Module 6

Grid Security

How did the yesterday's definition differ from tomorrow's?

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Module 6.2

Anticipating the contingencies

Plausibility vs. possibility. What are credible events?

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N-1 Contingency

Power Control Centers

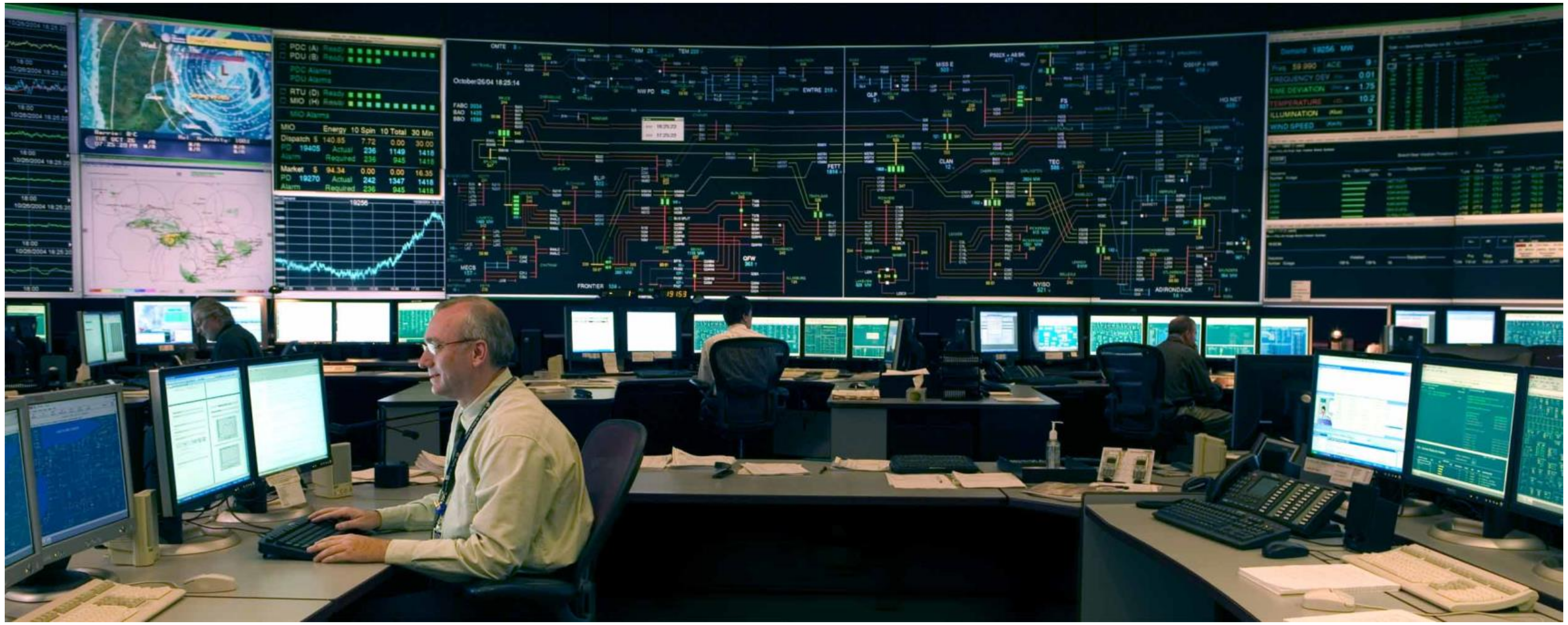
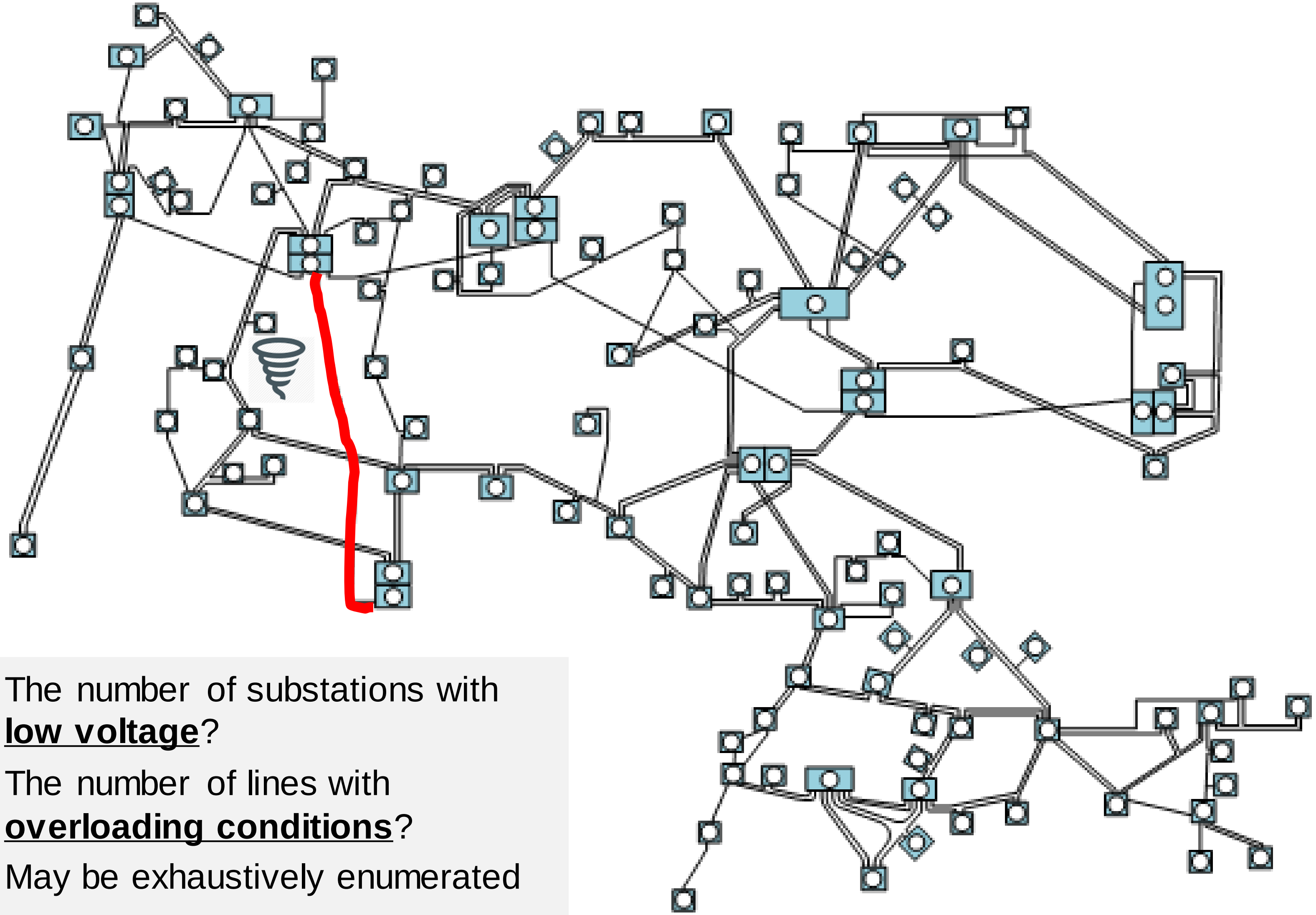


Photo Courtesy: http://www.temetprotection.com.ar/temet_advanced_shelter_control_system.html

- Supervisory Control and Data Acquisition (SCADA)
  - Data acquisition – analog (P, Q, V, etc.) and digital (switch status) measurements
  - **Alarms are derived** from these measurements over given time
  - Preventive and remedial controls

- Complete information of the physical health of a power system under a utility's grid territory

IEEE 118-bus System:
Traditional Power System **Security**: N-1 Contingency



- ☐ The number of substations with **low voltage**?
- ☐ The number of lines with **overloading conditions**?
- ☐ May be exhaustively enumerated

Power System Security

Major functions of security at Energy Management System (EMS) at the control center:

1. System monitoring
    1. State estimation
    2. Alarm processing
    3. Power flow
2. Contingency analysis
3. Security-constrained optimal power flow

Four Operating Objectives

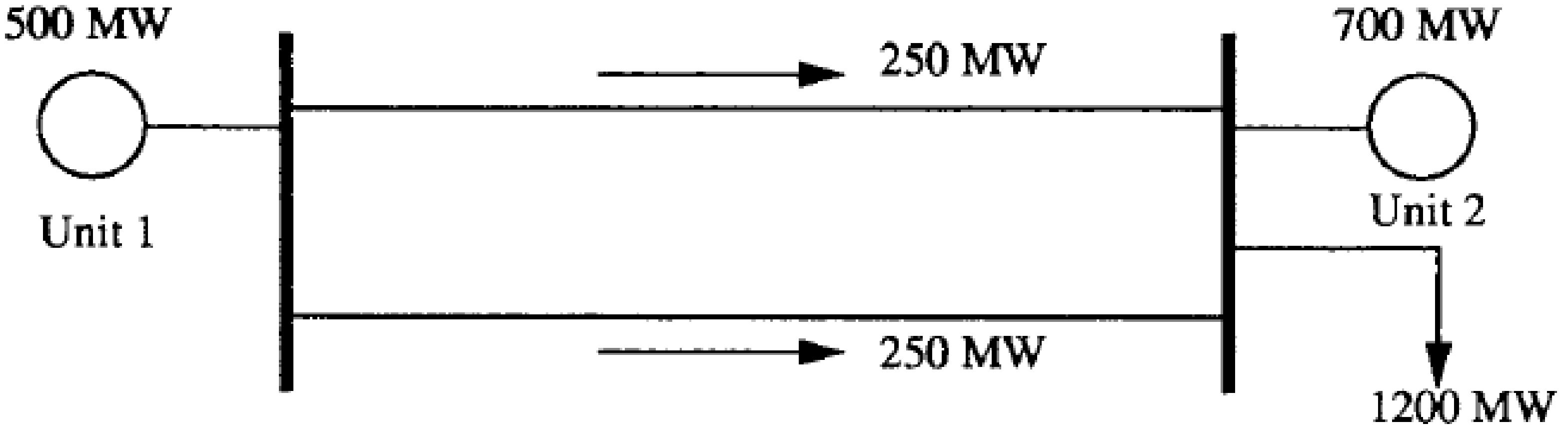
Normal state dispatch – optimally dispatch with respect to economic operation, but may not be secure

Post contingency – After a contingency occurs (N-1). Assumption is that the contingency has incurred violation of security limit, such as line or transformer overloaded or low voltage of buses

Secure dispatch – No contingency but correction was made to account for security violations

Secure post contingency – Remedial actions to security violations with corrective switching steps

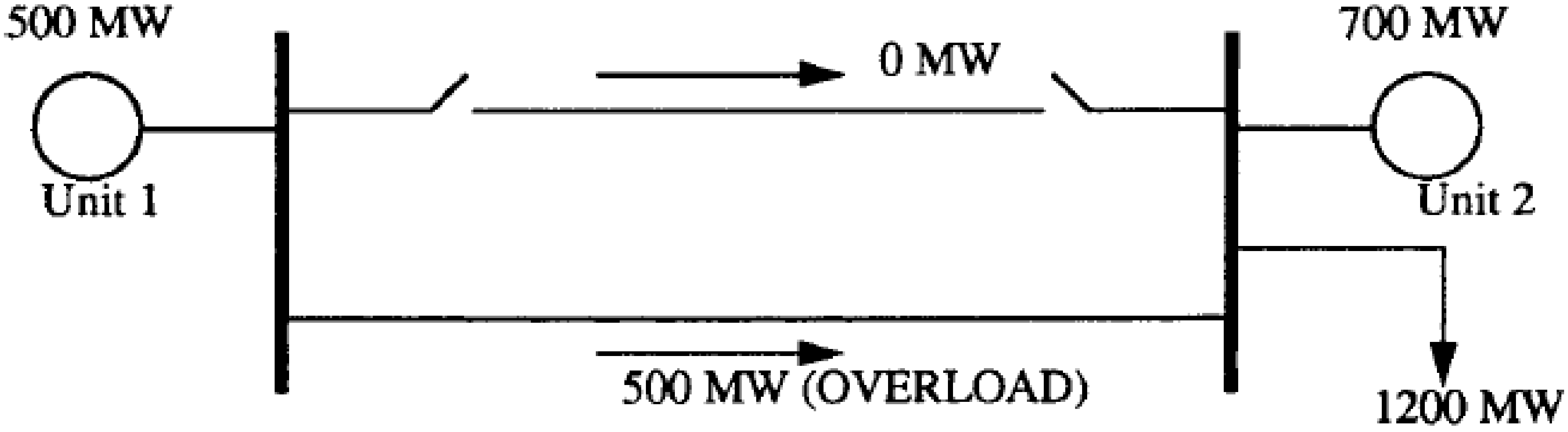
Normal Dispatch



NORMAL DISPATCH

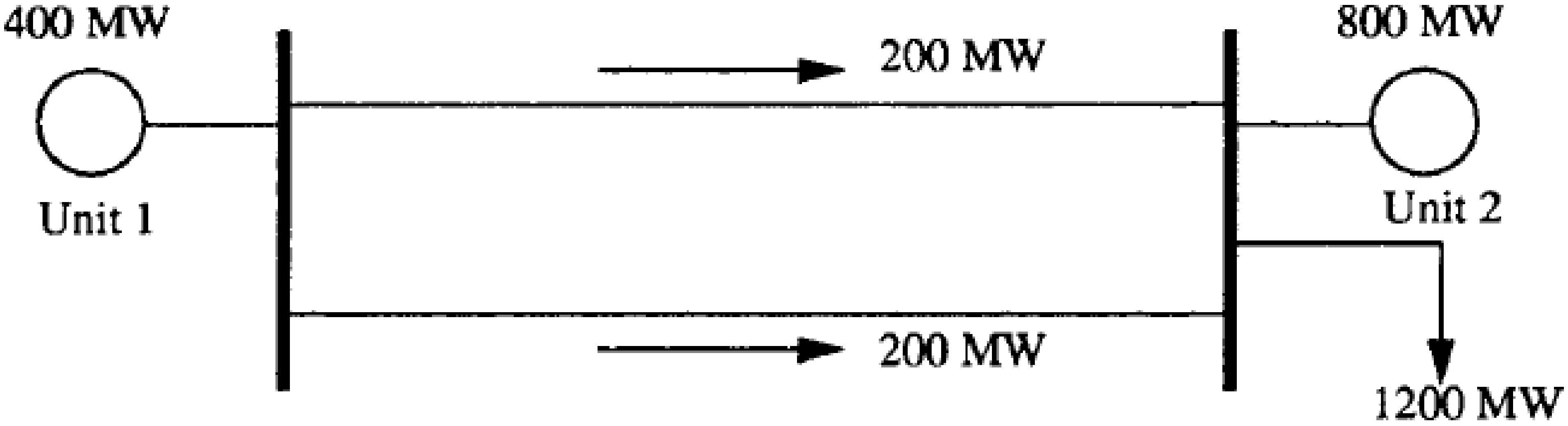
- ❑ Each transmission circuit has 400MW limit
- ❑ Optimal dispatch is 500MW from unit 1 and 700MW from unit 2
- ❑ These two units can be geographically dispersed that could be hundreds of miles away

