

Use of Planning Studies to Estimate Security Margins in Real-Time

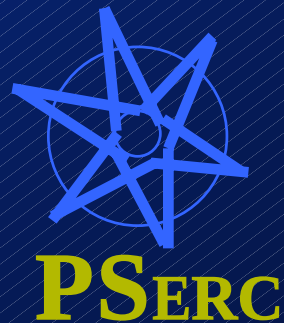
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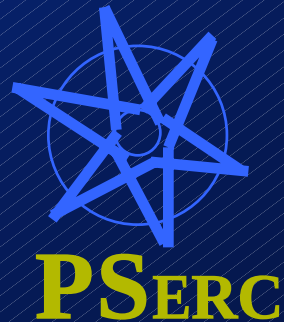
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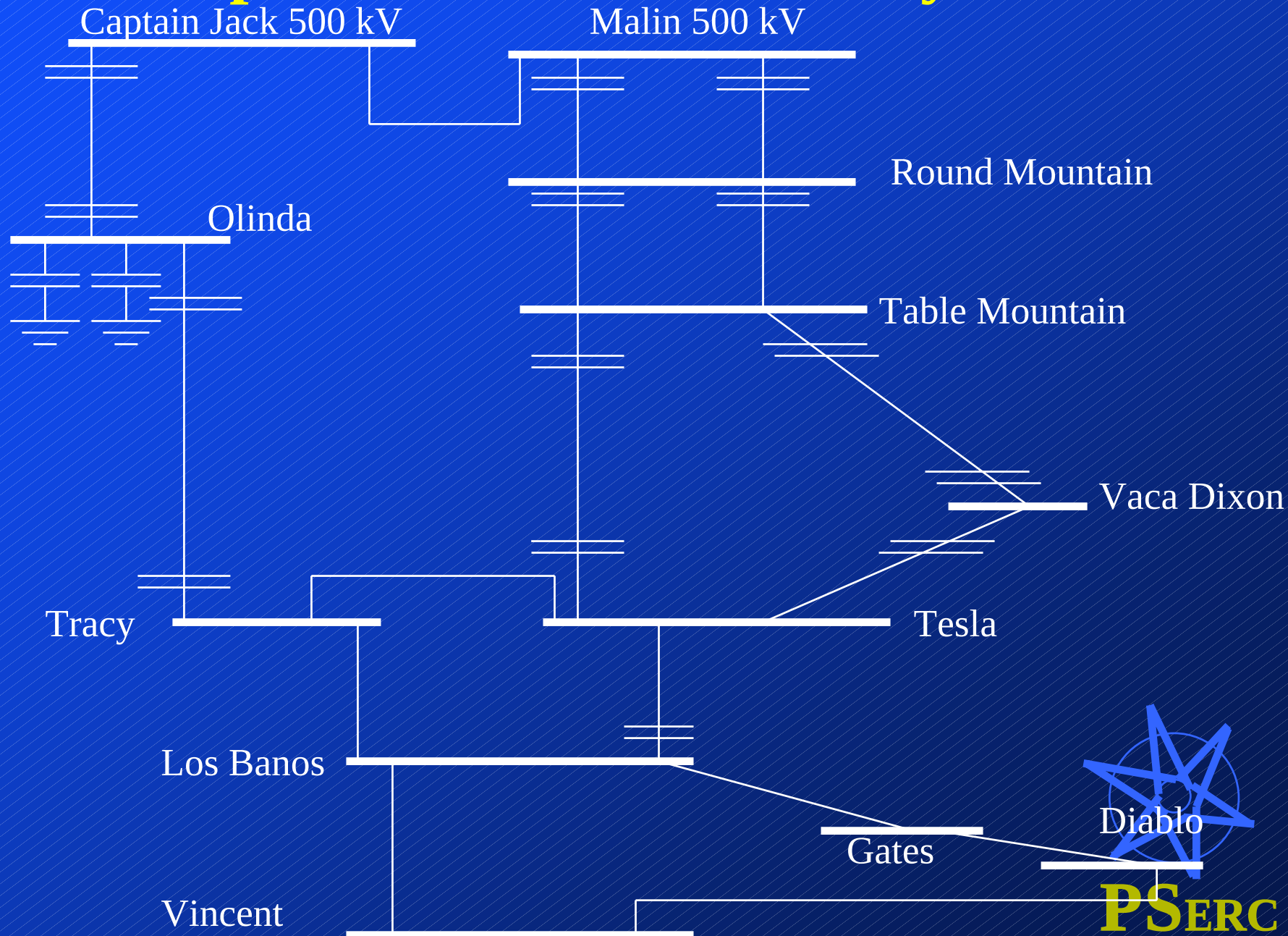
Background

Determination of Operation Limits

- **Operation schedules in California for transfer limits on COI and NOB.**
 - **Provides curtailment in the event of the first outage and protects against the next worst outage.**
- **For specified outages, load flow and stability studies are performed (off-line) to determine COI and NOB limits.**



Simplified PG&E 500 kV System



Example Table

TABLE 1A
500 KV AC SYSTEM
NORTH TO SOUTH CONTINGENCY RATINGS
SCHEDULE AND FLOW LIMIT (MW)
ON AC AND DC INTERTIES

Read Notes 1 Through 6

SINGLE AC LINE OUTAGE
BETWEEN COI AND MIDWAY
(Ratings administered by PG&E)

Line/Equipment O/S Prior to Next Outage	COI Limit	NOB Limit	Next Outage	LIMITING FACTOR
None (See Note 1)	3200	2000**	None	AC/DC Nomogram
Malin-Round Mt. #1 or #2	2800	2000**	PDCI	Thermal Limit: Malin-Round Mt. Line
Captain Jack - Olinda ♦	2800	2000**	Dbl AC	CASI Nomogram
Round Mt.-Table Mt. #1 or #2 *	2000	2000**	PDCI	Thermal Limit: Rnd Mt.-Table Mt. Line
Olinda - Tracy © * ♦	2800	2000**	Dbl AC	CASI Nomogram
Table Mountain - Vaca Dixon *	2800	2000**	PDCI	Thermal Limit: Table Mt.-Tesla Line
Table Mountain - Tesla *	2100	2000**	PDCI	Thermal Limit: Table Mt.-Vaca Line
Vaca Dixon - Tesla *	2800	2000**	PDCI	MVAR Margin
Tesla - Tracy *	3200	2000**	PDCI	MVAR Margin
Tesla - Los Banos *	3200	2000**	PDCI	MVAR Margin
Tracy - Los Banos *	3200	2000**	PDCI	MVAR Margin
Los Banos - Midway *	3200	2000**	PDCI	MVAR Margin
Los Banos - Gates *	3200	2000**	PDCI	MVAR Margin
Gates - Midway *	3200	2000**	PDCI	MVAR Margin

- © Upon occurrence of this outage immediately adjust schedules and contact BPA that a system separation is credible and the High generator dropping needs to be increased to protect against it. If planned outage still contact BPA. (BPA can see CJ-OL O/S)
- * Upon occurrence of this outage immediately adjust schedules and contact BPA to increase NW generator dropping to an amount equal to PDCI transfers up to 2850 MW. If PDCI flows at Celilo are below 1600 MW with 4800 MW on COI, or less than 3100 MW (@ Celilo) and less than 2200 MW on COI, it is not necessary to arm additional NW generator dropping.
- ♦ Upon occurrence of these outages, refer to Dispatching Instructions O-44 for further instructions.
- ** During Off-Peak hours (2300-0600) DC limit is increased to 2200 at NOB.

