An approach for contingency ranking analysis of electrical power system

Kassim A. Al-Anbarri
Electrical Engineering Department, College of Engineering, Mustansiriyah University, Bab Al-Muadham campus, 46049 Baghdad
E-mail: alanbarri@uomustansiriyah.edu.iq

ABSTRACT—This paper presents an algorithm for ranking the critical contingencies in a high voltage power system. The presented approach based on a hybrid weighted performance index. The hybrid performance index measures the overloaded transmission lines and bus voltage deviation out the permissible limits. A linear technique is used in computing the hybrid performance index. The proposed algorithm is applied to the IEEE24 bus reliability test system. There is a good match between the results obtained with the proposed algorithm with those obtained by applying a full AC load flow iterative method.

KEYWORDS- contingency; hybrid performance index; critical ranking; power system security

I. INTRODUCTION

With the increased growth of electric power demand, the transmission systems are operated in a much-stressed conditions. The environmental constraints and economic crisis pose difficulties in building a new transmission line. The secure operation is becoming a vital issue in power system utilities. One of the major functions of a security analysis is to study the severity of all possible contingencies (line outage, generation unit outage) on the performance of the power system elements. A detailed contingency assessment requires examining the effect of all contingencies of power system by a full AC load flow method. Such a detailed analysis on a large-scale power system would be infeasible for the substantial computer time requirements and the few real contingencies that threat the security of the power system. Contingency ranking is the process of selecting the critical contingencies that severely violate the operational limits of the system components. Contingency ranking techniques are the subject of extensive research since the pioneering work of El-Abiad [1]. Ranking critical contingencies in terms of transmission line overload had become the focus of many researchers [2-14]. Most of the algorithms are based on the concepts of adjoint networks and Tellegen’s theorem or using the first iteration of fast decoupled load flow. Other attempts tackled contingency ranking in terms of on its severity on bus voltage out of limit conditions [15-19]. An attempt to assess the branch outage contingencies using continuation method was presented in Reference [20]. A compact algorithm using reduced matrix has been implemented in steady state security assessment [21]. Artificial intelligence techniques have been proposed for contingency ranking [22-29]. The contingency ranking was addressed from a probabilistic point of view [30-31]. The real time contingency was based on a probabilistic index which considered the stochastic nature of the electric power system equipment outages.

A new algorithm, which ranks the critical contingencies, is proposed. Two linear non iterative power flow model are presented. Two performance indices which quantify the severity of the contingency are evaluated. The proposed algorithm was tested on IEEE 24 bus reliability test system. The ranking list obtained was compared with those obtained by applying full AC iterative load flow.

This paper is organized as follows: Section II presents the proposed performance indices. The proposed linear active and reactive power flow model are presented in section III. Section IV discusses the results obtained by applying the proposed algorithms on the IEEE 24 bus reliability system. Finally, section V presents the conclusion.
II. HYBRID PERFORMANCE INDEX

The most important features of a reliable contingency selection algorithm are its simplicity and the speed of filtering the most severe contingencies. For this end, a hybrid contingency performance index ($CPI_h$) have to be defined for quantifying the severity of the contingency. Since some contingencies may cause only violation of the bus voltage limit. Others may lead to overload the MVA rating of transmission lines. The proposed algorithm in this paper considered both effects simultaneously by defining a hybrid contingency performance index as follow:

$$CPI_h = CPI_S + CPI_E$$

Where

$CPI_S$ is the contingency performance index which provides a measure of the transmission line rating overload

$CPI_E$ is the contingency performance index which provides a measure of the deviation of buses voltage beyond their tolerable values

The components of the contingency performance index is given by Equations (2 and 3):

$$CPI_S = \sum_{l=1}^{n} W_S \left( \frac{S_{l_{flow}}}{S_{l_{max}}} \right)^{2n}$$

$$CPI_E = \sum_{i=1}^{n} W_E \left( \frac{|E_i| - |E_i^{limit}|}{|E_i^{limit}|} \right)$$