Post Contingency State



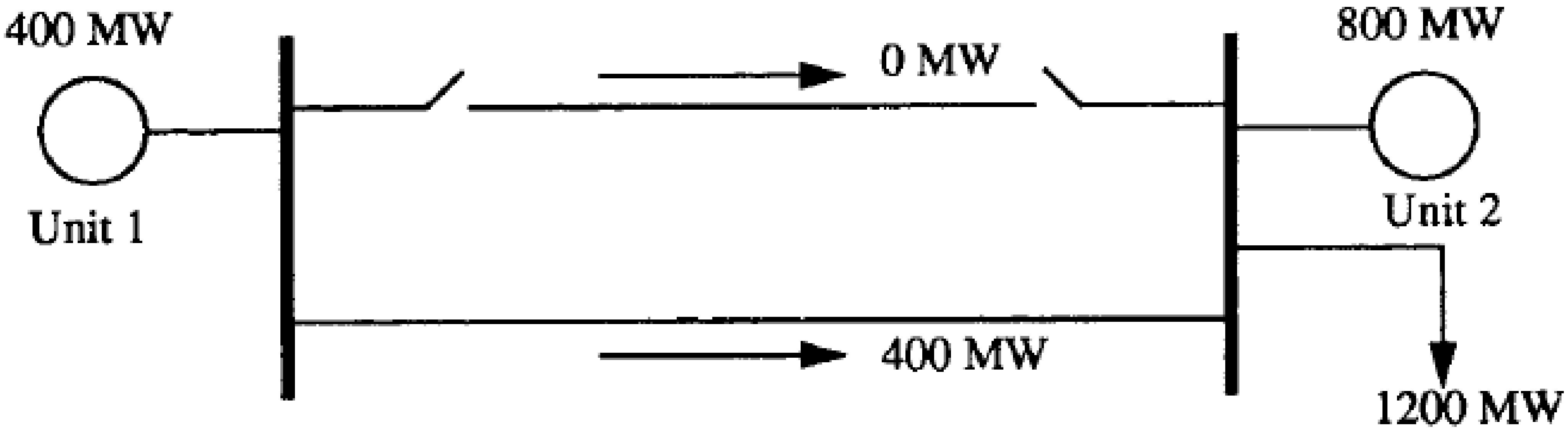
- ❑ One transmission circuit has an unforeseen trip, resulting 500MW flow to the only line that has 400MW limit
- ❑ 100MW more of the limit could cause the line sags
- ❑ Depending on the setup of relay, it may cascade further leads to blackout
- ❑ Solutions?

Secure State



- To optimize security constraints of those transmission circuits, the unit 1 is lower to 400MW in anticipating one circuit can be tripped and still maintain its operating limit
- Unit 2 is hence supplying 100MW to the 1200 MW local lump load.

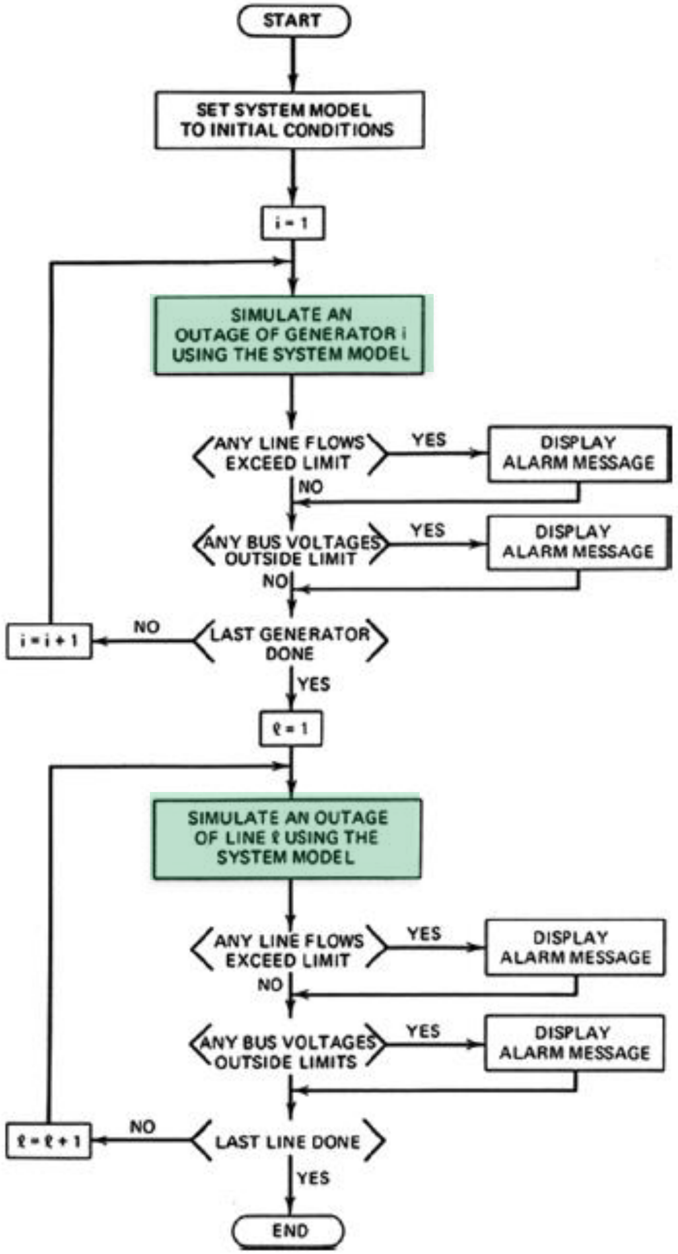
Secure Post Contingency State



- ❑ When one transmission circuit is tripped, the other line would still be able to carry the cheap power from unit 1 without any violation of the flow limit
- ❑ This is referred to security-constrained optimal power flow (SCOPF)
- ❑ These corrective action analysis is a very complex set of tools
- ❑ This module concentrates on contingency analysis

Why linear sensitivity factors are needed?

Full AC Power Flow Contingency



1. *AC Power Flow* plays a crucial role in validation of system security
2. All possible outages are studied
3. Speed of power flow solutions or sometimes power flow diverged
4. Common robust solution is to employ linearized "DC" power flow
5. Full "AC" power flow is needed if voltage information is needed.

Anticipating the contingencies

Linear sensitivity factors are then introduced:

1. Power Transfer Distribution Factors (PTDFs)
2. Line Outage Distribution Factor (LODFs)

Power Transfer Distribution Factors (PTDFs)

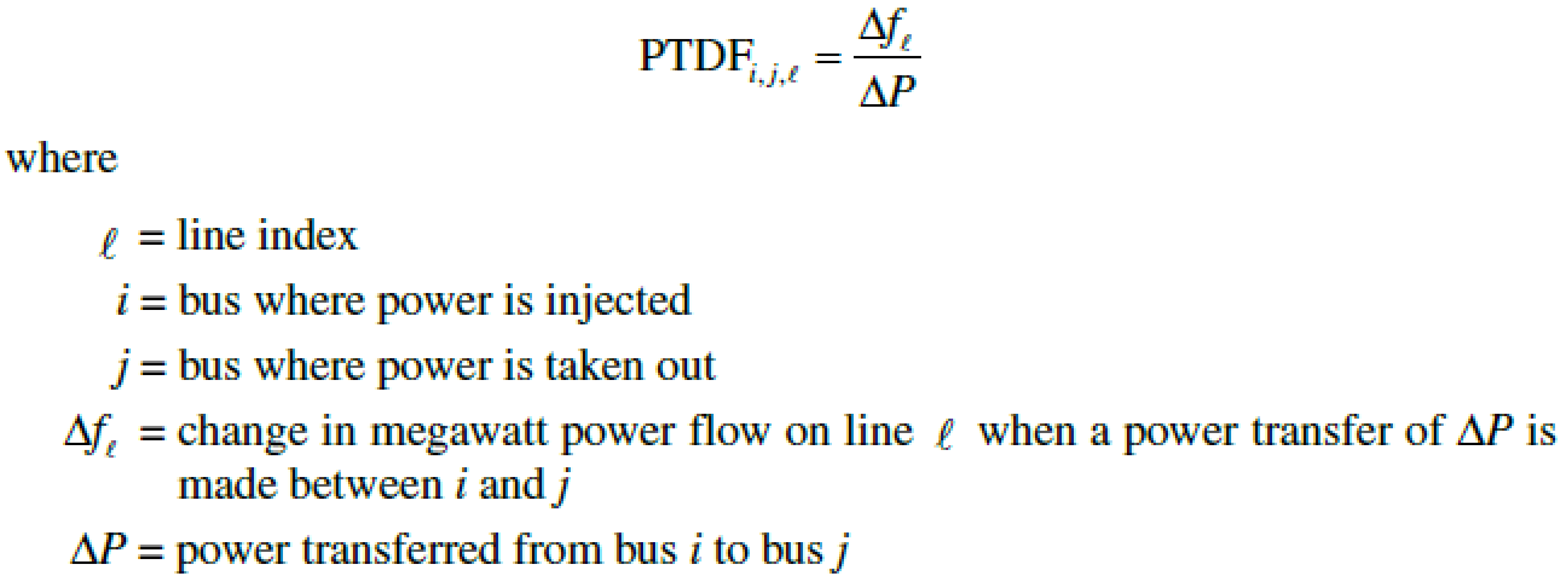
Before a generator/tie line inflow is sought for interconnection, PTDF is assessed to see the hypothesized flows on the existing status of the grid