Example - Voltage Stability Criteria

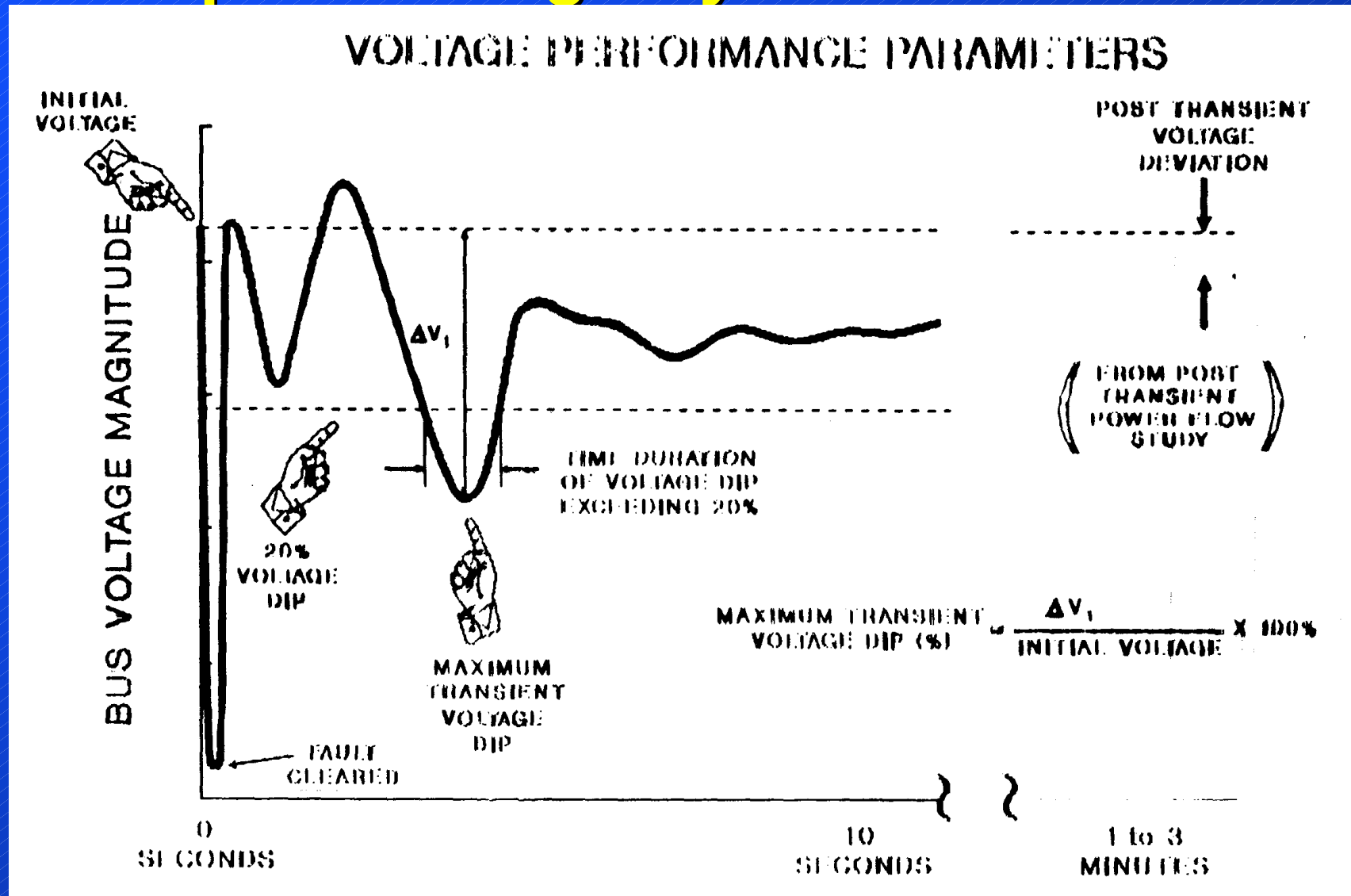
Table 1

WSCC VOLTAGE STABILITY CRITERIA

Performance Level	Disturbance (1)(2)(3) Initiated By: Fault or No Fault DC Disturbance	MW Margin (P-V Method) (4)(5)	MVAR Margin (V-Q Method) (5)
A	Any element such as: One Generator One Circuit One Transformer One Reactive Power Source One DC Monopole	$\geq 5\%$	Worst Case Scenario (6)
B	Bus Section	$\geq 2.5\%$	50% of Margin in Level A
C	Any combination of two elements such as: A Line and a Generator A Line and a Reactive Power Source Two Generators Two Circuits Two Transformers Two Reactive Power Sources DC Bipole	$\geq 1\%$	20% of Margin in Level A
D	Any combination of three or more elements such as: Three or More Circuits on ROW Entire Substation Entire Plant Including Switchyard	> 0	> 0



Example - Voltage Dynamic Performance



Example: WSCC Disturbance Performance

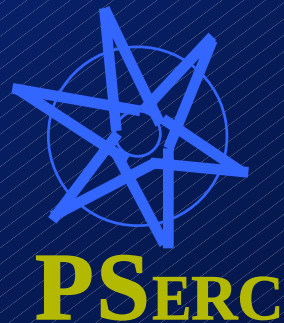
**WSCC DISTURBANCE-PERFORMANCE TABLE
OF ALLOWABLE EFFECT ON OTHER SYSTEMS⁽¹⁾**

Performance Level	Disturbance(2) Initiated By: No Fault 3 Ø Fault With Normal Clearing SLG Fault With Delayed Clearing DC Disturbance (3)	Transient Voltage Dip Criteria (4)(5)(6)	Minimum Transient Frequency (4)(5)	Post Transient Voltage Deviation (4)(5)(6)(7)	Loading Within Emergency Ratings	Damping
A	Generator One Circuit One Transformer DC Monopole (8)	Max V Dip - 25% Max Duration of V Dip Exceeding 20% - 20 cycles	59.6 Hz Duration of f Below 59.6 Hz - 6 cycles	5%	Yes	≥ 0
B	Bus Section	Max V Dip - 30% Max Duration of V Dip Exceeding 20% - 20 cycles	59.4 Hz Duration of f Below 59.4 Hz - 6 cycles	5%	Yes	≥ 0
C	Two Generators Two Circuits DC Bipole (8)	Max V Dip - 30% Max Duration of V Dip Exceeding 20% - 40 cycles	59.0 Hz Duration of f Below 59.0 Hz - 6 cycles	10%	Yes	≥ 0
D	Three or More circuits on ROW Entire Substation Entire Plant Including Switchyard	Max V Dip - 30% Max Duration of V Dip Exceeding 20% - 60 cycles	58.1 Hz Duration of f Below 58.1 Hz - 6 cycles	10%	No	≥ 0



Off-line Studies

- **Transfer limits and nomograms**
 - 20 second dynamic study
 - Load flow
 - “Governor” load flow
- **Must satisfy WSCC reliability criteria**
 - Transient voltage dip
 - Minimum transient frequency
 - Post transient voltage deviation
 - Damping
 - Loading within emergency rating
- **The studies are thorough - essentially all significant contingencies investigated**



Observations on Current Practice

- This framework is significantly different than the on-line security framework, since off-line
 - there is sufficient time to study all major contingencies (although only for some fixed set of base cases)
 - performance measures can be precise – i.e., no need to calculate security indices
 - emphasis is on key transfers and security margins
 - multiple outages can be investigated



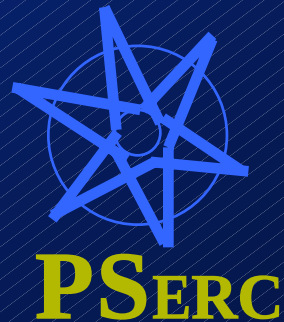
Observations on Current Practice (cont.)