Where

$W_S$ is line MVA rating weighting factor

$S_{l_{flow}}$ is MVA flow in line $l$

$S_{l_{max}}$ is the maximum MVA rating of the line $l$

$\alpha$ is the set of overloaded

$W_E$ is the bus voltage magnitude weighting factor

$|E_i|$ is the bus voltage magnitude at bus $i$

$|E_i^{limit}|$ is the bus voltage magnitude limit at bus $i$

$\mu$ is the set of buses whose voltage magnitude is out of the limits

The values of apparent power flow in the lines and bus voltages in Equations 2 and 3 are computed by a linear power flow model as presented in the next section

III. PROPOSED LINEAR POWER FLOW MODEL

The steady state performance at each bus of $n$ bus electrical power system may be described by the following current balance equation:

$$I_i = \frac{S_i^*}{E_i} = \sum_{k=1}^{n} Y_{ik} E_k$$

Where $Y_{ik}$ is the $i,k$th element of bus admittance matrix

$E_k$ is the bus voltage at bus $k$

The complex bus power $S_i$ may be specified by the following equation:

$$S_i = (P_{Gi} - P_{Di}) - j(Q_{Gi} - Q_{Di}) = P_i - jQ_i$$

Where $P_{Gi}$ is the active power generation at bus $i$

$P_{Di}$ is the active power demand at bus $i$

$Q_{Gi}$ is the reactive power generation at bus $i$

$Q_{Di}$ is the reactive power demand at bus $i$

Using (5), the left-hand side of (4) can be rearranged as:

$$\frac{P_i - jQ_i}{|E_i|} = \frac{P_i - jQ_i}{|E_i| e^{-j\theta_i}} = \frac{(P_i - jQ_i)e^{j\theta_i}}{|E_i|}$$
\[ \frac{(P_i - jQ_i)(\cos \theta_i + j\sin \theta_i)}{|E_i|} \] 

(6)

The right-hand side of (4) may be arranged as:

\[ \sum_{k=1}^{n} Y_{ik} E_k = \sum_{k=1}^{n} |E_k|(G_{ik} + jB_{ik})(\cos \theta_k + j\sin \theta_k) = |E_i|(G_{ii} + jB_{ii})(\cos \theta_i + j\sin \theta_i) \]

\[ + \sum_{k=1, k\neq i}^{n} |E_k|(G_{ik} + jB_{ik})(\cos \theta_k + j\sin \theta_k) \] 

(7)

By substituting Equations (6) and (7) into Equation (4), and separating the real part and imaginary part of the resulting equation yield the following two real nonlinear algebraic equations at each bus:

\[ \frac{P_i \cos \theta_i + Q_i \sin \theta_i}{|E_i|} = \sum_{k=1}^{n} \frac{|E_k|(G_{ik} \cos \theta_k - B_{ik} \sin \theta_k)}{|E_i|} \] 

(8)

\[ \frac{P_i \sin \theta_i - Q_i \cos \theta_i}{|E_i|} = \sum_{i=1}^{n} \frac{|E_k|(B_{ik} \cos \theta_k + G_{ik} \sin \theta_k)}{|E_i|} \] 

(9)

Using the decoupling behavior of the high voltage power system, equation (8) is simplified and used to solve for the voltage angle \(\theta\) while equation (9) is simplified and used to solve for voltage magnitude \(|E|\) as follow:

### A. LINEAR ACTIVE POWER FLOW MODEL

To determine the bus voltage angle \(\theta\), equation (8) may be simplified by assuming all the voltage magnitude to be 1 p.u. Also, the trigonometric functions may be expressed by using Taylor series with only first linear term. This is justified in practice by the small value of the operating power angle:

\[ \cos \theta = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} + \ldots \] 

(10)

\[ \sin \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} + \ldots \] 

(11)

One feature of the high transmission networks is their line conductances are much less than line susceptances.

