PSERC

Decision Tree Based Online Voltage Security Assessment Using PMU Measurements

Vijay Vittal

Ira A. Fulton Chair Professor

Arizona State University

PSERC Seminar, January 27, 2009

Project Team

PSERC

Ph.D. Student

- Ruisheng Diao

Post-doc

- Dr. Kai Sun – Now at EPRI

Industry Advisors

AEP

- Navin B. Bhatt
- Rob O'Keefe
- Mike Richardson
- Dwayne Stradford
- Sanjoy Sarawgi

Powertech Labs

- Lei Wang
- Frederic Howell
- Kip Morison

Contents

PSERC

Main Problems

PSERC

- Deregulation has resulted in market driven environments
- Lack of sufficient coordination among different operating entities
- Increase in load demand has outpaced the growth of generation capacity
- Difficulty of installing new transmission lines due to environmental and investment concerns
- Power networks are operated under greater stress
- Critical contingencies may violate voltage security limits and even initiate voltage instability
- Historically large scale blackouts were caused by multiple events in a short time period

Voltage Stability Problem

PSERC

- The ability to maintain bus voltage magnitudes within normal operating limits both at normal operating conditions and after disturbances
- Usually caused by the lack of sufficient reactive power support to a load area with a large amount of reactive power demand
- Initiated by a serious disturbance like a fast load increase or a contingency
- Voltage magnitudes progressively decline to an unacceptable level
- Once the voltage magnitude starts to decline, the loads such as motors try to recover the voltage magnitudes by consuming more reactive power
- It can exhaust the available reactive power reserve and further cause the voltage magnitudes to drop

Voltage Stability Problem

PSERC

- Not only affect the local load area, but can also spread throughout adjacent areas of the power system
- As voltage stability is largely impacted by load components, especially induction motors, voltage stability is also referred to as *load stability*

Challenge of Online Security Assessment

PSERC

- Large interconnected power systems are highly nonlinear
- With thousands of system states
- Detailed analysis in near real time horizon is a great challenge due to the large computational burden
- Oversimplification of system model will reduce assessment accuracy
- Traditional method performs security analysis on selected contingencies in the interval of several minutes
- Not rapid enough to arm timely control actions for fast events
- Hard to indicate secure operation boundaries

A New Assessment Tool

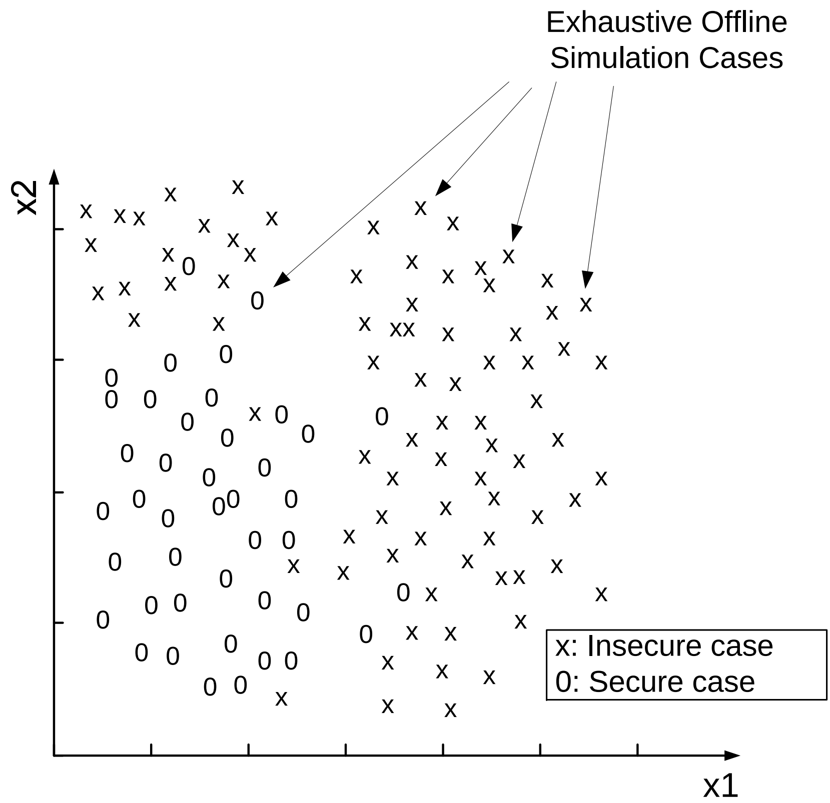
PSERC

- Need for a new assessment tool
  - Capture full system behavior accurately
  - Fast enough to arm control actions as soon as a vulnerable situation occurs
  - Effectively characterize the vulnerability of the current operating condition (OC)
- Solution – Decision Trees (DTs)
  - The underlying principle:

  "Derive an internal rule (in terms of thresholds) between multiple inputs and the predictive objective that can accurately classify both the foreseen and unforeseen cases"