- Easy to misinterpret compiled data from the tables
- Ratings and limits are conservative based on highly stressed system conditions
- Impractical to study all combinations of equipment outages so some limits are unavailable, or overly conservative.
- Guidelines do not provide redispatching instructions, or other remedial actions.



Proposed Estimation Framework

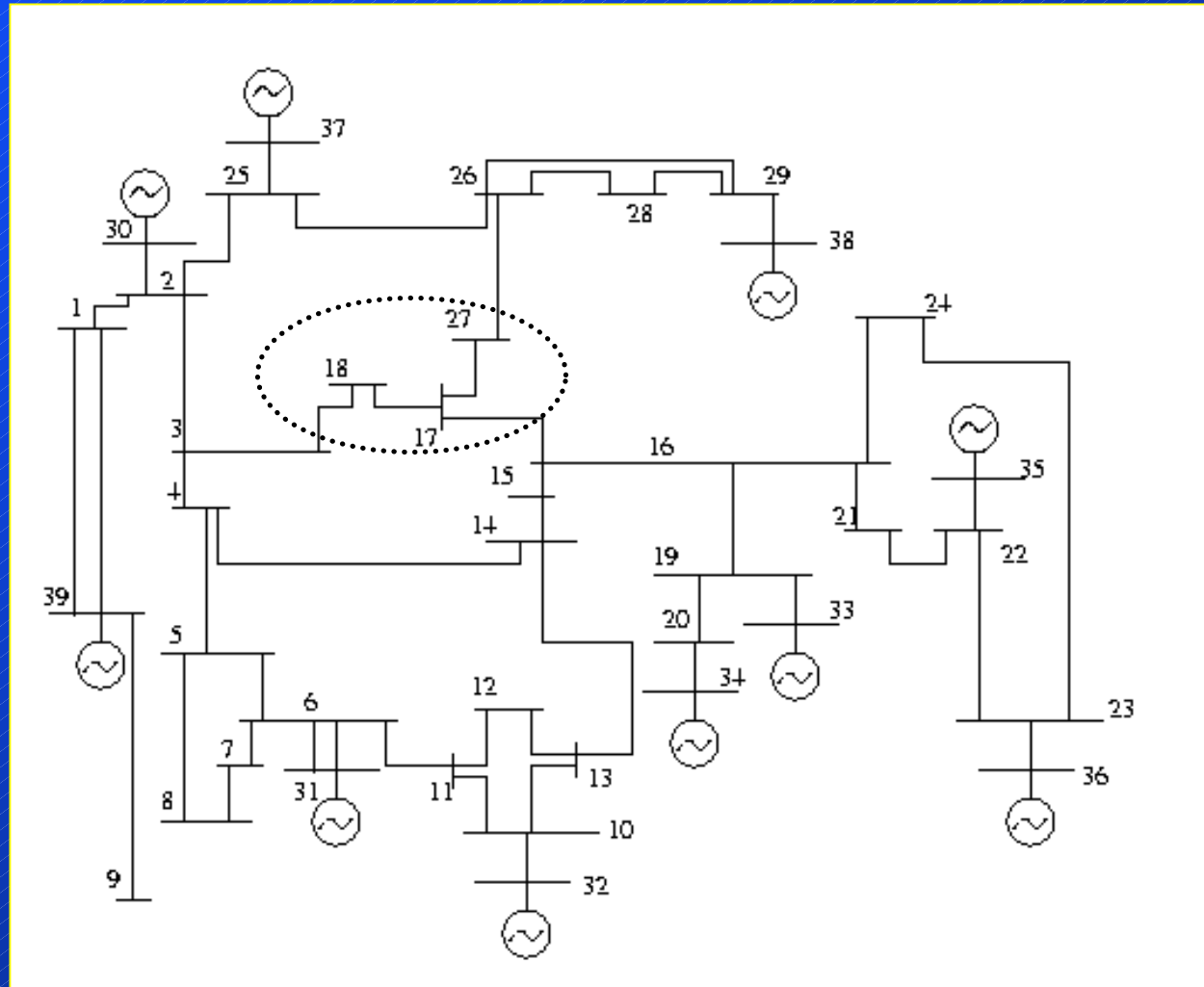
- Record detailed off-line studies and then use a “pattern matching” approach to estimate margins for unstudied cases
 - Estimates calculated essentially instantaneously given inputs from State Estimator
- Follow operations planning studies precisely without using the traditional on-line security approaches



Example - MVar Margin (Q-V Curves)

- General approach
 - Calculate MVar margin for all study cases
 - Select appropriate set of features for this measure
 - Estimate MVar margins for test cases based on training cases
- Pattern Matching Techniques
 - Linear regression (curve fitting)
 - e.g., $Q_m = P^T A P + B^T P + c$
 - Interpolation - associative memory
 - Kohonen self-organized networks
 - Feed-forward neural networks

New England 39 Bus System



Feature Selection and Study Cases

- **Features**
 - Tie line flows
 - Flows on lines that connect weak buses
- **Study cases**
 - Base case
 - 5 different loading cases
 - All single line outages

Correlation Coefficients Between Line Flows and MVar Margin

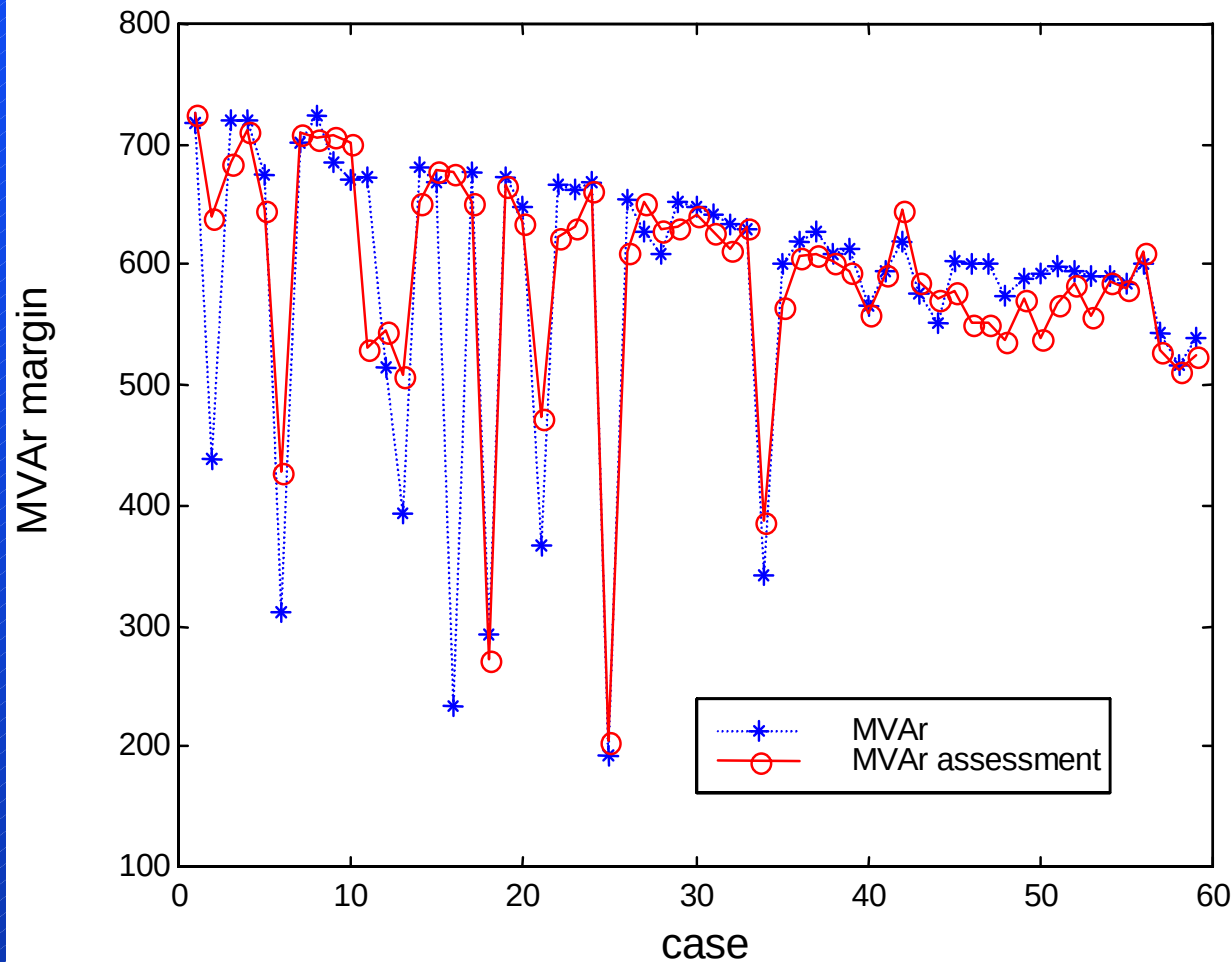
Line	original	Modified (coding for line outage)
tie lines*	-0.6386	-0.4468
03-18*	-0.4356	-0.4331
16-17*	-0.1031	-0.2035
17-18*	0.0766	-0.0889
17-27*	-0.0781	-0.1915
26-27*	-0.2250	-0.3444
25-26	0.0271	0.0689
02-03	-0.0554	-0.0029
14-15	0.0472	0.0523
15-16	-0.0123	-0.0266
16-19	-0.0195	0.0151
16-21	-0.1020	-0.0459