\( (G_{ik} \sin \theta_k) \ll (B_{ik} \cos \theta_k) \)

Also, the reactive power flow from a particular bus is much higher than the injected reactive power at that bus

\( ((E_i^2 B_{ii}) \gg (Q_i)) \)

By considering the above approximations, Equation (8) can be described by the following linear form:

\[ P_i = \sum_{k=1}^{n} -B_{ik} \theta_k \] 

(12)

Equation (12) can be written in matrix form as:

\[ [S^p] = [H^p][\theta] \] 

(13)
Where $\mathbf{S}^P$ a vector is whose elements are the left-hand side of (12). The matrix $\mathbf{H}^P$ is a real and square matrix whose elements are the negative of the bus susceptance matrix.

**B. REACTIVE POWER FLOW MODEL**

A linear reactive power flow model can be obtained by simplifying equation (9) as follow:

The variable $|E|$ appears in Equation (9) can be expanded around the nominal value 1 p.u. by using Taylor series expansion and retaining only the first order term:

$$|E| = |E|_{1.0} + \Delta|E| = 1.0 + \Delta|E| \quad (14)$$

$$\frac{1}{|E|} = (|E|^{-1})_{1.0} - \Delta|E| = 1.0 - \Delta|E| \quad (15)$$

Again, the trigonometric functions may be expressed by using Taylor series with only linear term is considered. Substituting the above simplification into (9) yields the following linear form:

$$P_i \theta_i - Q_i - \sum_{k=1}^{n} (G_{ik} \theta_k + B_{ik}) = (P_i \theta_i - Q_i + G_{ii} \theta_i + B_{ii}) \Delta|E_i|$$

$$+ \sum_{k=i}^{n} (G_{ik} \theta_k + B_{ik}) \Delta|E_k| \quad (16)$$

Equation (16) can be written in matrix form as:

$$\begin{bmatrix} \mathbf{S}^Q \\ \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{H}^Q \end{bmatrix} \begin{bmatrix} \mathbf{\Delta|E|} \end{bmatrix} \quad (17)$$

Each element of the vector $\mathbf{S}^Q$ is evaluated by the left hand side of (16). The matrix $\mathbf{H}^Q$ is a real and square matrix whose elements are as follow:

$$H_{ii}^Q = (P_i \theta_i - Q_i + G_{ii} \theta_i + B_{ii}) \quad (18)$$

$$H_{ik}^Q = \sum_{k=i}^{n} (G_{ik} \theta_k + B_{ik}) \quad (19)$$

**IV. PROPOSED ALGORITHM**

The following algorithm may be adopted to rank the critical contingencies:

i. Read the transmission system parameters, bus data
ii. Build the bus admittance matrix
iii. Solve the linear active power model by using equation to get the bus voltage angles
iv. Solve the linear reactive power model by using equation to get the bus voltage magnitudes
v. Evaluate the performance indices using equation
vi. Short list the critical contingencies according to their corresponding performance indices

It is worth to be noted that the ranking is carried out simultaneously for both line overloads and voltage violation. Fig. (1) shows the flow chart of the proposed algorithm.
Read line data and bus data

Set the contingency counter \( i = 0 \)

Modify \( Y_{bus} \) for line outage simulation

Calculate the MVA flow using equation (13) and corresponding performance index \( CPI_L \) using Equation (2) for overloaded lines

Calculate the bus voltage using Equation (17) and corresponding performance index \( CPI_{V} \) using Equation (3) for voltage violation buses

Increment the counter \( i = i + 1 \)

Is there any line outage contingency?