1. Very powerful methodology in electricity market
2. Allow market operators to anticipate violations and make adjustment
3. Gateway flow from tie switches with other control areas

Power Transfer Distribution Factors (PTDFs)

Power Transfer Distribution Factors (PTDFs)

PTDF is defined as:



$$\text{PTDF}_{i,j,\ell} = \frac{\Delta f_\ell}{\Delta P}$$

where

ℓ = line index

i = bus where power is injected

j = bus where power is taken out

Δf_ℓ = change in megawatt power flow on line ℓ when a power transfer of ΔP is made between i and j

ΔP = power transferred from bus i to bus j

Power Transfer Distribution Factors (PTDFs)

PTDF represents sensitivity of flow on line to a shift of power from *i* to *j*. The flow of each transmission will then be updated using following equation:

$$\hat{f}_\ell = f_\ell^0 + \mathrm{PTDF}_{\mathrm{i,ref},\ell}\Delta P$$

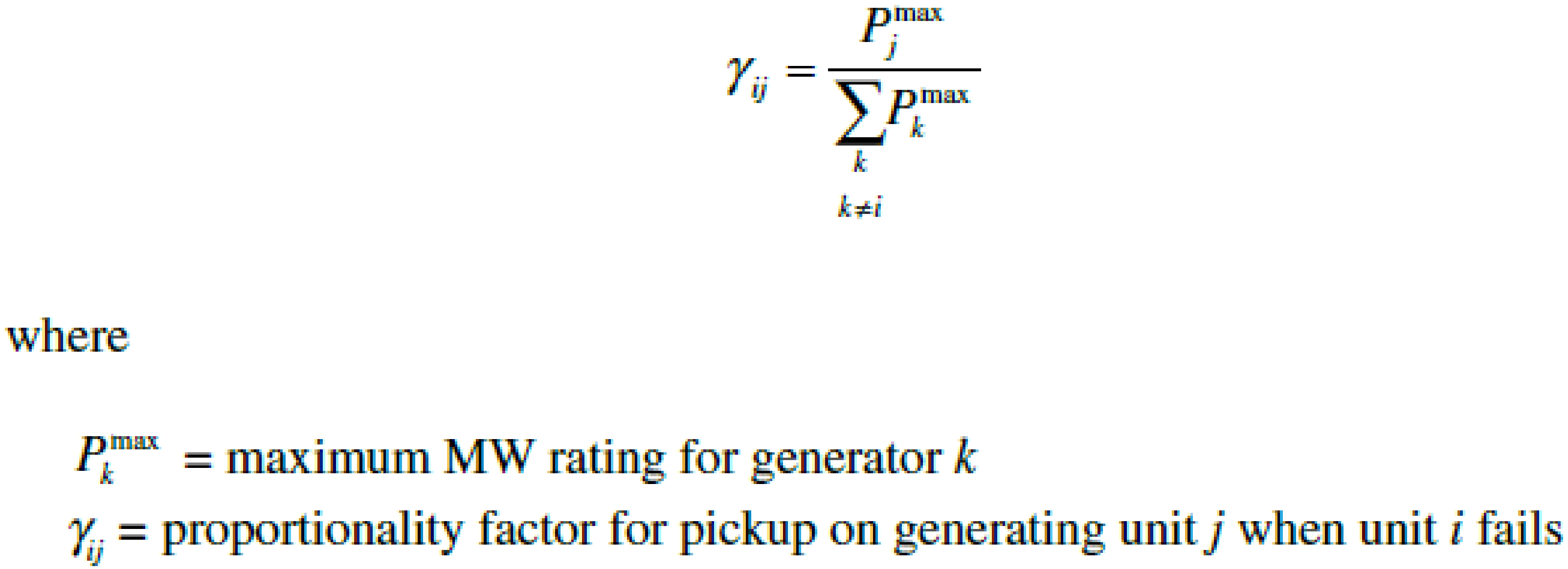
for $\ell = 1 \ldots L$
where

$\hat{f}_\ell$ = flow on line ℓ after the generator on bus i fails
f_ℓ^0 = flow before the failure

Power Transfer Distribution Factors (PTDFs)

❑ It is a linear estimates that can be calculated through superposition

❑ Remaining generators would pick up proportion to the maximum MW rating



$$\gamma_{ij} = \frac{P_j^{\max}}{\sum\limits_{\substack{k \\ k \neq i}} P_k^{\max}}$$

where

$P_k^{\max}$ = maximum MW rating for generator k

γ_{ij} = proportionality factor for pickup on generating unit j when unit i fails

Power Transfer Distribution Factors (PTDFs)

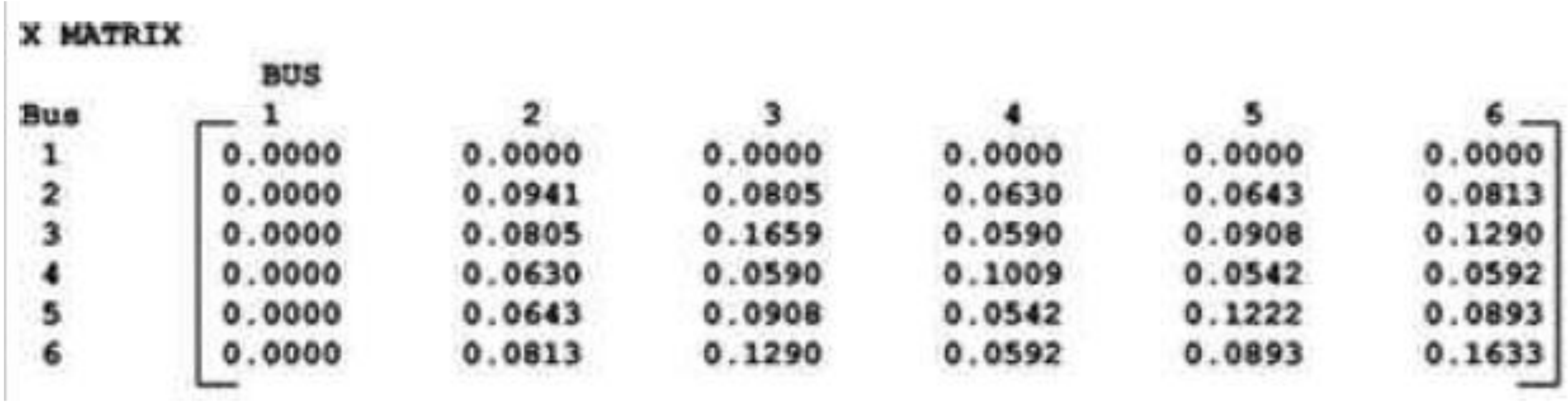
- Interconnection participate in making up the loss would be

$$\hat{f}_{\ell} = f_{\ell}^{0} + \mathrm{PTDF}_{i,\mathrm{ref},\ell}\Delta P_i - \sum_{j\neq i}\left[\mathrm{PTDF}_{\mathrm{ref},j,\ell}\gamma_{ji}\Delta P_i\right]$$