*: selected feature set

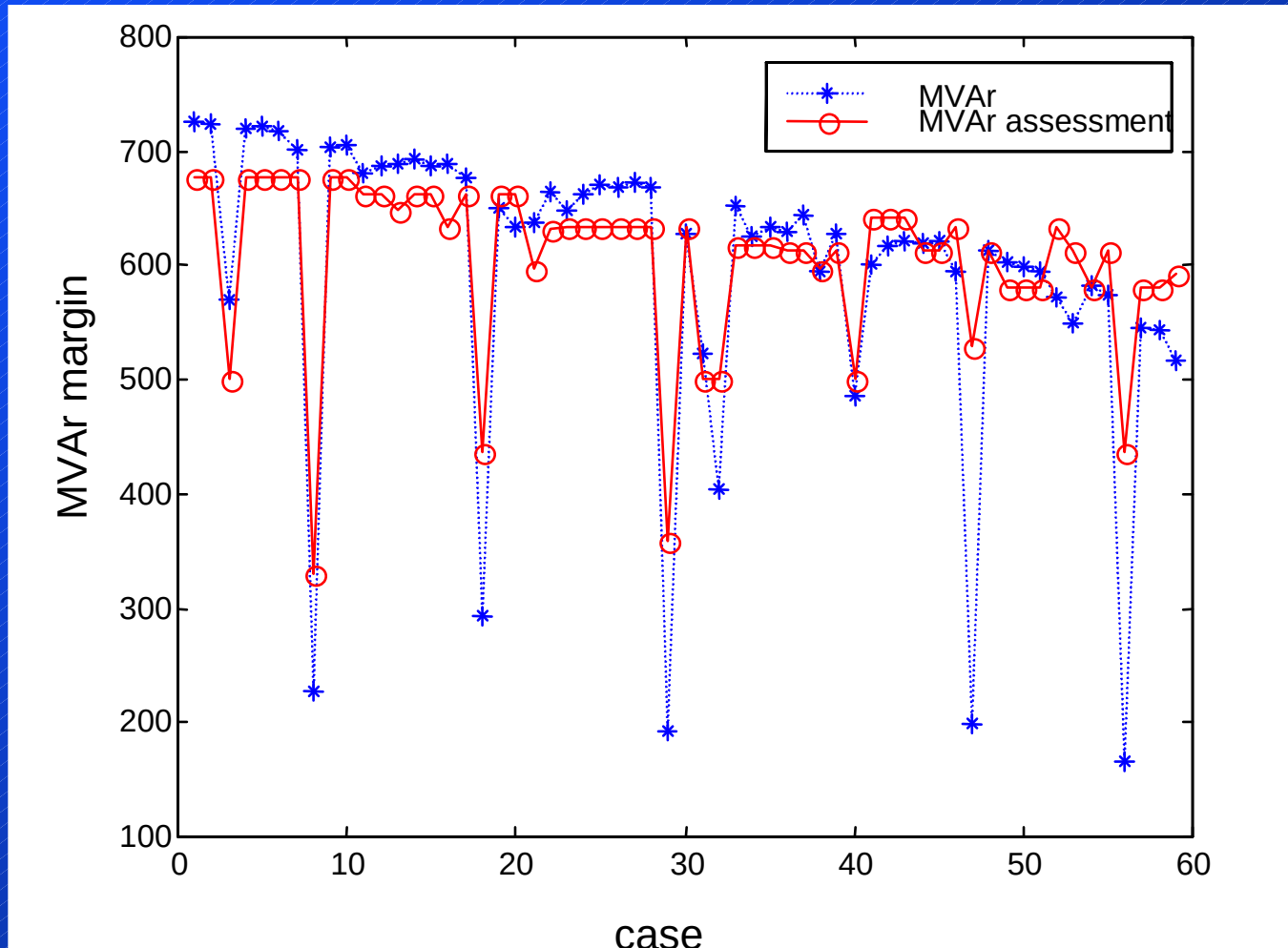


PSERC

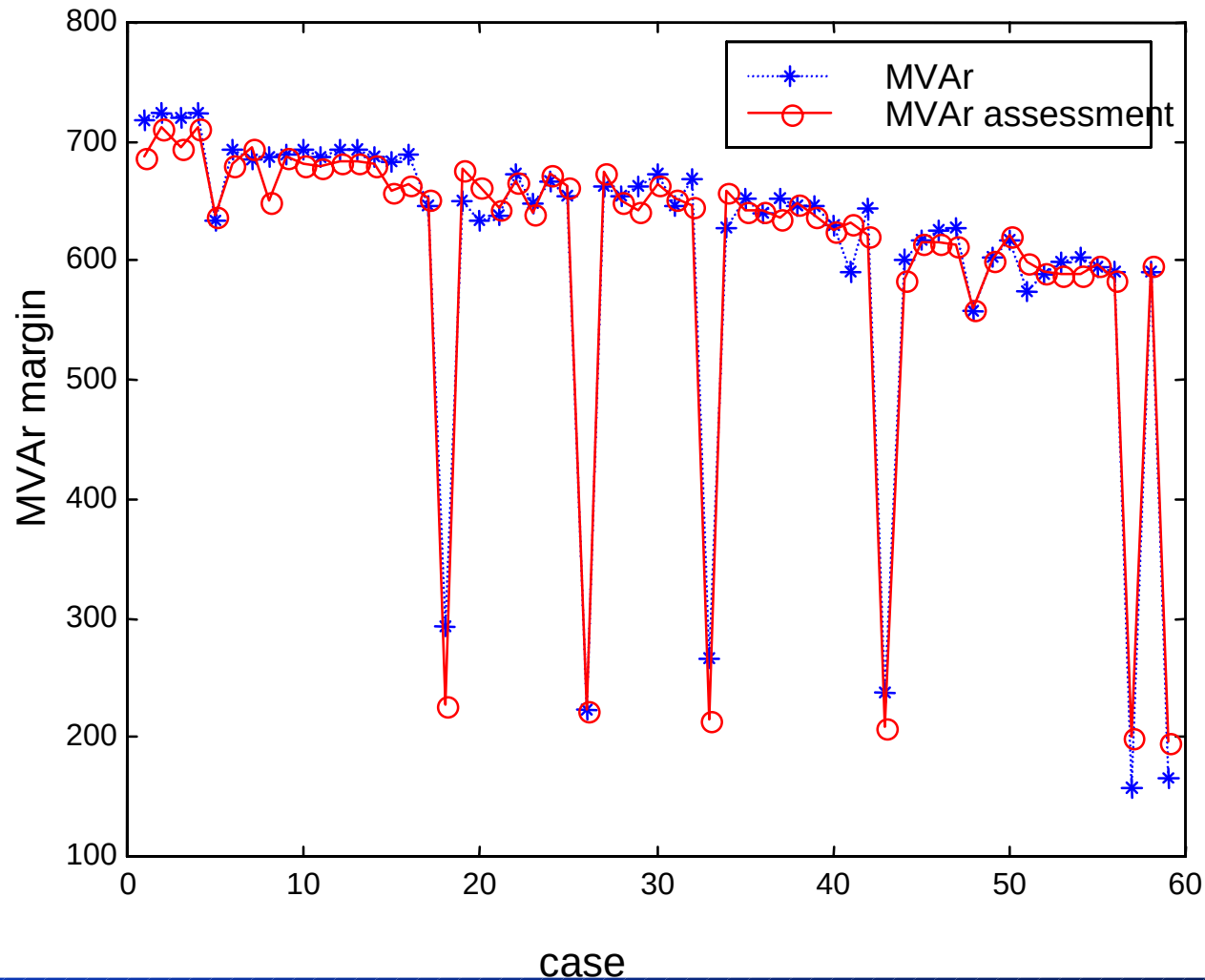
MVAr Margin Estimate using Regression Method



MVAr Margin Estimate using Kohonen Map



MVAr Margin Estimate using Feedforward Network



Voltage Security WSCC System Study

- P-V method
- Study area: California and Nevada
- Study tie line: California-Oregon Intertie (COI)
- Generators scaled up to meet load: B.C. Hydro, Pacific Northwest, Montana
- Area load up from 35,489 to 40,289 MW
- COI transfer from 1684 to 3476 MW
- Studies:
 - Area: 5 load levels, 354 contingencies (1775 cases)
 - Intertie: 11 load levels, 32 different contingencies (336 cases)
- Input Features: real power flow, reactive power reserve, reactive power loss



Neural Network Approach

- **Feature selection**
 - Inputs are power flows on all major lines and reactive reserves at key generators