No

Yes

Rank the contingencies in descendent order

Carry out a full AC load flow study for the most severe contingencies

End

Fig (1) Flow chart of the proposed contingency ranking algorithm
V. RESULTS AND DISCUSSION

The proposed algorithm was applied to the 24 IEEE reliability test system. The bus data and the line data is given in Appendix A (Table A1 and A2). The system has twelve generating stations and 39 transmission lines. The performance index is evaluated for each contingency and the contingencies are ranked in descending order as given in Table 1 for the first top ten contingencies. It is shown that outage of the line connecting bus 15 to bus 21 has a pronounced effect on system security.

The ranking of the critical contingencies obtained by the proposed algorithm is like those obtained by using full AC iterative load flow. Fig.2 shows the discrepancy in the value of performance index of the critical contingencies which is due to simplification of the proposed algorithm.

### TABLE 1 CONTINGENCY RANKING FOR IEEE24BUS TEST SYSTEM

| Line outage No. | S. E. | R.E. | Performance Index CPI | Rank No. | No. & type of violations (Line overload and bus voltage out of limit) |
|-----------------|------|------|-----------------------|----------|------------------------------------------------------------------|
| 25              | 15   | 21   | 87.656                | 1        | L_{11},L_{27},L_{29},E_3,E_{24}                                  |
| 26              | 15   | 24   | 13.899                | 2        | L_{11},E_3,E_9,E_{24}                                           |
| 7               | 3    | 24   | 6.479                 | 3        | L_{11},E_3,E_{9}                                                |
| 4               | 2    | 4    | 5.912                 | 4        | L_{11},E_3,E_4                                                 |
| 2               | 1    | 3    | 5.233                 | 5        | L_{11},E_3,E_4                                                 |
| 23              | 14   | 16   | 5.081                 | 6        | L_{11},E_3,E_{24}                                               |
| 14              | 9    | 11   | 4.341                 | 7        | L_{11},E_3,E_4,E_9                                            |
| 28              | 16   | 19   | 4.012                 | 8        | L_{11},E_3,E_{24}                                               |
| 27              | 16   | 17   | 4.104                 | 9        | L_{11},E_3,E_{24}                                               |
| 15              | 9    | 12   | 3.918                 | 10       | L_{11},E_3,E_4,E_9                                            |
| 6               | 3    | 9    | 3.616                 | 11       | L_{11},E_3                                                     |
| 10              | 6    | 10   | 3.278                 | 12       | L_{11},E_3                                                     |
VI. CONCLUSION
An algorithm for ranking critical contingencies in power systems has been presented. The proposed algorithm is based on two
decoupled linear power flow model. A weighted combination of two performance indices which quantify the severity of the
contingency. The results obtained reveals the accuracy of the new linear non iterative technique compared to the full AC load
flow iterative technique.

ACKNOWLEDGMENT
The author would like to thank the Department of Electrical Engineering, Faculty of Engineering, Mustansiriyah University
(www.uomustansiriyah.edu.iq)Baghdad-Iraq for its support in the present work.

REFERENCES
[1] A.H.El-Abiad and G.W. Stagg, “Automatic Evaluation of Power System Performance-Effects of Line and Transformer Outages”, AIEEE Trans. On Power Apparatus and Systems, Vol.81, Feb. 1963.
[2] G.C. Ejebe and B.F. Wollenberg, “Automatic Contingency Selection”, IEEE Trans. On Power Apparatus and Systems, Vol. PAS-98, No.1, Jan/Feb. 1979, pp. 97-103.
[3] J.F. Dopazo, G. G. Irisarri, and A.M.Sasson, “Real Time External System Equivalent for On-line Contingency Analysis”, IEEE Trans. On Power Apparatus and Systems, Vol. PAS-98, No.10, Nov/Dec. 1979, pp. 2153-2171.
[4] G.D. Irisarri and A.M.Sasson, “An Automatic Contingency Selection Method for On-line Security Analysis ”, IEEE Trans. On Power Apparatus and Systems, Vol. PAS-100, No.4, April, 1981, pp.1838-1843.
[5] S. Vemuri, and R.E. Usher, "On-line Automatic Contingency Selection Algorithm", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-102, No.2, Feb. 1983, pp. 346-354.