- No generator would hit its maximum
- Hence a more detailed generation algorithm to pick up that took account of generation limit would be needed

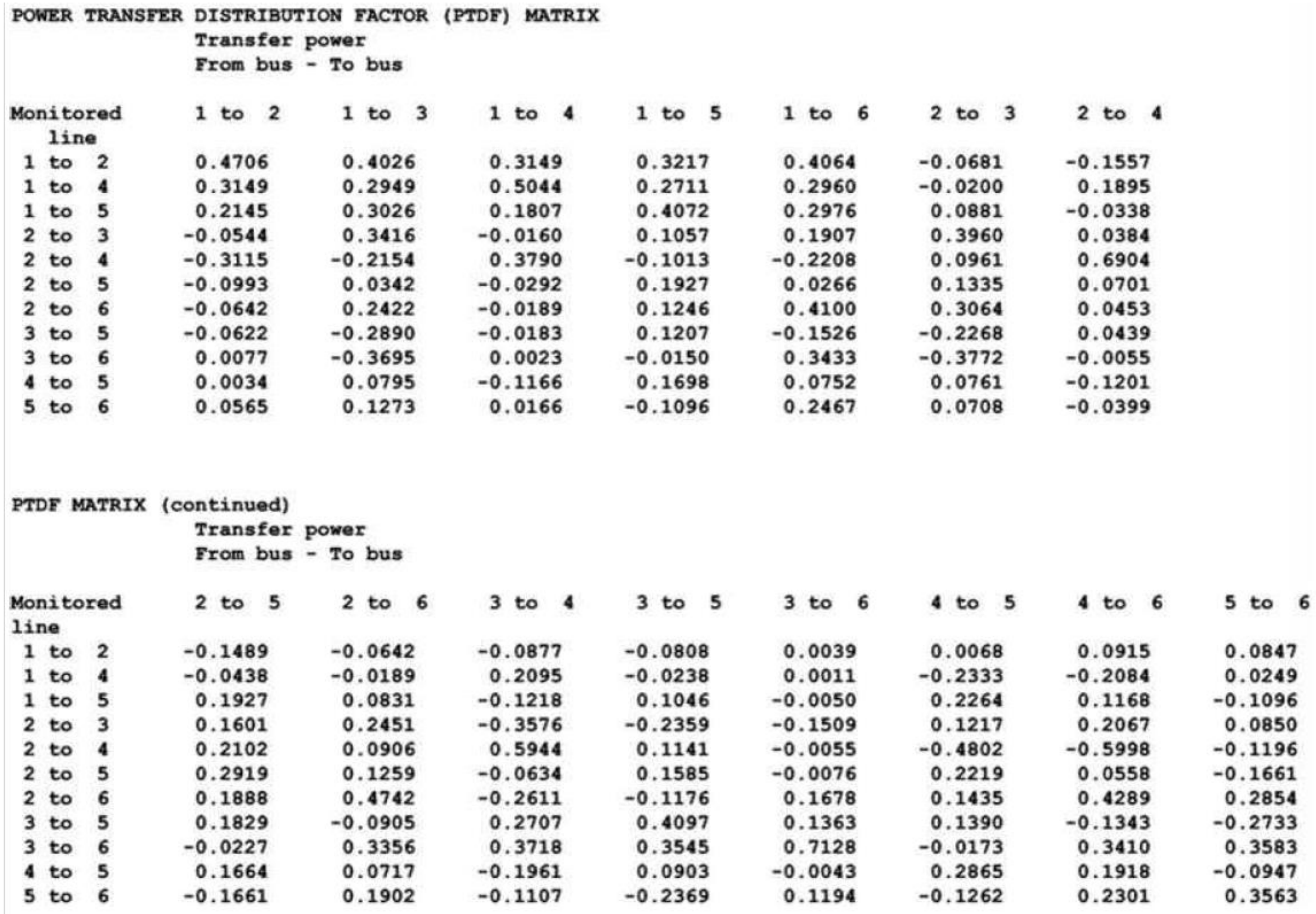
Example of Reactance Matrix

MATLAB output for the 6-bus power system:



```
X MATRIX
              BUS
Bus            1          2          3          4          5          6
 1          0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
 2          0.0000     0.0941     0.0805     0.0630     0.0643     0.0813
 3          0.0000     0.0805     0.1659     0.0590     0.0908     0.1290
 4          0.0000     0.0630     0.0590     0.1009     0.0542     0.0592
 5          0.0000     0.0643     0.0908     0.0542     0.1222     0.0893
 6          0.0000     0.0813     0.1290     0.0592     0.0893     0.1633
```

Example of PTDF matrix

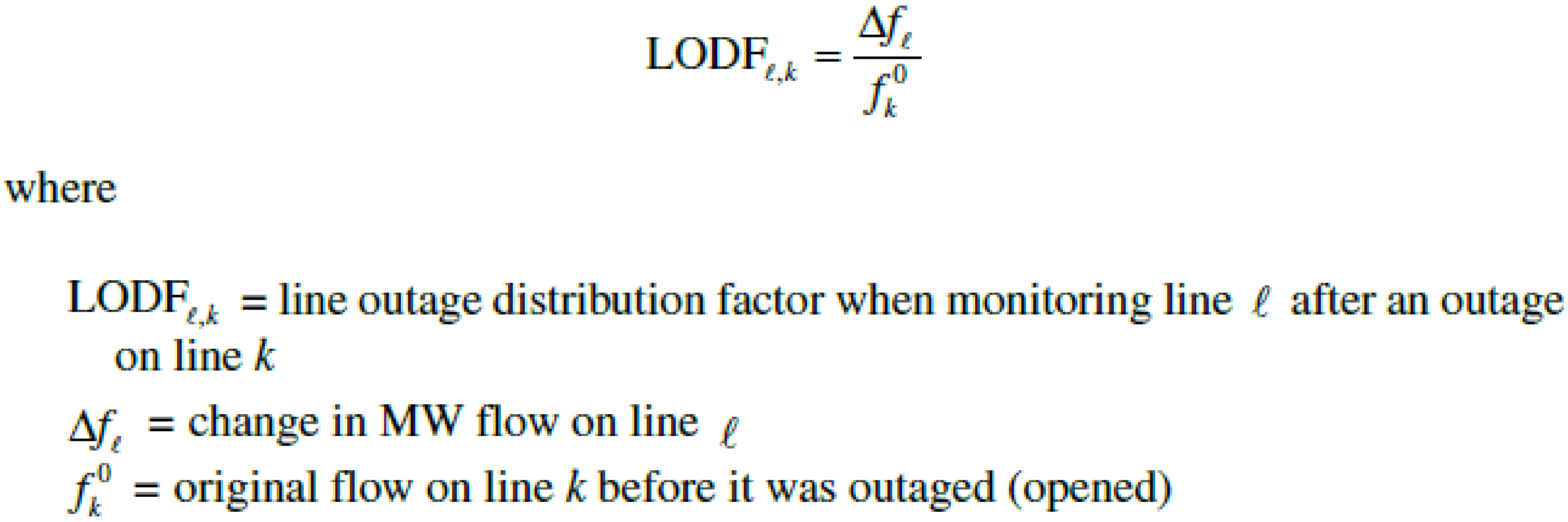


```
POWER TRANSFER DISTRIBUTION FACTOR (PTDF) MATRIX
                Transfer power
                From bus - To bus

Monitored       1 to  2     1 to  3     1 to  4     1 to  5     1 to  6     2 to  3     2 to  4
   line
 1 to  2        0.4706      0.4026      0.3149      0.3217      0.4064     -0.0681     -0.1557
 1 to  4        0.3149      0.2949      0.5044      0.2711      0.2960     -0.0200      0.1895
 1 to  5        0.2145      0.3026      0.1807      0.4072      0.2976      0.0881     -0.0338
 2 to  3       -0.0544      0.3416     -0.0160      0.1057      0.1907      0.3960      0.0384
 2 to  4       -0.3115     -0.2154      0.3790     -0.1013     -0.2208      0.0961      0.6904
 2 to  5       -0.0993      0.0342     -0.0292      0.1927      0.0266      0.1335      0.0701
 2 to  6       -0.0642      0.2422     -0.0189      0.1246      0.4100      0.3064      0.0453
 3 to  5       -0.0622     -0.2890     -0.0183      0.1207     -0.1526     -0.2268      0.0439
 3 to  6        0.0077     -0.3695      0.0023     -0.0150      0.3433     -0.3772     -0.0055
 4 to  5        0.0034      0.0795     -0.1166      0.1698      0.0752      0.0761     -0.1201
 5 to  6        0.0565      0.1273      0.0166     -0.1096      0.2467      0.0708     -0.0399



PTDF MATRIX (continued)
                Transfer power
                From bus - To bus

Monitored       2 to  5     2 to  6     3 to  4     3 to  5     3 to  6     4 to  5     4 to  6     5 to  6
line
 1 to  2       -0.1489     -0.0642     -0.0877     -0.0808      0.0039      0.0068      0.0915      0.0847
 1 to  4       -0.0438     -0.0189      0.2095     -0.0238      0.0011     -0.2333     -0.2084      0.0249
 1 to  5        0.1927      0.0831     -0.1218      0.1046     -0.0050      0.2264      0.1168     -0.1096
 2 to  3        0.1601      0.2451     -0.3576     -0.2359     -0.1509      0.1217      0.2067      0.0850
 2 to  4        0.2102      0.0906      0.5944      0.1141     -0.0055     -0.4802     -0.5998     -0.1196
 2 to  5        0.2919      0.1259     -0.0634      0.1585     -0.0076      0.2219      0.0558     -0.1661
 2 to  6        0.1888      0.4742     -0.2611     -0.1176      0.1678      0.1435      0.4289      0.2854
 3 to  5        0.1829     -0.0905      0.2707      0.4097      0.1363      0.1390     -0.1343     -0.2733
 3 to  6       -0.0227      0.3356      0.3718      0.3545      0.7128     -0.0173      0.3410      0.3583
 4 to  5        0.1664      0.0717     -0.1961      0.0903     -0.0043      0.2865      0.1918     -0.0947
 5 to  6       -0.1661      0.1902     -0.1107     -0.2369      0.1194     -0.1262      0.2301      0.3563
```