- **Reduction of inputs**
 - Principal component analysis to reduce highly correlated inputs
 - Statistical correlation to eliminate insignificant inputs
- **Determination of neural network parameters**
 - Optimization technique
 - Use multiple networks with voting
- **Splitting training data for estimation and validation**
 - Statistical technique to ensure performance measures valid

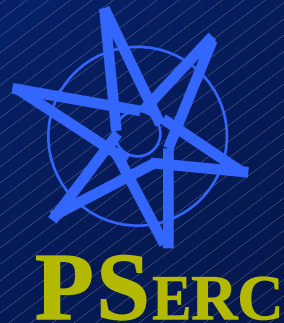
Principal Component Analysis

- Orthogonalizes input vectors
- Order by variation
- Eliminate those inputs with small contribution

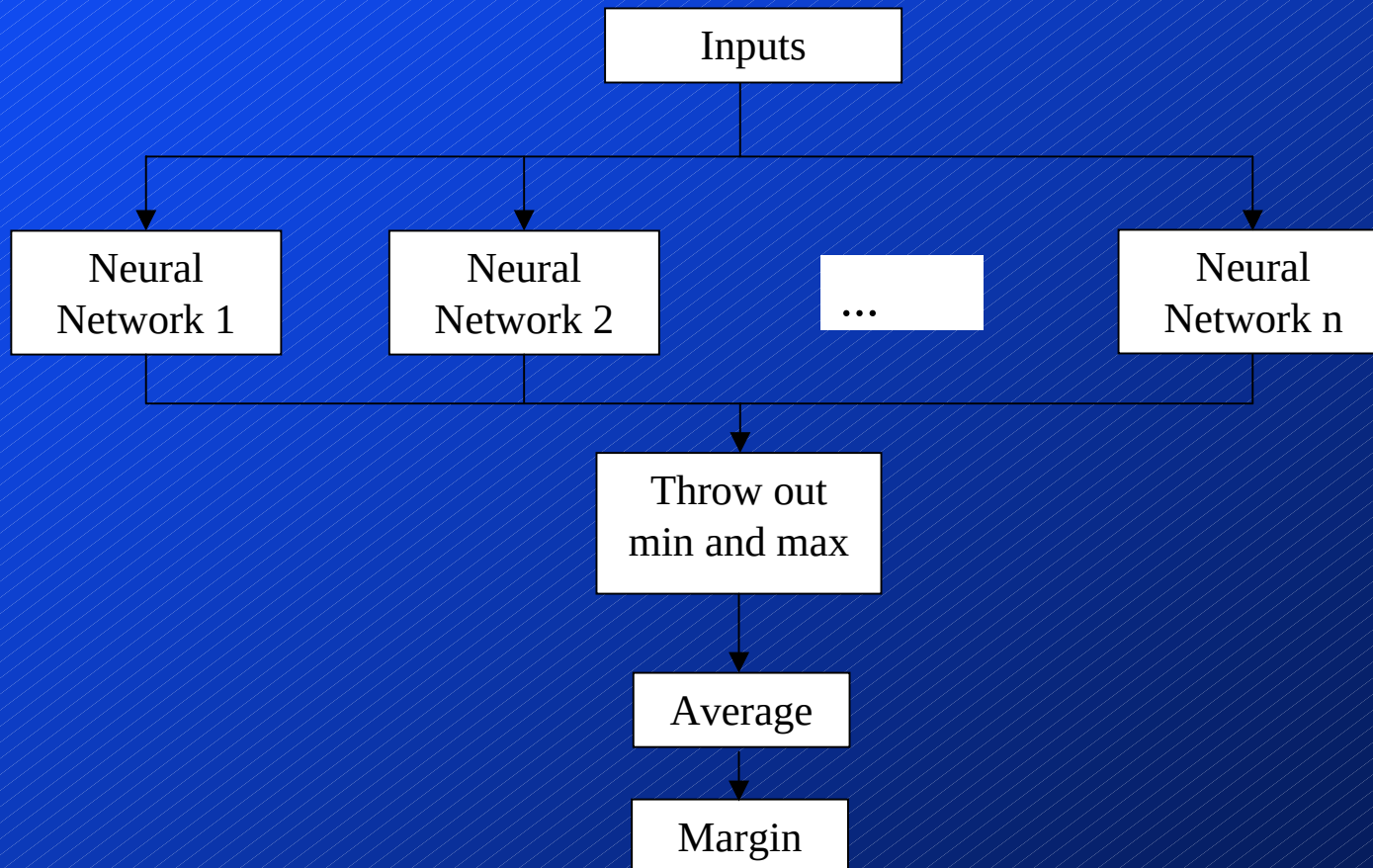
Achieving Better Performance

- Use of examples that result in large training error
- Using an antisymmetric activation function is faster than using a nonsymmetric function
- Normalize inputs and target values
- Good choice of initialization
- Momentum