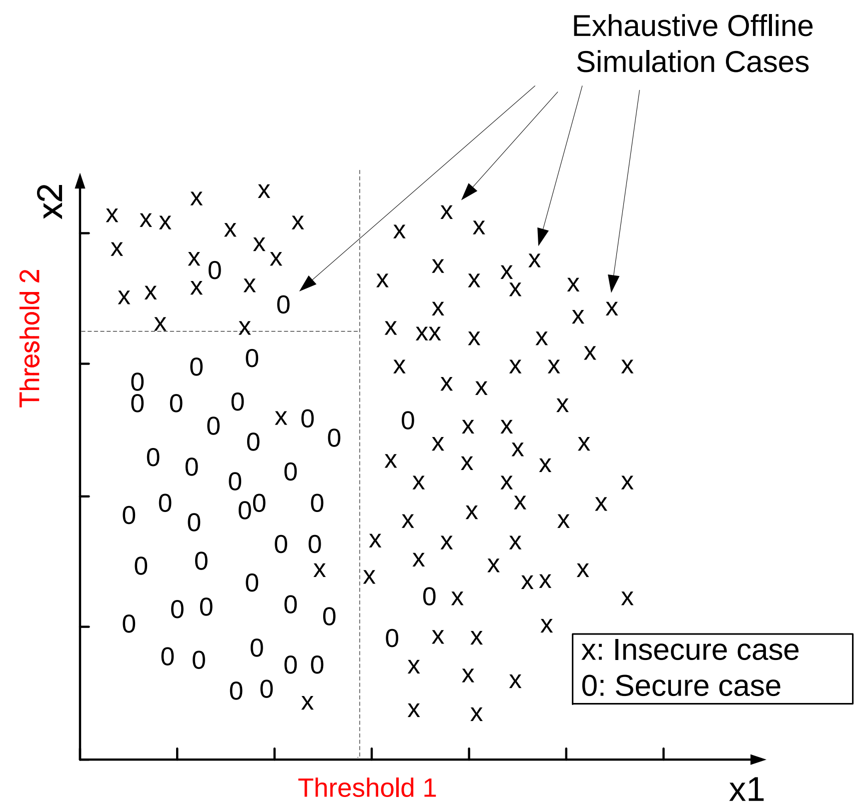
Basic Idea

- Exhaustive offline study
- Select predictors



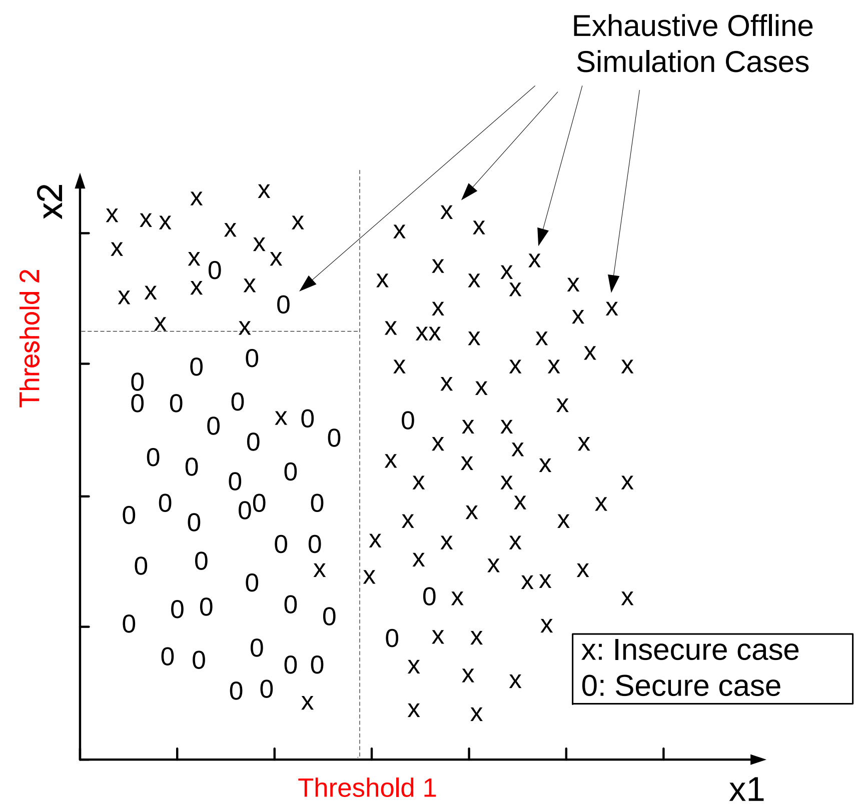
Basic Idea

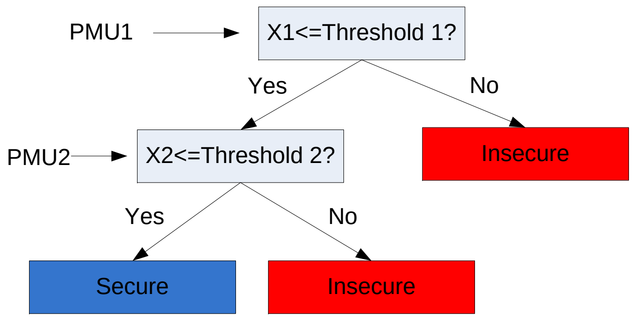
- Exhaustive offline study
- Select predictors
- Discover underlying rules



Basic Idea

- Exhaustive offline study
- Select predictors
- Discover underlying rules
- Compare PMU measurement with offline determined thresholds
- Obtain a prediction result





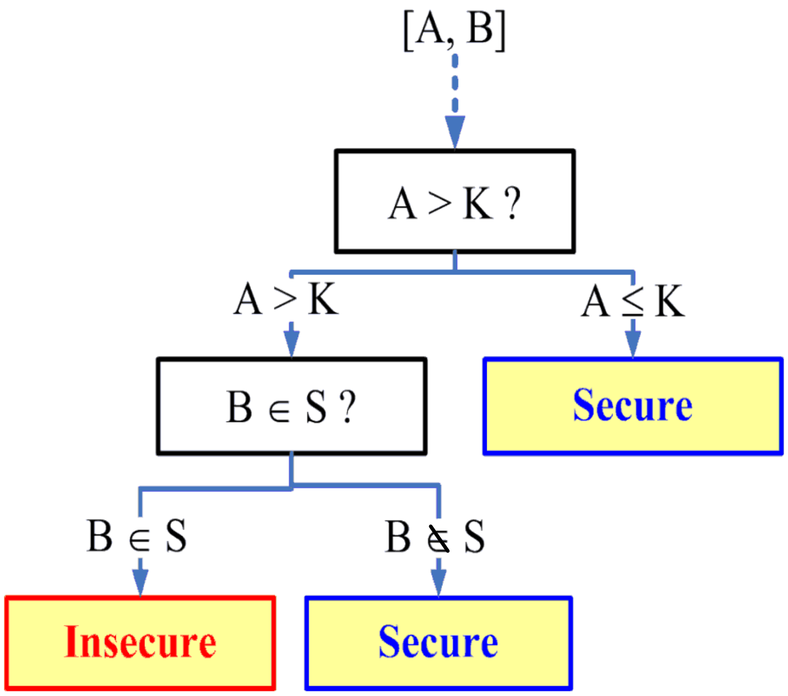
Classification Based on Decision Trees

PSERC

- Flowchart representing a classification system or predictive model for an object
- Structured as a sequence of simple questions based on critical attributes (CAs)
- Answers to these questions trace a path down the tree
- Terminal node determines the final classification or prediction result
- In 1984, Breiman introduced the CART (Classification and Regression Trees) methodology

Example of Classification Tree

- Object is characterized by a vector of CAs, voltage magnitude violation, thermal violation, transient stability, voltage stability, etc
- For numerical attribute A, question compares it with a threshold (K)
- For categorical attribute B, question checks if it belongs to a particular set (S)
- A class (Secure or Insecure) is assigned to the object at the terminal node