[6] T.F. Halpin, R. Fischl and R. Fink, "Analysis of Automatic Contingency Selection Algorithms", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-103, No.5, May. 1984, pp. 938-945.

[7] J. Kim, G. Maria and V. Wong, "Contingency Ranking and Simulation for On-line Use", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-104, No.9, Sep. 1985, pp. 2401-2407.

[8] S. Vemuri, and R.E. Usher, "On-line Automatic Contingency Selection Algorithm", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-102, No.1, Jan. 1983, pp. 346-354.

[9] B. Stott, O. Alsac and F.L. Alvarado, "Analytical and Computational Improvements in Performance-Index Ranking Algorithms for Networks", Inter. J. on Electric Power and Energy System, Vol. 7, Issue 3, July. 1985, pp. 154-160.

[10] L.A.F.M. Ferreira and H.B. Puttgen, "Adjoint Network Sensitivity Based Performance Index Evaluation for Large-Scale Contingency Events", Electric Power System Research, Vol. 13, 1987, pp. 241-246.

[11] A.O. Ekwue, "On-line Automatic Contingency Selection Algorithm", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-101, No.1, Jan. 1982, pp. 107-112.

[12] K. Lo, M. Arshad Bismil, R.P. McColl and A.M. Moffatt "A comparison of MW Ranking Methods ", Electric Power System Research, Vol. 15, 1988, pp. 157-171.

[13] A.O. Ekwue, "On the Ranking of Contingencies for On-line Applications ", Electric Power System Research, Vol. 19, 1990, pp. 207-212.

[14] R. Golob, F. Gubina and R. Debs, "Improved Adjoint Network Algorithm for On-Line Contingency Analyses ", Electric Power System Research, Vol. 38, 1996, pp. 161-168.

[15] A.O. Ekwue, "On the Ranking of Contingencies for On-line Applications ", Electric Power System Research, Vol. 19, 1990, pp. 207-212.

[16] A.K. Jana, P.B.Duttagupta and G. Durga Prasrd, "An Improved Linearised method for Evaluation of Bus Voltages for Line Outage Contingency ", Inter. J. on Electric Power and Energy System, Vol. 15, , No.5, 1993. pp.301-305.

[17] F. Albuyeh, A. Bose and B. Heath, "On-line Automatic Contingency Selection Algorithm", IEEE Trans. On Power Apparatus and Systems, Vol. PAS-101, No.1, Jan. 1982, pp. 107-112.

[18] K. Lo, M. Arshad Bismil, R.P. McColl and A.M. Moffatt "A comparison of MW Ranking Methods ", Electric Power System Research, Vol. 15, 1988, pp. 157-171.

[19] L.D.Arya, S.C.Choube, and D.P.Kothari, "Line outage Ranking for Voltage Limit Violations with Corrective Rrescheduling Avoiding Masking ", Electric Power & Energy Systems, Vol. 30, 2001. pp. 837-846.

[20] M. Dester and C.A.Castro, "Multi- Criteria Contingency Ranking Method for Voltage Stability", Electric Power System Research, Vol. 79, 2009, pp. 220-225.

[21] H.R. Baghaee and M. Abedi, "Calculation of  Weighting Factors of Static Security Indices Used in Contingency Ranking of Power Systems  Based on Fuzzy Logic and Analytical Hierarchy Process", Electric Power & Energy Systems, Vol. 31, 2011. pp. 855-860.

[22] D. Devaraj, B. Yegnanarayana, and K.Ramer, "Radial Basis Function Networks for Fast Contingency Ranking", Electric Power & Energy Systems, Vol. 24, 2002. pp.387-395.

[23] K. Verma and K.R. Niazi, "Supervised Learning Approach to Online Contingency Screening and Ranking in Power Systems", Electric Power & Energy Systems, Vol. 38, 2012. pp. 97-104.