$$\Delta w_{ji}(n) = \alpha \Delta w_{ji}(n-1) + \eta \delta_j(n) y_i(n)$$



Margin Estimator with Voting



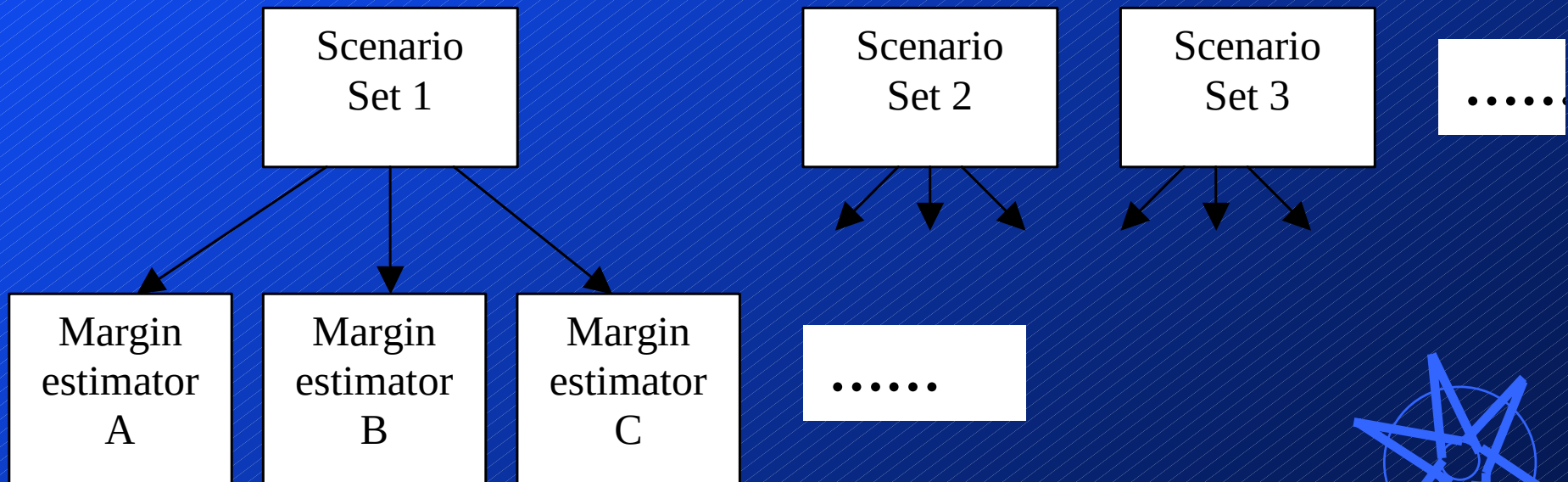
Comments on Studies to Date

- The following don't appear to be workable approaches
 - Linear regression methods
 - Individual ANNs applied to widely different system topologies
 - Individual ANNs applied to different security measures (say MVar margin and thermal limits for example)
- Accurate estimates were obtained using
 - Groups of ANNs applied to specific security criteria
 - ANNs that make estimates on systems considering a limited number of topologies



Overall Margin Estimation

- **Seperate estimators for each**
 - Security measure (margin)
 - Scenario set, i.e., major equipment outages
- **Multiple ANNs for each estimator**

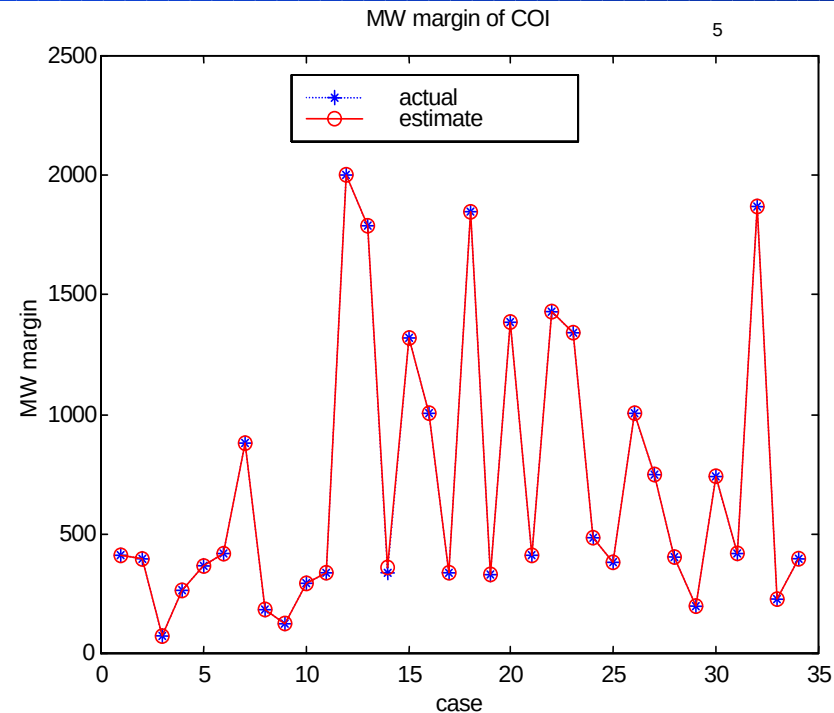
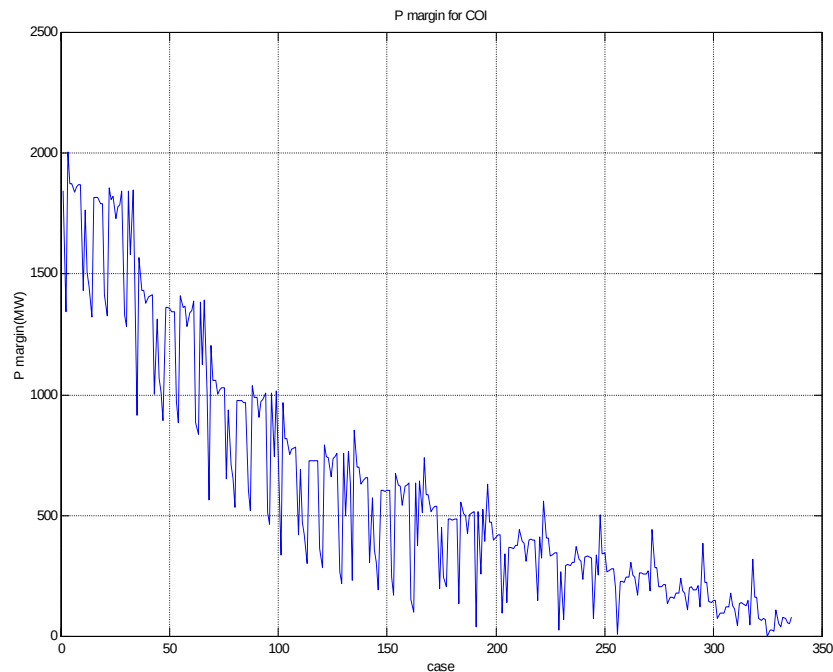


COI Margin

(no major outages - single contingencies only)