Building a Good DT

PSERC

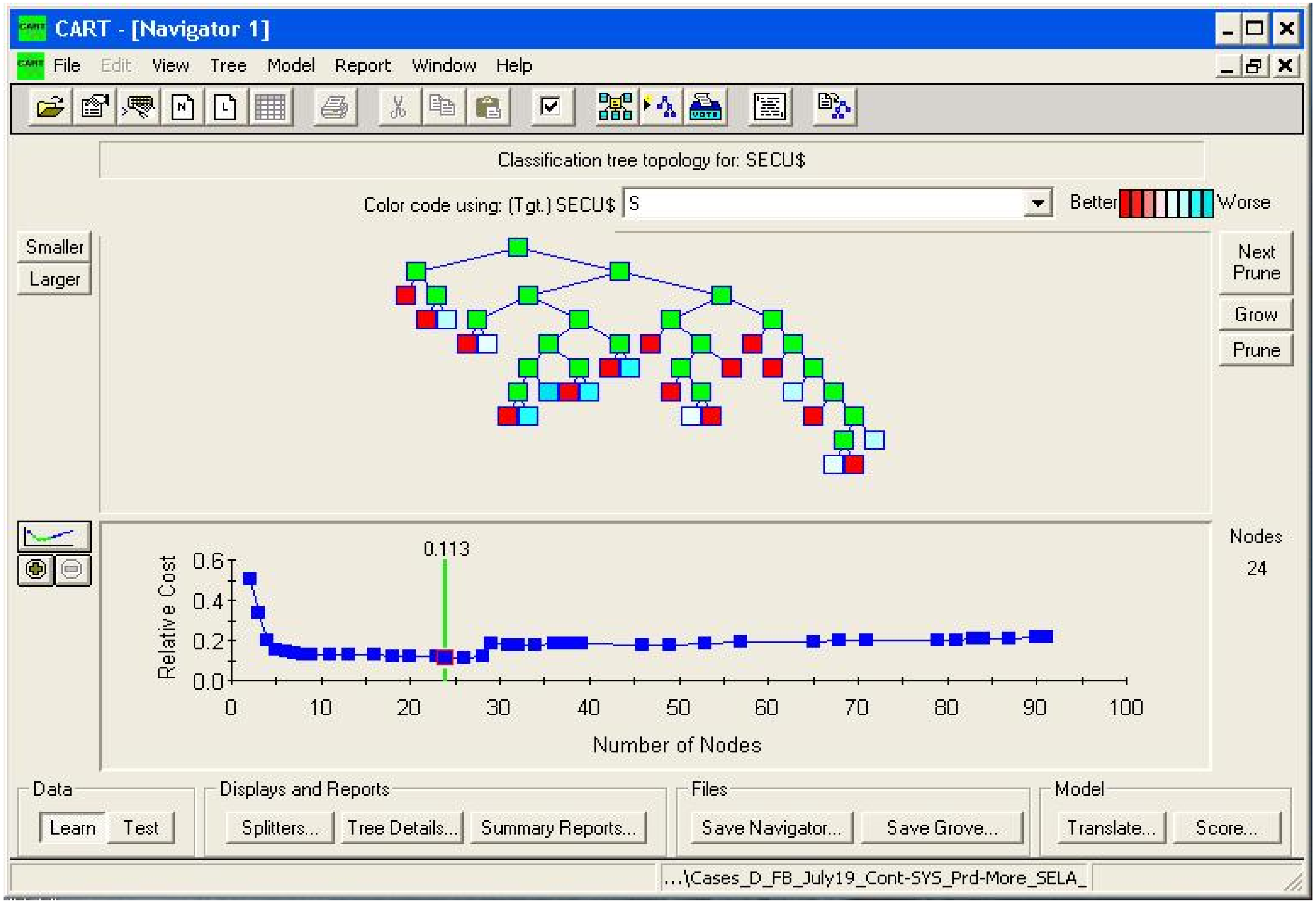
- Preparation
  - A sufficiently large database
  - Cases with different classifications are separated **randomly** into a learning set (LS) and a test set (TS)
  - Predictors are selected from available PMU measurements
- DT growing
  - A maximal binary tree is grown by recursively splitting the learning set
  - At each splitting, questions about predictors are scored by purities of two child nodes

Building a Good DT

PSERC

  - Question with highest score is selected and called "Critical Splitting Rule" (CSR)
  - **Parameter used in CSR is CA**
  - As the tree grows, nodes become more homogeneous
- DT pruning:
  - The maximal tree is pruned step by step to generate a series of DT's with descending sizes
  - Performance of each DT is checked on the test set
  - Minimizing the misclassification cost
  - Meeting additional requirements (about **size**, **correctness rate**, …)

DT Training in CART



Performance Parameters

PSERC

- Main parameters defined by the CART methodology:
  - $\boldsymbol{R^{ts}}$ --- Misclassification cost

$$R^{ts} = \frac{1}{N^{ts}} \sum_{i,j} c(i \mid j) \cdot N_{ij}^{ts}$$

  - $\boldsymbol{CR_i^{ts}}$ --- Correctness rate for classifying class-*i* cases

$$CR_i^{ts} = N_{ii}^{ts} / N_i^{ts} \times 100\%$$

  - $\boldsymbol{c(i|j)}$ --- Cost of misclassifying a class-*j* case as class-*i*
  - $\boldsymbol{N^{ts}}$ --- Number of test cases
  - $\boldsymbol{N_{ij}^{ts}}$ --- Number of the class-*j* cases predicted as class-*i*

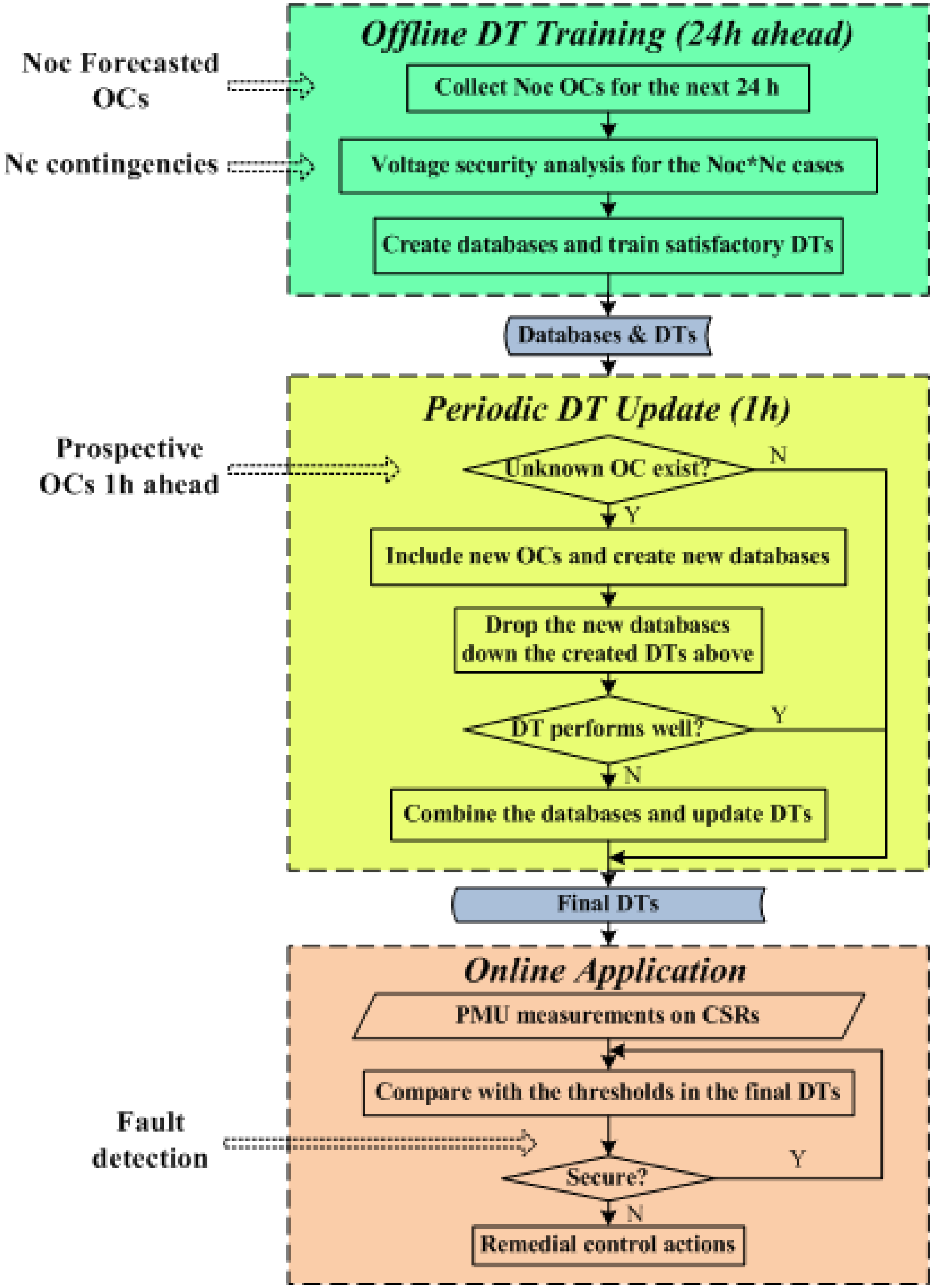
Critical Attributes (CAs)