[24] J.C.S.Souza, M.B.D. Gutto Filho, and M.Th. Schilling, "Fast Contingency Selection Through a Pattern Analysis Approach", Electric Power System Research, Vol. 62, 2002. pp. 13-19.

[25] J. Nahman, I. Skokljev, " Probabilistic Steady-state Power System Security Indices",Electrical Power & Energy Systems,vol.21, PP.515-522, 1999.

[26] N.A. Mijuskovic, D. Stojnic, " Probabilistic Real-time Contingency Ranking Method ",Electrical Power & Energy Systems,vol.22, PP.531-535, 2000.
## Appendix A

### Table A1: BUS DATA OF IEEE24 RELIABILITY TEST SYSTEM

| Bus No. | Bus Type | Bus Voltage | Generation | Load | Generating Unit |
|---------|----------|-------------|------------|------|------------------|
|         |          | | | | Capability MVAr |
|         |          | | | | \( |E|\) pu \(0\) rad | \(P_G\) (MW) | \(Q_D\) (MVAr) | \(P_D\) (MW) | \(Q_D\) (MVAr) | \(Q_{min}\) | \(Q_{max}\) |
| 1 PV    | 1.0      | 0.0         | 190        | 108  | 22               | -50  | 80             |
| 2 PV    | 1.0      | 0.0         | 190        | 97   | 20               | -50  | 80             |
| 3 Load  | 1.0      | 0.0         |            | 180  | 37               |      |                |
| 4 Load  | 1.0      | 0.0         |            | 74   | 15               |      |                |
| 5 Load  | 1.0      | 0.0         |            | 71   | 14               |      |                |
| 6 PV    | 1.0      | 0.0         |            | 136  | 28               | 100  | 0              |
| 7 PV    | 1.0      | 0.0         | 300        | 125  | 25               | 0    | 180            |
| 8 Load  | 1.0      | 0.0         |            | 171  | 35               |      |                |
| 9 Load  | 1.0      | 0.0         |            | 175  | 36               |      |                |
| 10 Load | 1.0      | 0.0         |            | 195  | 40               |      |                |
| 11 Load | 1.0      | 0.0         |            |      |                  |      |                |
| 12 Load | 1.0      | 0.0         |            |      |                  |      |                |
| 13 PV   | 1.0      | 0.0         | 590        | 265  | 54               | 0    | 240            |
| 14 PV   | 1.0      | 0.0         |            | 194  | 39               | 50   | 200            |
| 15 PV   | 1.0      | 0.0         | 220        | 317  | 64               | -50  | 110            |
| 16 PV   | 1.0      | 0.0         | 155        | 100  | 20               | -50  | 80             |
| 17 Load | 1.0      | 0.0         |            |      |                  |      |                |
| 18 PV   | 1.0      | 0.0         | 400        | 333  | 68               | -50  | 200            |
| 19 Load | 1.0      | 0.0         |            | 181  | 37               |      |                |
| 20 Load | 1.0      | 0.0         |            | 128  | 26               |      |                |
| 21 PV   | 1.0      | 0.0         | 400        |      | -50              | 200  |                |
| 22 PV   | 1.0      | 0.0         | 300        |      | -60              | 96   |                |
| 23 Slack| 1.0      | 0.0         | 660        |      | -125             | 310  |                |
| 24 Load | 1.0      | 0.0         |            |      |                  |      |                |
### Table A2  LINE DATA OF IEEE 24 BUS RELIABILITY TEST SYSTEM