All study cases

Estimation test

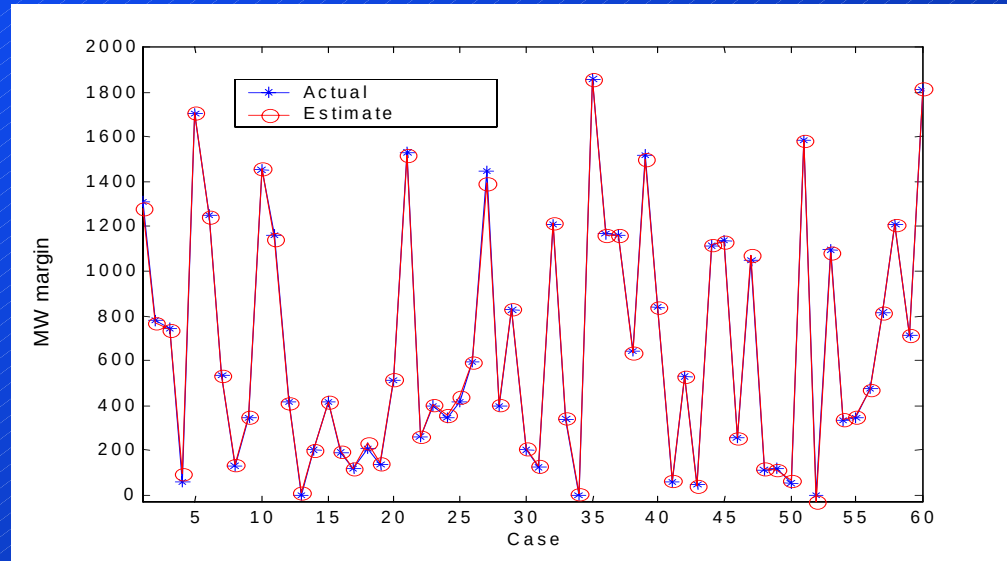


Network	ANN 1	ANN 2	ANN 3	ANN 4	ANN 5	System with Voting
Max error (MW)	23.45	8.02	32.86	16.64	21.25	7.84
Mean error (MW)	4.07	1.80	7.07	3.03	5.57	1.39
Standard deviation	4.05	1.77	6.91	3.01	5.63	1.38



Multiple Contingencies and COI Margin

Table Mountain-Tesla outage and other single contingencies

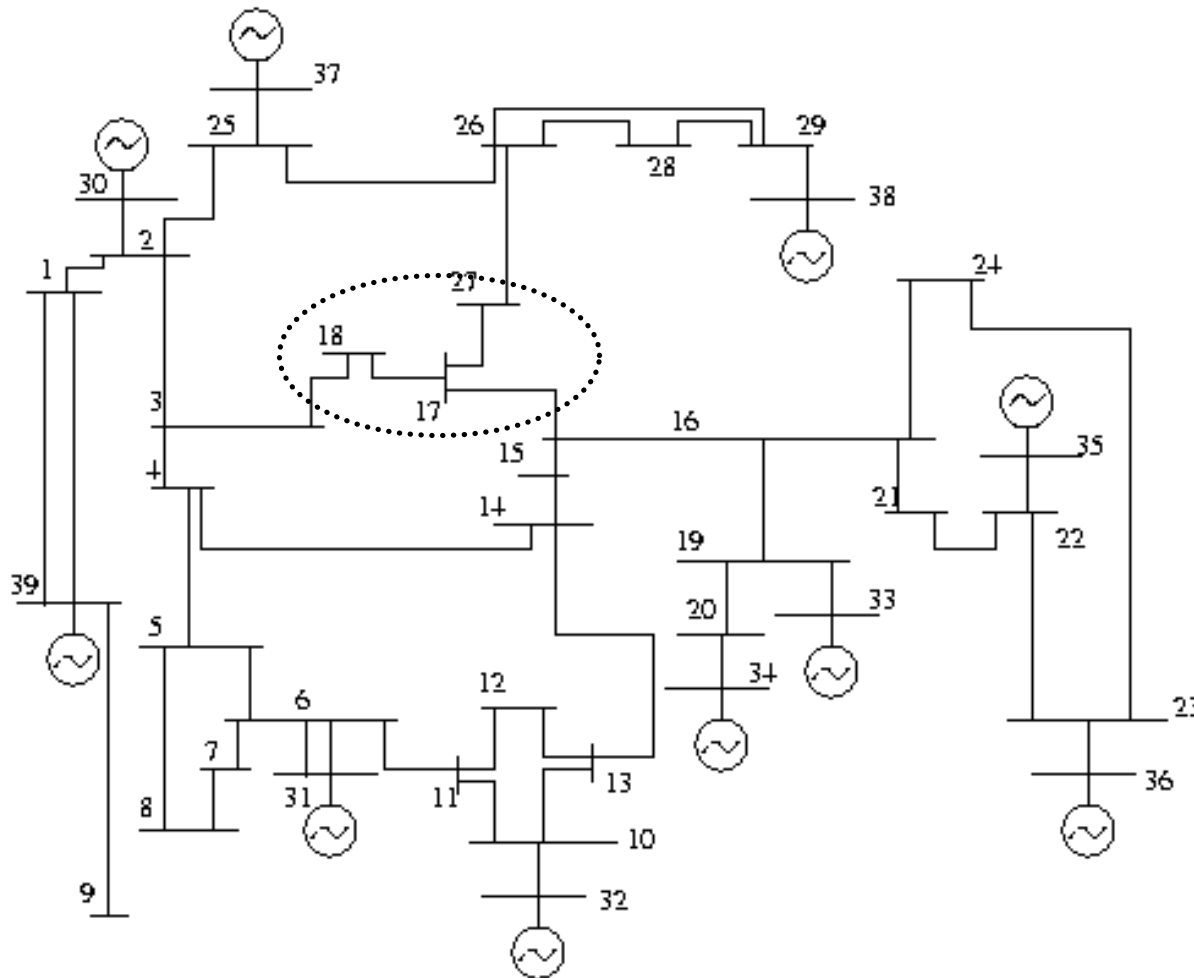


Performance Comparison

Network	ANN 1	ANN 2	ANN 3	ANN 4	ANN 5	System w/voting
Max error (MW)	46.68	44.04	82.38	112.7	50.44	25.94
Mean error (MW)	11.53	10.02	14.39	38.94	11.00	5.63
Standard deviation	11.54	10.05	14.45	39.10	11.05	5.66

Work on Other Security Criteria

New England 39 bus system



Study

- The system is divided into two zones
- One load center with only load buses including buses 17, 18 and 27
- The other contains all the other load and generation buses
- The training and testing data come from ETMSP studies
- Three-phase fault on each line is studied, 31 total contingencies
- The P margin is decided by increasing the real load of the load center step by step until there is any violation in the performance criteria. The smallest step is 25 MW.