PSERC

- The CAs are measured simultaneously by the PMUs
- The thresholds of the CAs define an operating nomogram
- If the OC drives a CA to violate its threshold then arming could be performed
- If the contingency corresponding to the CA threshold occurs then preventive action will have to be taken to maneuver the system to a safe OC

Proposed Scheme

- **Offline DT Training (24 hours ahead)**
- **Periodic DT update (every hour)**
- **Online security assessment & control**



System Analysis Tools

PSERC

- DSA^TOOLs: Dynamic Security Analysis Tool, Powertech, Canada
  - PSAT: Powerflow & Short-circuit Analysis Tool, generation and tuning operating conditions
  - VSAT: Voltage Security Assessment Tool, voltage security analysis

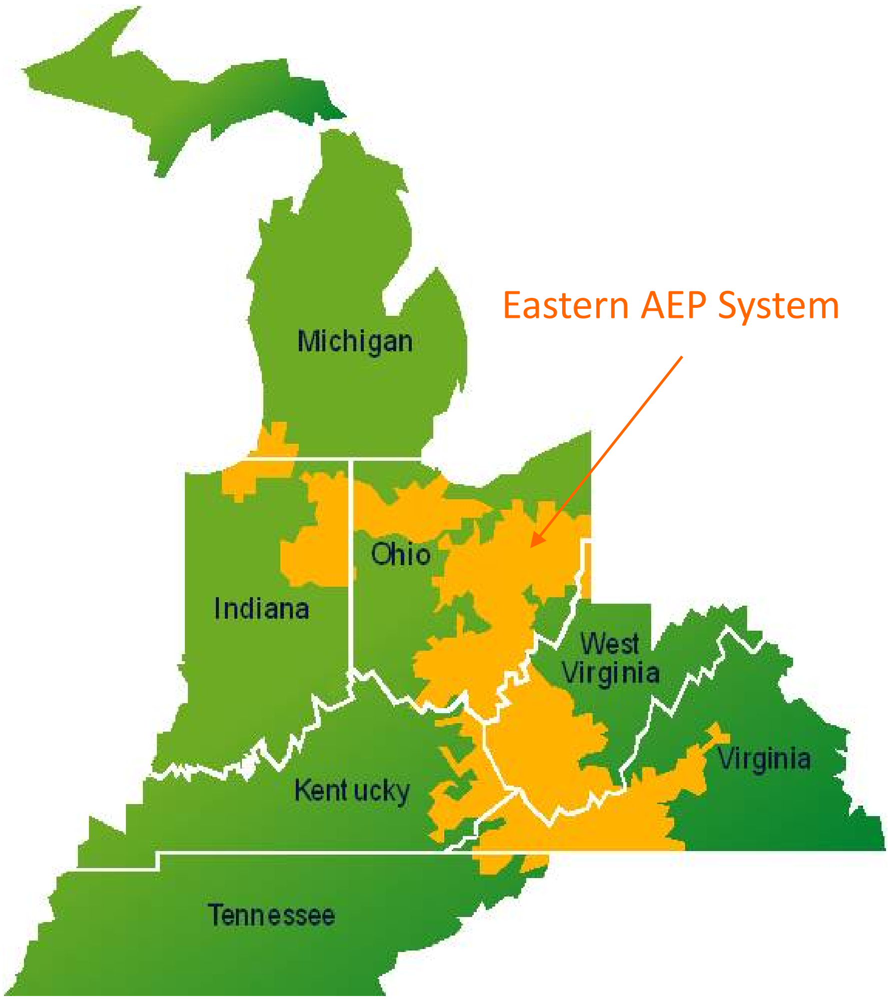
- CART: Classification and Regression Trees, Salford Systems, CA, training and testing decision trees