| Line No. | SE | RE | R pu  | X pu  | B pu  | Normal MVA rating | Equipment       |
|----------|----|----|-------|-------|-------|-------------------|-----------------|
| 1        | 1  | 2  | 0.0026| 0.0139| 0.4611| 193               | 138 kV cable    |
| 2        | 1  | 3  | 0.0546| 0.2112| 0.0572| 208               | 138 kV line     |
| 3        | 1  | 5  | 0.0218| 0.0845| 0.0229| 208               | 138 kV line     |
| 4        | 2  | 4  | 0.0328| 0.1267| 0.0343| 208               | 138 kV line     |
| 5        | 2  | 6  | 0.0497| 0.1920| 0.0520| 208               | 138 kV line     |
| 6        | 3  | 9  | 0.0308| 0.1190| 0.0322| 208               | 138 kV line     |
| 7        | 3  | 24 | 0.0023| 0.0839|       | 510               | Transformer     |
| 8        | 4  | 9  | 0.0268| 0.1037| 0.0281| 208               | 138 kV line     |
| 9        | 5  | 10 | 0.0228| 0.0883| 0.0239| 208               | 138 kV line     |
| 10       | 6  | 10 | 0.0139| 0.0605| 0.2459| 193               | 138 kV cable    |
| 11       | 7  | 8  | 0.0159| 0.0614| 0.0166| 208               | 138 kV line     |
| 12       | 8  | 9  | 0.0427| 0.1651| 0.0447| 208               | 138 kV line     |
| 13       | 8  | 10 | 0.0427| 0.1651| 0.0447| 208               | 138 kV line     |
| 14       | 9  | 11 | 0.0023| 0.0839|       | 510               | Transformer     |
| 15       | 9  | 12 | 0.0023| 0.0839|       | 510               | Transformer     |
| 16       | 10 | 11 | 0.0023| 0.0839|       | 510               | Transformer     |
| 17       | 10 | 12 | 0.0023| 0.0839|       | 510               | Transformer     |
| 18       | 11 | 13 | 0.0061| 0.0476| 0.0999| 600               | 230 kV line     |
| 19       | 11 | 14 | 0.0054| 0.0418| 0.0879| 600               | 230 kV line     |
| 20       | 12 | 13 | 0.0061| 0.0476| 0.0999| 600               | 230 kV line     |
| 21       | 12 | 23 | 0.0124| 0.0966| 0.2030| 600               | 230 kV line     |
| 22       | 13 | 23 | 0.0111| 0.0865| 0.1818| 600               | 230 kV line     |
| 23       | 14 | 16 | 0.0050| 0.0389| 0.0818| 600               | 230 kV line     |
| 24       | 15 | 16 | 0.0022| 0.0173| 0.0364| 600               | 230 kV line     |
| 25       | 15 | 21 | 0.0063| 0.0490| 0.1030| 600               | 230 kV line     |
| 26       | 15 | 21 | 0.0063| 0.0490| 0.1030| 600               | 230 kV line     |
| 27       | 15 | 24 | 0.0067| 0.0519| 0.1091| 600               | 230 kV line     |
| 28       | 16 | 17 | 0.0033| 0.0259| 0.0545| 600               | 230 kV line     |
| 29       | 16 | 19 | 0.0030| 0.0231| 0.0485| 600               | 230 kV line     |
| 30       | 17 | 18 | 0.0018| 0.0014| 0.0303| 600               | 230 kV line     |
| 31       | 17 | 22 | 0.0135| 0.1053| 0.2212| 600               | 230 kV line     |
| 32       | 18 | 21 | 0.0033| 0.0259| 0.0545| 600               | 230 kV line     |
| 33       | 18 | 21 | 0.0033| 0.0259| 0.0545| 600               | 230 kV line     |
| 34       | 19 | 20 | 0.0051| 0.0396| 0.0833| 600               | 230 kV line     |
| 35       | 19 | 20 | 0.0051| 0.0396| 0.0833| 600               | 230 kV line     |
| 36       | 20 | 23 | 0.0028| 0.0216| 0.0455| 600               | 230 kV line     |
| 37       | 20 | 23 | 0.0028| 0.0216| 0.0455| 600               | 230 kV line     |
| 38       | 21 | 22 | 0.0087| 0.0678| 0.1424| 600               | 230 kV line     |