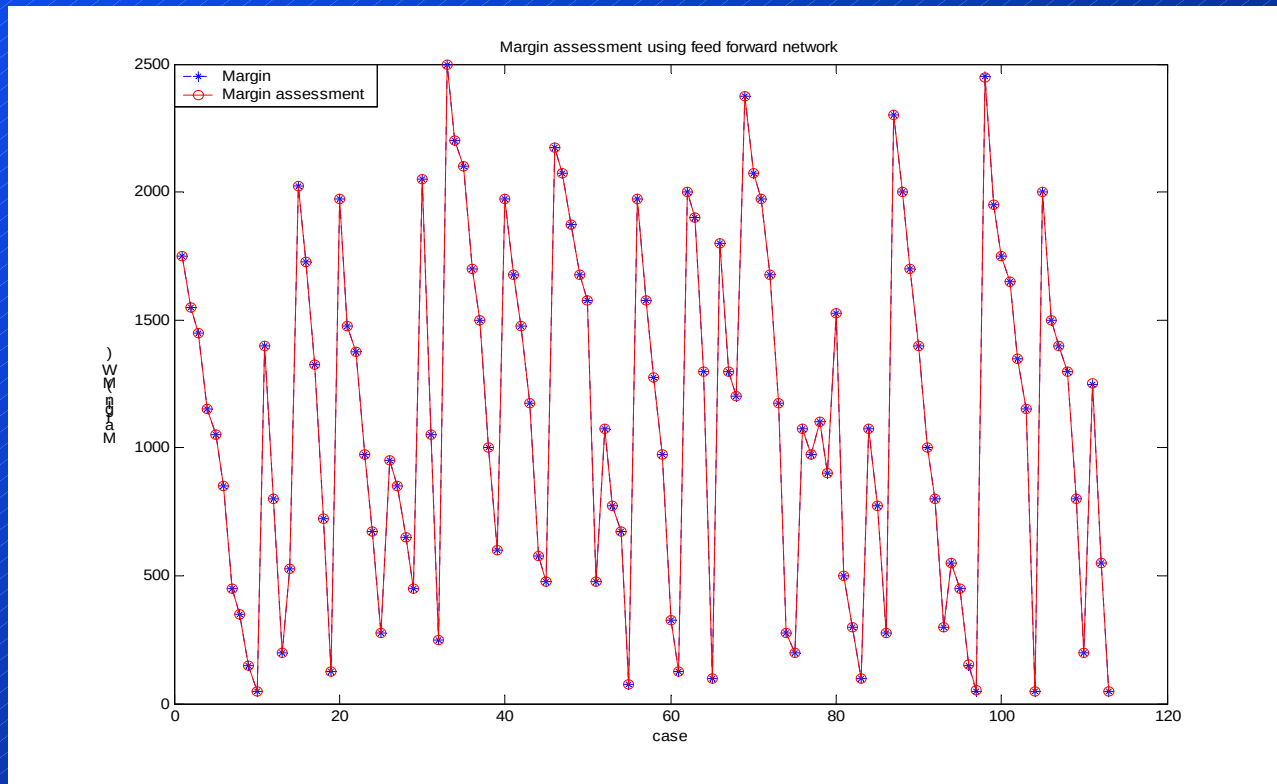
WSCC Reliability Criteria

- **Voltage criteria**
 - Maximum voltage dip - 25%
 - Maximum duration of voltage dip exceeding 20% - 20 cycles
 - Post transient voltage deviation - 5%
- **Frequency criteria**
 - Maximum duration of frequency below 59.6 Hz - 6 cycles
- For both voltage and frequency, damping > 0



Numerical Results

- Power margin for voltage criteria
 - 96 total features, 30 left after PCA and 14 left after CC
 - 579 total samples, 20% for testing and 30% for validation

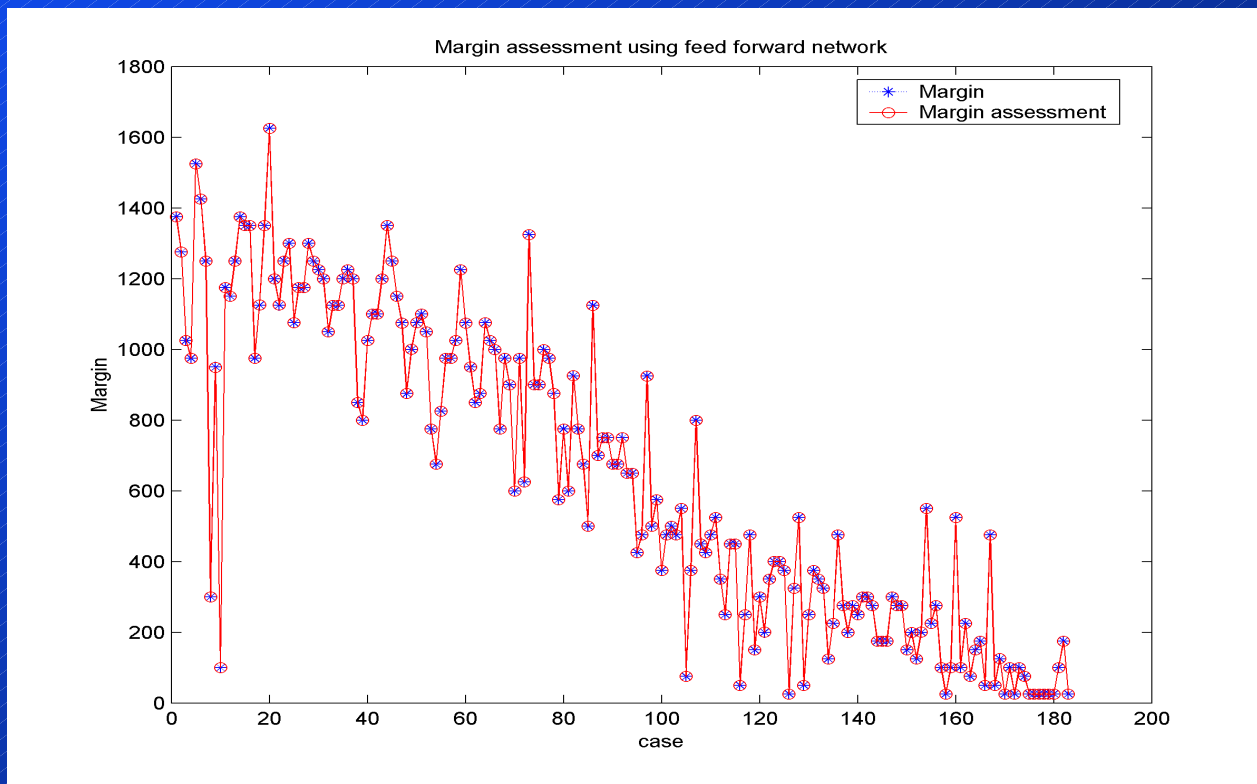


Numerical Results (cont.)

Training Method	Max error (MW/%)	Min error (MW/%)	Mean error (MW/%)	Mean Square error (MW ²)	Standard Deviation (MW)	Number of hidden neurons
Levenberg-Marquardt	4.6984 3.7455%	0.0024 0.0003%	0.3617 0.1569%	0.7254	0.5215	17
Bayesian Regulation	1.7270 1.5057%	0.0036 0.0003%	0.3364 0.0801%	0.2392	0.4911	5

Numerical Results (cont.)

- Real power margin for frequency criteria
 - 983 total samples, 20% for testing and 30% for validation
 - 96 total features, 31 left after PCA and 11 left after CC

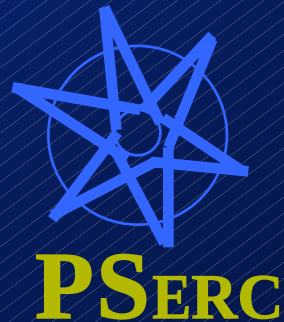


Numerical Results (cont.)

Training Method	Max error (MW/%)	Min error (MW/%)	Mean error (MW/%)	Mean Square error (MW ²)	Standard Deviation (MW)	Number of hidden neurons
Levenberg-Marquardt	8.1880 3.8815%	0.0024 0.0005%	0.4891 0.1466%	0.6339	0.7956	21
Bayesian Regulation	1.0752 1.9049%	0.0014 0.0002%	0.1460 0.1097%	0.0408	0.2023	7

Comments

- Estimators based on existing algorithms and operations procedures
- Estimator effectively acts as a multi-dimensional nomogram
- Accuracy depends on limiting considered conditions and must be system specific (i.e., contingency and operating conditions)
- Performance for dynamic security remains to be proven on large systems



On-going Work

- Develop multiple networks to cover greater variety of operating conditions
- Complete dynamic studies on WSCC system
 - A practical challenge is finding cases that violate a specific performance criteria
 - Improve software to automate system studies
- Using margin estimates to estimate transfer limits
 - e.g., vary inputs until margin reached
- Other applications
 - Useful for estimating ATC
 - Since essentially instantaneous estimate it could be used to initiate remedial action schemes (RAS).