Line Outage Distribution Factor (LODFs)

Line Outage Distribution Factor (LODFs)

The application of this factor is very similar to PTDFs, i.e., determination of potential overloads incurred by a single contingency, i.e., N-1



$$\mathrm{LODF}_{\ell,k} = \frac{\Delta f_{\ell}}{f_k^0}$$

where

$\mathrm{LODF}_{\ell,k}$ = line outage distribution factor when monitoring line ℓ after an outage on line k

Δf_{ℓ} = change in MW flow on line ℓ

f_k^0 = original flow on line k before it was outaged (opened)

Line Outage Distribution Factor (LODFs)

Flows change on other lines based on the hypothesized list of contingencies. The flows are updated based on the following equation:

$$\hat{f}_\ell = f_\ell^0 + \mathrm{LODF}_{\ell,k} f_k^0$$

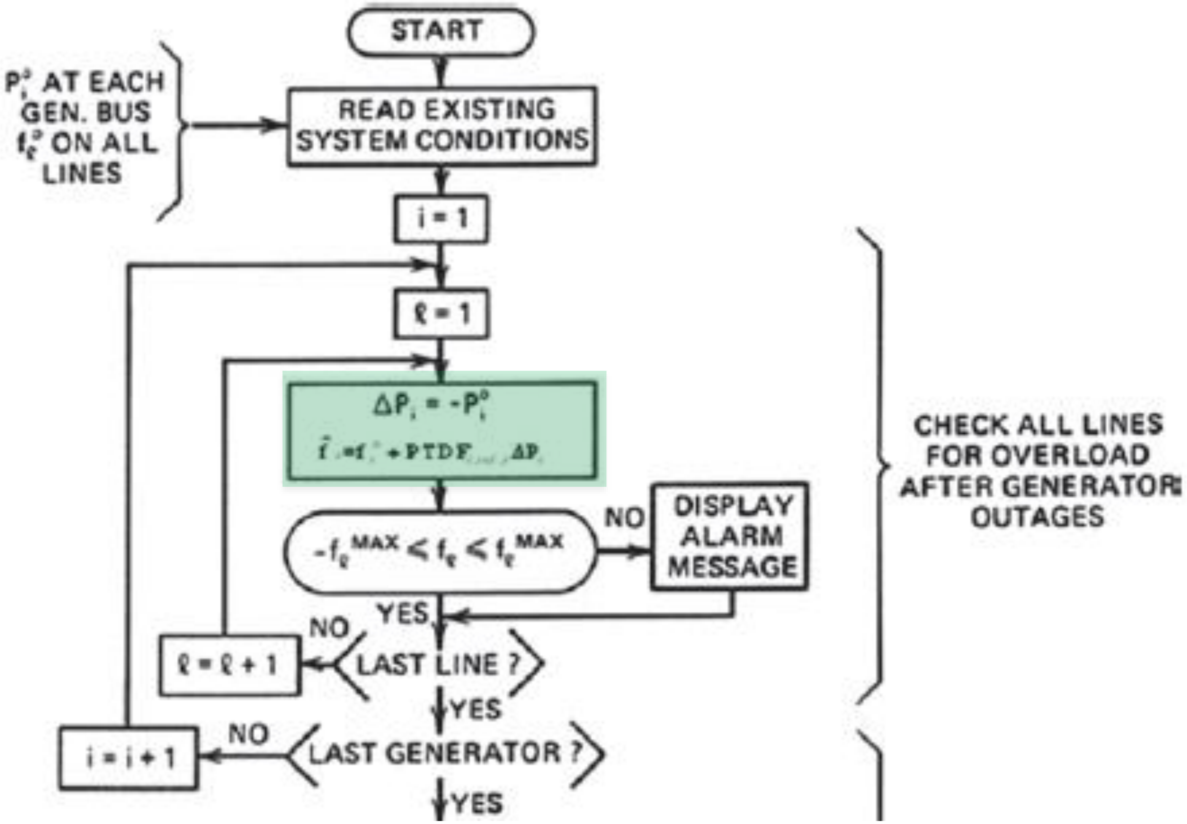
where

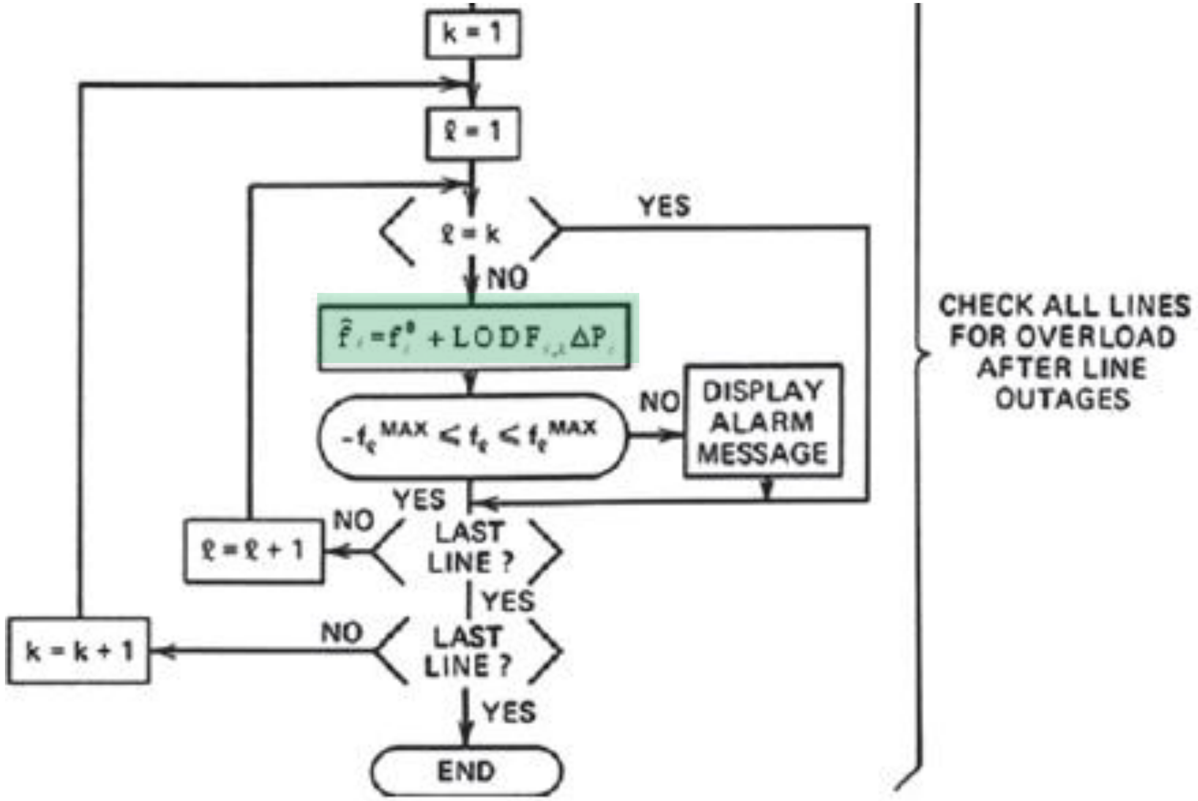
f_ℓ^0, f_k^0 preoutage flows on lines ℓ and k, respectively

$\hat{f}_\ell$ = flow on line ℓ with line k out

Line Outage Distribution Factors (LODFs)

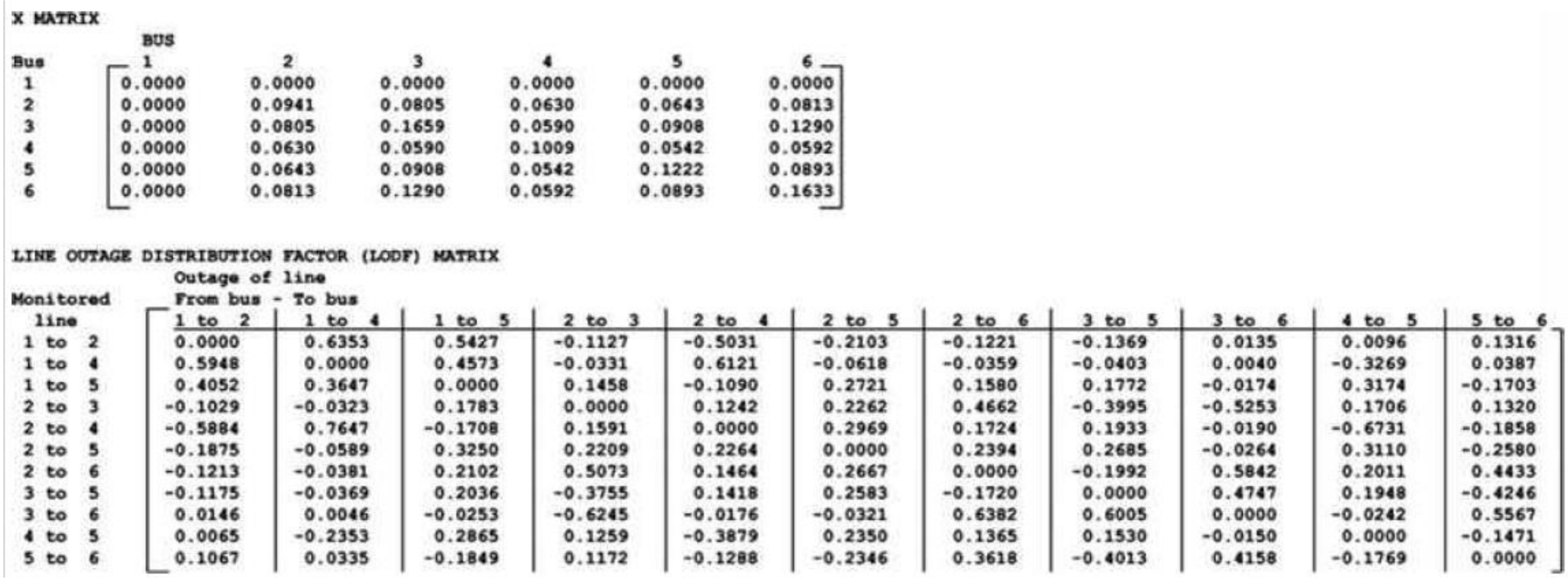
The updated flowchart using the sensitivity factors:





Example of LODF matrix

The following are reactance and LODF matrices:



X MATRIX

Bus	BUS 1	2	3	4	5	6
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0941	0.0805	0.0630	0.0643	0.0813
3	0.0000	0.0805	0.1659	0.0590	0.0908	0.1290