- MATLAB and VC++: data collection and conversion, database creation, etc

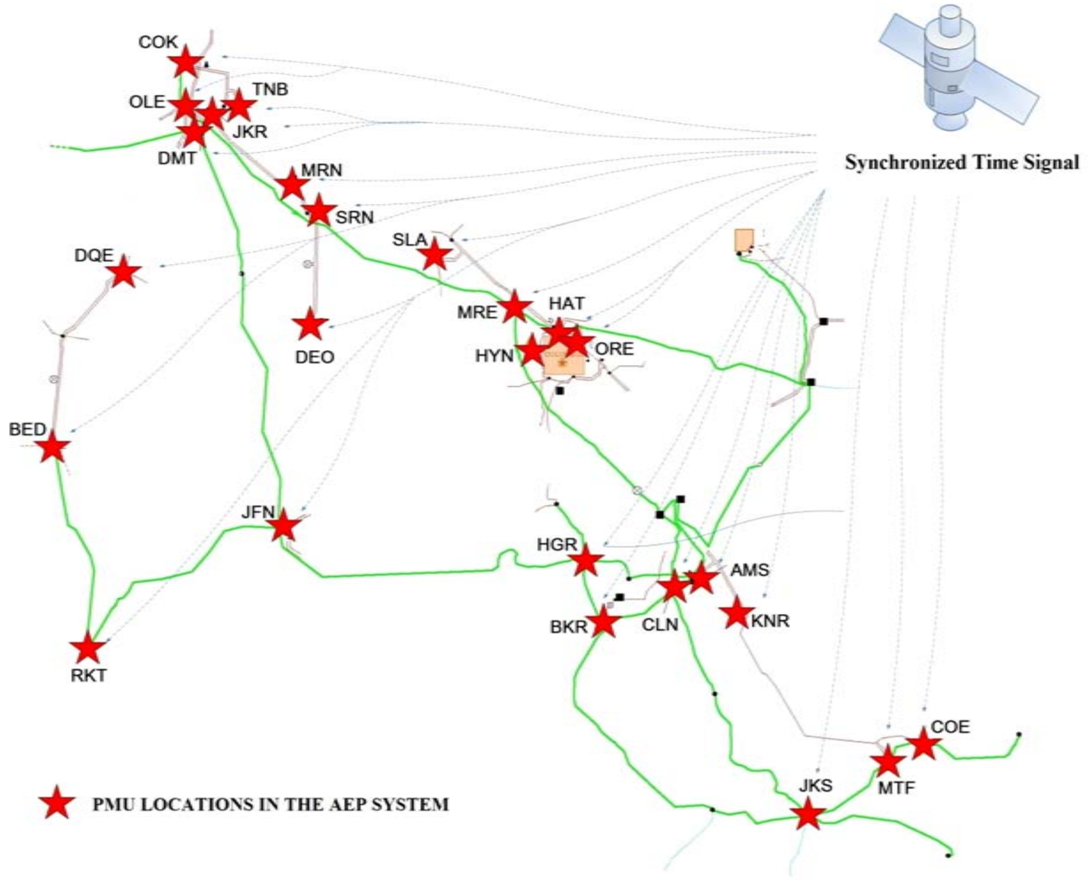
Implementation on the AEP system

PSERC

- AEP system
  - A subset of the Eastern Interconnection in North America
  - Cover several states, serve about 10% of load demand in Eastern Interconnection
  - Divided into western AEP and eastern AEP
  - Operational model of eastern AEP:
    - 2414 buses, 116 generators, 2416 transmission lines
    - Voltage level: 4 kV to 765 kV
    - 39,000-mile network



PMU Locations in the Eastern AEP System



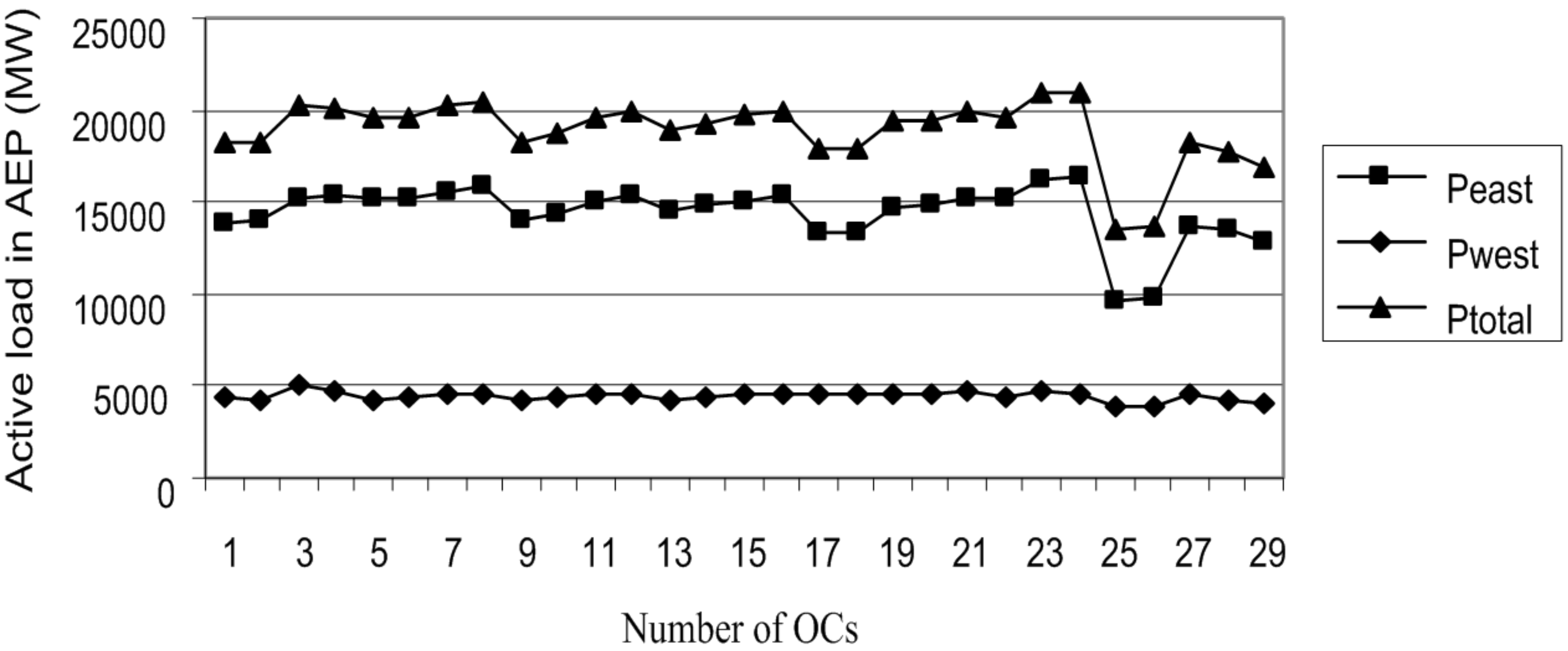
- 27 phasor measurement units in eastern AEP (12 installed and 15 additional units planned)
- Monitor the states of the key buses and stations

Operating Condition Generation

PSERC

- 29 operating conditions are generated in PSAT based on the generation and load patterns provided by the AEP operations staff
- They represent stressed OCs that include the details of load levels, generator outputs and branch power flows during a specific period of time
- The voltages of all the buses in the eastern AEP system are within reasonable levels
  - All the bus voltage magnitudes are adjusted to be between 0.90 and 1.10 p.u.
  - The voltages of 138~765kV buses are adjusted in the range of 0.95~1.10 p.u.

