18	542.55	48.69321	6.720671E-05
15	502.1865	44.39969	8.535032E-05
13	399.5125	34.52377	4.776947E-05
8	393.6066	25.13773	9.464344E-05
9	389.318	26.31327	1.251057E-04
6	380.533	19.94648	8.754858E-05
14	323.2038	28.3544	1.085765E-04
3	321.331	24.49608	1.362187E-04
7	307.29	30.23307	1.522992E-05
19	264.4091	23.46406	1.210885E-04
2	238.6546	12.98052	5.149069E-05
5	189.1355	10.46227	8.105940E-05
20	188.8235	16.76508	8.915811E-05
4	170.5551	10.8653	1.014419E-04
16	161.5939	14.35877	1.092920E-04

TABLE VI
NODE PROBABILITIC INDICES OF IEEE RTS 79 CONSIDERING BUS ARRANGEMENT

node	EENNS(*Mwh*)	NEDLC(*Mw*)	PNDLC
10	566.2712	32.83795	8.130786E-05
18	545.803	48.70604	6.799459E-05
15	504.591	44.42944	8.616417E-05
13	399.0499	34.52223	4.827312E-05
8	391.1227	25.0814	9.577592E-05
9	389.1003	26.30349	1.265312E-04
6	353.347	19.38625	8.560751E-05
14	327.9944	28.24737	1.106674E-04
3	327.9638	24.51844	1.376443E-04
7	306.984	30.18935	1.528812E-05
19	269.6927	23.47363	1.220670E-04
2	240.9563	12.98208	5.205131E-05
20	188.0269	16.75137	9.011065E-05
5	188.393	10.43071	8.128711E-05
4	169.9734	10.8437	1.017783E-04
16	160.0188	14.34587	1.104017E-04

Seen from Table IV, indices of system lose transient stability changes very much as considering bus arrangement. It is means that traditional probabilistic security model without considering bus arrangement is not accurate, especially when evaluate system probabilistic stability. Seen from Tables IV-VI, dynamic load curtailment indices changes very little because statistical load curtailment only under scenario of system stability which quantity is very large. So the risk indices show that PSD-PRE can makes the probabilistic security evaluation results more accurate.

VI. CONCLUSION

New probabilistic security evaluation software named PSD-PRE is developed. It achieves the probabilistic security evaluation for bulk power system considering bus arrangement. This makes calculating results more accurate. Accelerating algorithm is adopted to alleviate the calculation burden of PSD-PRE. Simulation results show that PSD-PRE is valid and available for bulk power system considering bus arrangement and indices can be used as the basis of transmission network planning.

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