4	0.0000	0.0630	0.0590	0.1009	0.0542	0.0592
5	0.0000	0.0643	0.0908	0.0542	0.1222	0.0893
6	0.0000	0.0813	0.1290	0.0592	0.0893	0.1633

LINE OUTAGE DISTRIBUTION FACTOR (LODF) MATRIX

Monitored line	Outage of line From bus - To bus 1 to 2	1 to 4	1 to 5	2 to 3	2 to 4	2 to 5	2 to 6	3 to 5	3 to 6	4 to 5	5 to 6
1 to 2	0.0000	0.6353	0.5427	-0.1127	-0.5031	-0.2103	-0.1221	-0.1369	0.0135	0.0096	0.1316
1 to 4	0.5948	0.0000	0.4573	-0.0331	0.6121	-0.0618	-0.0359	-0.0403	0.0040	-0.3269	0.0387
1 to 5	0.4052	0.3647	0.0000	0.1458	-0.1090	0.2721	0.1580	0.1772	-0.0174	0.3174	-0.1703
2 to 3	-0.1029	-0.0323	0.1783	0.0000	0.1242	0.2262	0.4662	-0.3995	-0.5253	0.1706	0.1320
2 to 4	-0.5884	0.7647	-0.1708	0.1591	0.0000	0.2969	0.1724	0.1933	-0.0190	-0.6731	-0.1858
2 to 5	-0.1875	-0.0589	0.3250	0.2209	0.2264	0.0000	0.2394	0.2685	-0.0264	0.3110	-0.2580
2 to 6	-0.1213	-0.0381	0.2102	0.5073	0.1464	0.2667	0.0000	-0.1992	0.5842	0.2011	0.4433
3 to 5	-0.1175	-0.0369	0.2036	-0.3755	0.1418	0.2583	-0.1720	0.0000	0.4747	0.1948	-0.4246
3 to 6	0.0146	0.0046	-0.0253	-0.6245	-0.0176	-0.0321	0.6382	0.6005	0.0000	-0.0242	0.5567
4 to 5	0.0065	-0.2353	0.2865	0.1259	-0.3879	0.2350	0.1365	0.1530	-0.0150	0.0000	-0.1471
5 to 6	0.1067	0.0335	-0.1849	0.1172	-0.1288	-0.2346	0.3618	-0.4013	0.4158	-0.1769	0.0000