Operating Condition Generation



Load Pattern of the 29 Stressed OCs

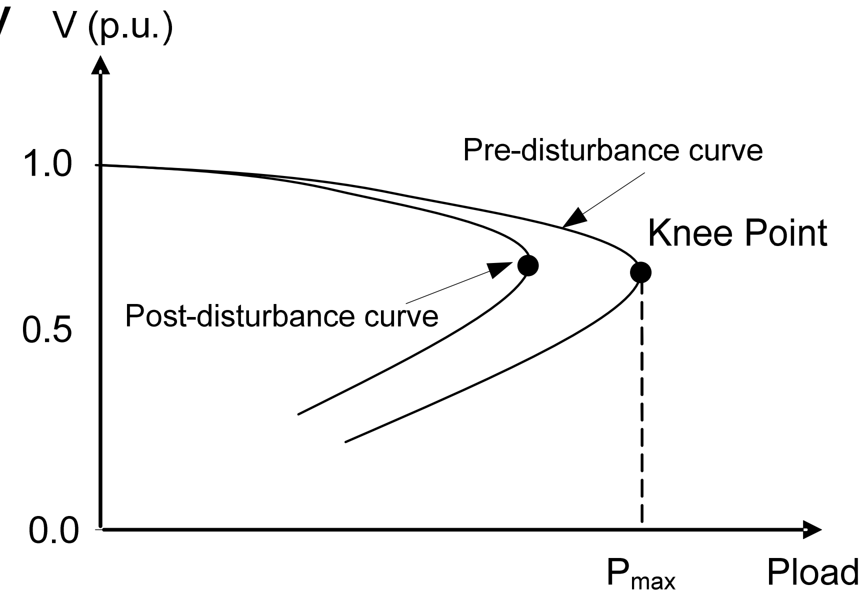
Voltage Security Evaluation

PSERC

- A list of contingencies that may cause severe voltage problems is selected according to previous operating experiences in the AEP system
- This list contains 163 N-1 contingencies including different transmission line and transformer outages
- This project adopts a static analysis method to evaluate post-contingency voltage security in VSAT
- A voltage instability judgment is given when a contingency results in the divergence of the power flow solution
- A total number of 29*163=4727 voltage stability simulations are conducted, with either secure or insecure labels marked on each case
- 34.46% of the total cases are insecure

Voltage Stability Criterion

- One commonly used method is the P-V curve method
- The knee point of a P-V curve indicates the maximum power transfer without causing voltage instability
- Further increase in the load over the knee point will cause progressive voltage decline
- Greatly affected by contingency
- A contingency at stressed OCs can cause a power flow solution to diverge



Predictor Selection

PSERC

- Two main types of predictors, closely related to voltage security problems
- Type 1: Contingency-dependent predictors
  - An unordered bus pair x and y is adopted to denote the faulted branch
  - To eliminate the ordering of the two buses of a critical branch during DT training, each contingency case is doubled in the form of “Bus-1=x and Bus-2=y” and “Bus-1=y and Bus-2=x”
  - Allows the DTs to identify buses or substations common to contingencies that are more prone to cause voltage collapse
- Type 2: Pre-contingency system parameters
  - Chosen from the existing PMU measured pre-disturbance system parameters
  - Different types of system variables are collected

Predictor Selection

PSERC

- 8 groups of predictors are defined, all from the existing PMUs

No.	Predictors
Group 1	Faulted bus (FB) and Other bus (OB) of the contingency branch
Group 2	Voltage phase angle differences (A_x_y)
Group 3	A_x_y, FB, OB
Group 4	Current magnitudes on branches (I_x_y), FB, OB
Group 5	MVAr flows on branches (Q_x_y), FB, OB
Group 6	Square of voltage magnitudes (V^2_x), FB and OB
Group 7	Absolute value of current magnitude multiplied by branch impedance (IZ_x_y), FB and OB
Group 8	A_x_y, Q_x_y, I_x_y, V^2_x, IZ_x_y, FB, OB

Database Example

PSERC

SECU$	FB$	OB$	Q_35_129	I_4513_4515	A_35_129	…
S	1998	2266	-398.5	13.4	0.9	
S	2266	1998	-398.5	13.4	0.9	
I	5983	9319	-398.5	13.4	0.9	
I	9319	5983	-398.5	13.4	0.9	**for OC1**
S	1205	1207	-398.5	13.4	0.9	
S	1207	1205	-398.5	13.4	0.9	
…	…	…	…	…	…	
I	1998	2266	-410	15	1.2	…
I	2266	1998	-410	15	1.2	
S	5983	9319	-410	15	1.2	
I	9319	5983	-410	15	1.2	**for OC2**
S	1205	1207	-410	15	1.2	
S	1207	1205	-410	15	1.2	
…	…	…	…	…	…	…

- First column is the predictive objective, secure or insecure
- The other columns represent different predictors defined above
- Each row represents one voltage security simulation case
- For the same OC, the only difference rests with the faulted branch

DT Training and Performance

- All the 9454 cases in the created database are given equal weight
- 1891 cases (20%) are randomly selected to form a test set (TS)
- The cost of misclassifying an insecure case to be a secure case is reasonably increased
- Different algorithms including ‘Gini’, ‘Symmetric Gini’, ‘Entropy’, ‘Class Probability’, ‘Twoing’ and ‘Ordered Twoing’ are tested and compared
- 8 optimal DTs are trained using the above predictor groups

Opt. DTs	Size	Learning Set Accuracy (%)			Test Set Accuracy (%)		
		I	S	Overall	I	S	Overall
DT1	24	71.4	63.31	66.08	68.82	60.95	63.72
DT2	7	87.61	76.99	80.63	86.96	80.07	82.50
DT3	36	98.69	94.33	95.82	91.00	93.63	92.70
DT4	**50**	**99.50**	**95.66**	**96.97**	**92.95**	**94.93**	**94.24**
DT5	31	98.11	93.89	95.33	87.11	93.3	91.12
DT6	38	96.49	92.42	93.81	88.91	91.91	90.85
DT7	55	99.69	95.19	96.73	91.00	93.46	92.6
DT8	51	99.11	96.00	97.06	90.55	94.44	93.07

Observations

PSERC

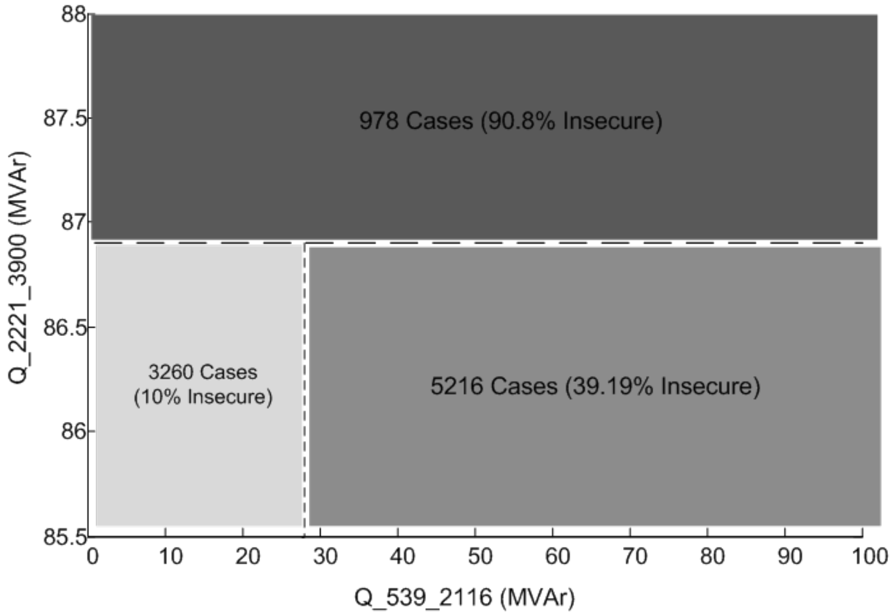
- Pre-contingency parameters are more important than contingency information in voltage security prediction at stressed OCs (DT2 performs much better than DT1)
- The combination of FB, OB and different pre-contingency parameters are helpful for building much better DTs (DT3-DT8)
- A single DT with the highest accuracy on the test set is obtained by using current magnitudes measured by PMUs
- Combining all the predictors did not improve the overall accuracy on the test set
    - Over-fitting problem
    - Predictor masking problem

Efficiency of DTs & Nomogram

- Optimal DTs are very efficient. Only a small number of CSRs are selected in DT3 to DT8

DTs	Ns/Nt	DTs	Ns/Nt
DT3	15/353	DT6	13/29
DT4	16/87	DT7	17/87
DT5	12/87	DT8	18/635

- Nomogram determined by DT5



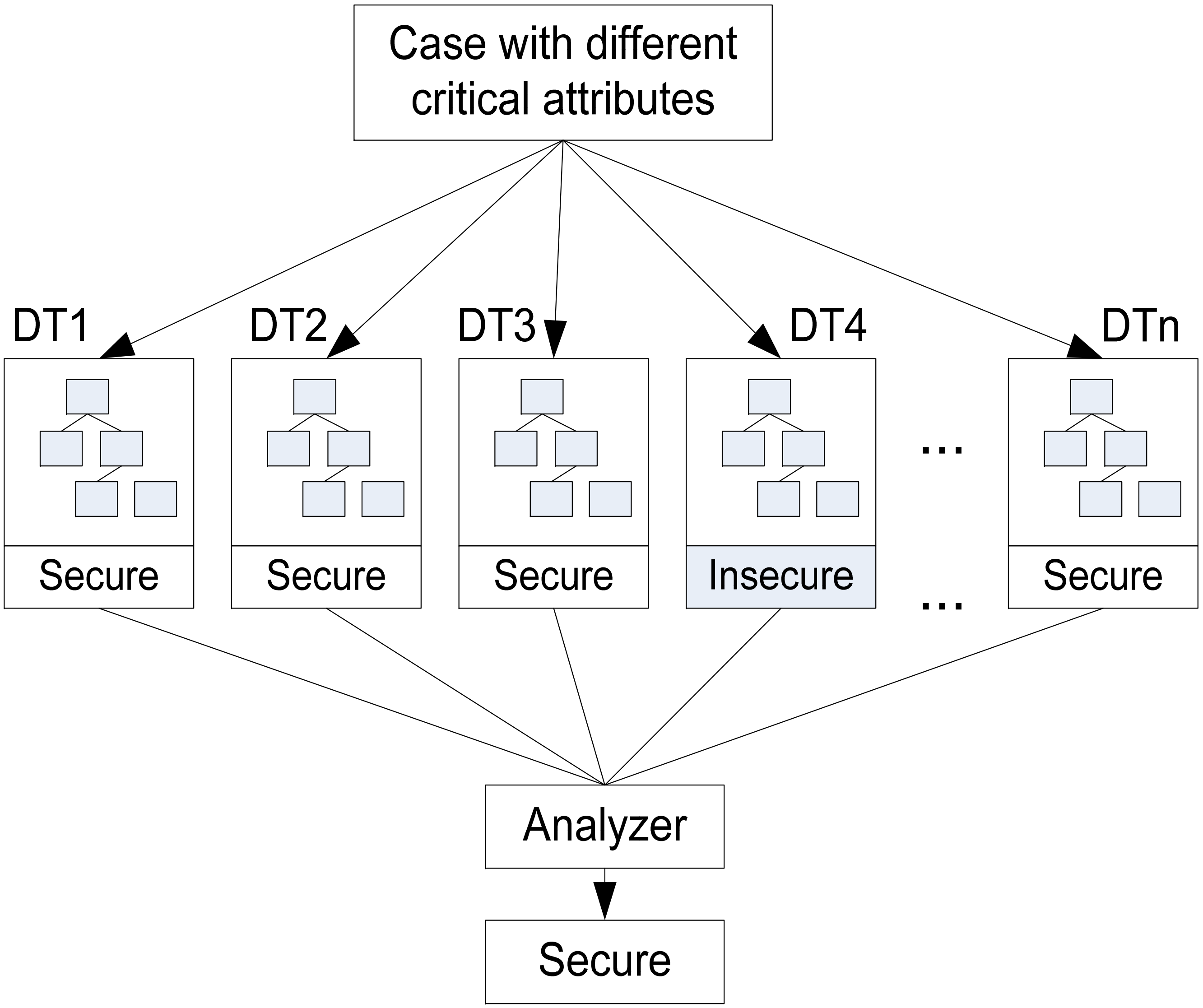
Nomogram in terms of the top two CSRs in DT5

DT Performance Improvement

PSERC

- Method 1: Multiple DTs
  - Motivation - The combination of all the available predictors may not improve the DT performance on the test set
  - Trusting only one DT has limitations
  - This method takes advantage of all the DTs that satisfy a desired threshold of performance instead of trusting the tree with the best performance only
  - The cases that are misclassified by the best DT may be correctly predicted by the other trees that use different PMU-measured critical attributes.
  - All the optimal DTs are used to obtain a comprehensive classification result

Concept of Multiple DTs



Multiple DTs

- A heuristic search is conducted to identify different combinations of these predictors that contribute to good decision trees
- The multiple DTs that are used for online application should be sufficiently different from each other.
- Certain types of predictors can be totally masked when combined with other predictors, e.g., V^2_x
- 9 DTs with good performance on the TS are obtained by predictor combination
- The result shows most of them offer better prediction performance on the TS than the DTs trained before predictor combination.
- All the 15 (6+9) decision trees from DT3 to DT17 are used for online application since they are capable of correctly predicting over 91% of cases in the TS