Summary

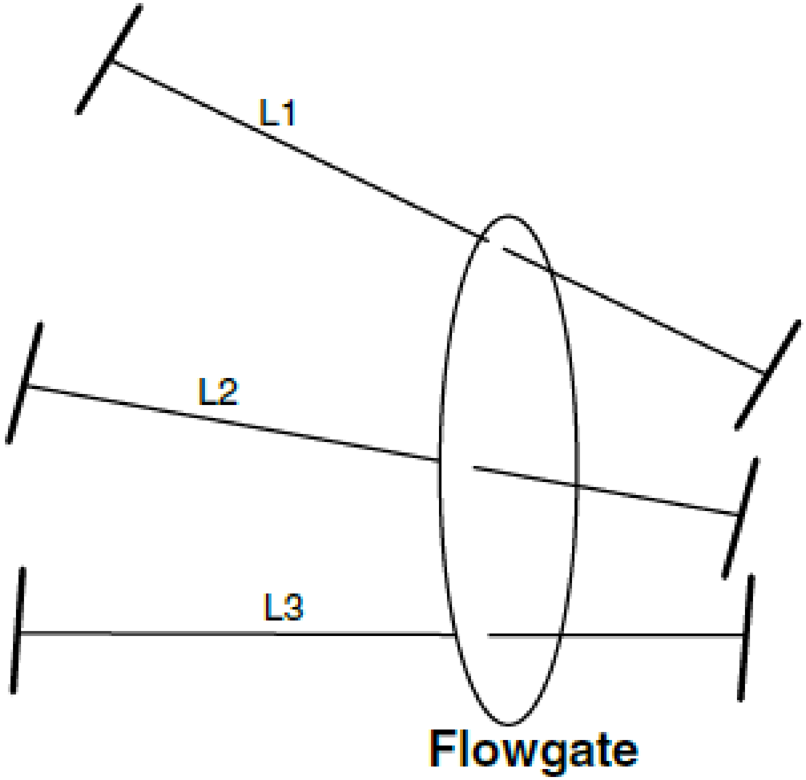
- Transactions occur within an organization
- Combinations of hypothesized outages
- No trouble with too much time to take to evaluate all combinations
- No trouble to deal with power flow diverged cases
- Straightforward calculation based the current switching status of power grid
- **A power grid is not a single company – many companies within a large interconnection. How to deal with it?**

Flowgate is introduced!

Definition of Flowgate

- Transactions in a power pool within an interconnection
- Accounting of how much it is exported or imported to a control area (referred to a transmission utility)
- Selling or buying power from different transmission utilities
- Flowgate concept came from Paul Barber of Midwest Reliability organization
- “*We noted that network flow limitations seldom depended upon single lines but rather on groups of lines that could be modeled by partial cutsets. We first called them tollgates because we had envisioned a revenue sharing scheme to get transmission owners paid for the use of their investments but it created quite an uproar so I suggested calling them flowgates to avoid the revenue arguments*.”

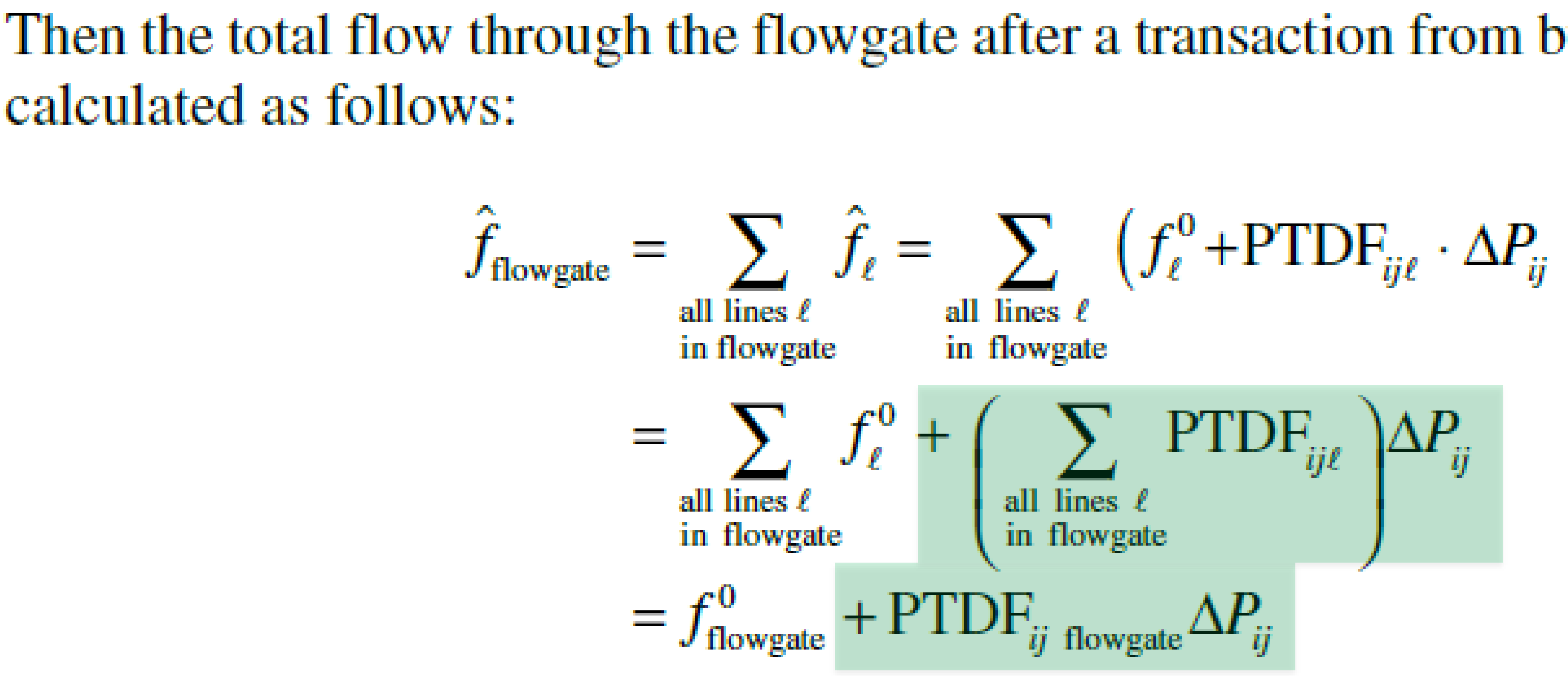
Definition of Flowgate



- ❑ Build on the PTDF and LODF factors
- ❑ Flowing from or to a control area of transmission companies
- ❑ The tie lines may not be used and hence it is 0MW
- ❑ Voltages of both terminals would define how power flow between control areas
- ❑ Flow is defined as:

$$f_{\text{flowgate}} = f_{\text{L1}} + f_{\text{L2}} + f_{\text{L3}}$$

Updated Total Flow on PTDFs



Then the total flow through the flowgate after a transaction from bus *i* to bus *j* can be calculated as follows:

$$\begin{aligned}\hat{f}_{\text{flowgate}} &= \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \hat{f}_\ell = \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \left(f_\ell^0 + \text{PTDF}_{ij\ell} \cdot \Delta P_{ij}\right) \\ &= \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} f_\ell^0 + \left(\sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \text{PTDF}_{ij\ell}\right)\Delta P_{ij} \\ &= f_{\text{flowgate}}^0 + \text{PTDF}_{ij\ \text{flowgate}}\,\Delta P_{ij}\end{aligned}$$

- ❑ Updated flow is after a transaction is made
- ❑ The 0 indicates the flow before a transaction is made
- ❑ Account for all lines in the flowgate from other control areas

Updated Total Flow on LODFs

- Similarly, the line outage is applied the same “accounting,” i.e., the power flowing through the hypothesized line outage will be distributed in the neighborhood of the connected nodes

$$
\begin{aligned}
\hat{f}_{\text{flowgate}} = \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \hat{f}_{\ell} &= \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \left(f_{\ell}^{0} + \text{LODF}_{\ell,k} \cdot f_{k}^{0} \right) \\
&= \sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} f_{\ell}^{0} + \left(\sum_{\substack{\text{all lines } \ell \\ \text{in flowgate}}} \text{LODF}_{\ell,k} \right) f_{k}^{0} \\
&= f_{\text{flowgate}}^{0} + \text{LODF}_{\text{flowgate},k} f_{k}^{0}
\end{aligned}
$$