Performance of the 9 DTs

PSERC

DT Performance for Different Predictor Combinations

Opt. DTs	Size	Predictor combinations	Test Set Accuracy (%)		
			I	S	Overall
DT9	59	A_x_y, I_x_y, FB,	90.4	95.59	93.76
DT10	49	A_x_y, Q_x_y, FB,	89.21	95.02	92.97
DT11	47	A_x_y, IZ_x_y, FB,	90.85	94.12	92.97
DT12	55	I_x_y, Q_x_y, FB,	92.95	95.26	94.45
DT13	45	Q_x_y, IZ_x_y, FB,	91.00	93.79	92.81
DT14	53	A_x_y, I_x_y, Q_x_y, FB,	92.95	95.18	94.39
DT15	47	A_x_y, I_x_y, IZ_x_y, FB,	90.85	94.12	92.97
DT16	53	I_x_y, Q_x_y, IZ_x_y, FB,	91.15	93.14	92.44
DT17	45	A_x_y, Q_x_y, IZ_x_y, FB,	91.00	93.79	92.81

Performance Using the 15 DTs

PSERC

- For any contingency case, 15 voltage stability assessments are obtained separately and a final assessment is given in terms of the majority classification result, either secure or insecure
- A statistical analysis is conducted on the 1891 cases in the TS and 7563 cases in the LS using these 15 DT models
- The overall prediction accuracy on the TS is increased to 94.66%; while the accuracy on the LS is increased to 97.75%
- Using multiple DTs in real time will not cause a significant increase in the security assessment time
- The DTs are all trained offline and the assessment process using different DTs can be conducted individually

DT Performance Improvement

PSERC

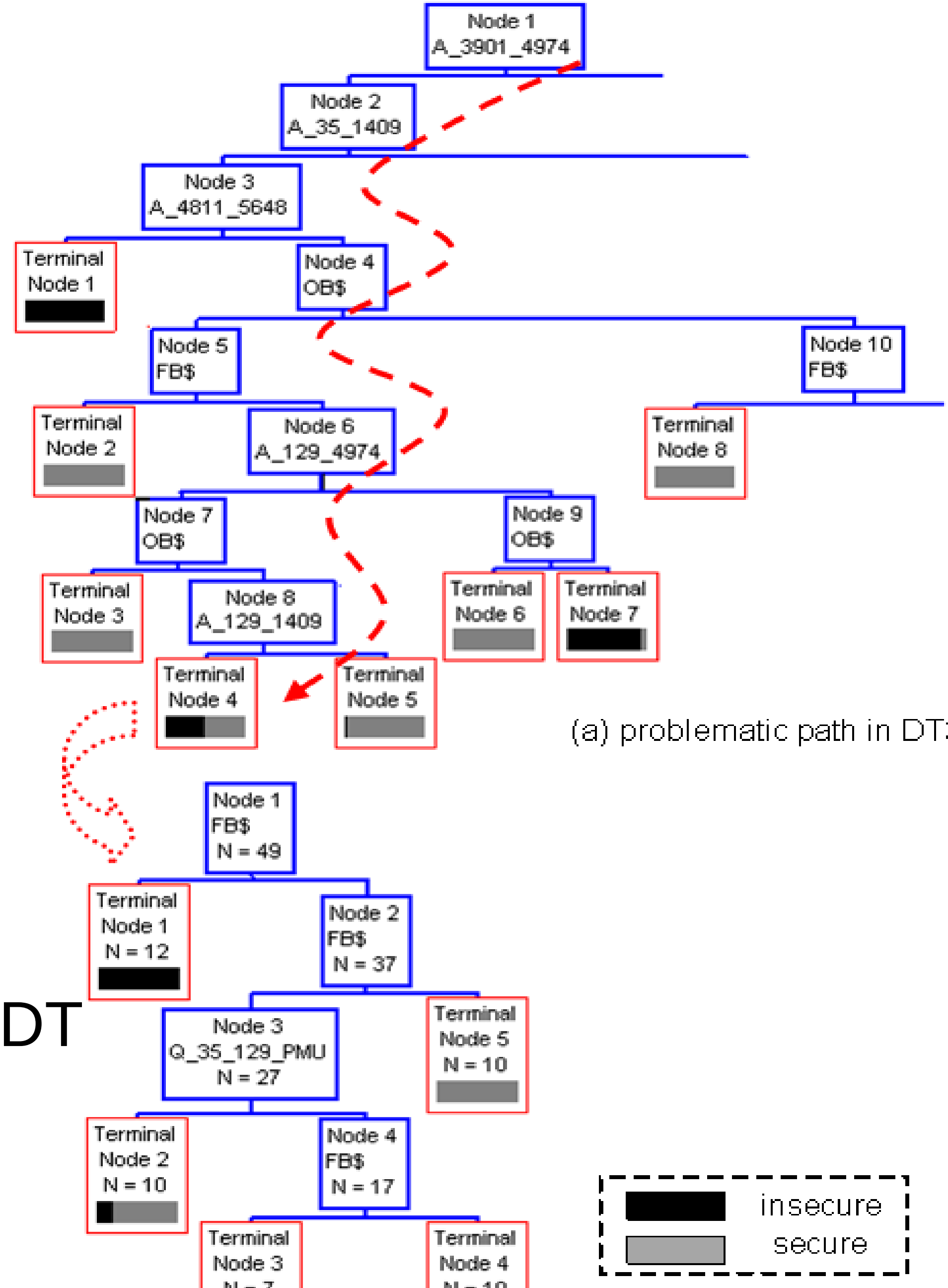
- Method 2: Corrective DTs
  - An important observation from the trained DTs is that most of the paths in a single DT trained by only one type of pre-contingency parameter (e.g. DT3) have excellent prediction behavior
  - Only a few paths have severe misclassification problems
  - Idea: to replace the problematic paths with corrective DTs for accuracy improvement
  - For each of the paths with poor performance, a corrective DT is trained by including more system information for all the cases that fall into this path in the original database
  - For example, a path with poor performance in DT3 is taken to explain how this method works

Corrective DTs

- Focusing on Terminal Node 4
  - 49 cases in the LS
    (24 cases are misclassified)
  - 14 cases in the TS
    (6 cases are misclassified)

- Train one corrective DT by including more predictors

- Performance of the corrective DT
  - 5 cases misclassified in LS'
  - 3 cases misclassified in TS'



(a) problematic path in DT3

(b) corrective DT

Corrective DTs

PSERC

- This approach preserves the branches with high accuracy
- It only modifies the paths with severe misclassification problems
- The improved DT performance

Opt. DTs	Overall LS Accuracy (%)		Overall TS Accuracy (%)	
	Corrected	Original	Corrected	Original
DT3’	97.46	95.82	94.02	92.70
DT4’	98.21	96.97	**95.45**	94.24
DT5’	98.70	95.33	92.07	91.12
DT6’	97.38	93.81	93.39	90.85
DT7’	98.40	96.73	93.92	92.6

Conclusions

PSERC

- An online voltage security assessment scheme using PMUs and DTs is proposed
- This scheme is tested on the AEP power system
- Properly trained DTs perform well in predicting post-contingency voltage security
- DTs can identify key system parameters as voltage security indicators and provide operators effective nomograms
- Two new methods to improve DT performance are introduced, including “Multiple DTs” and “Corrective DTs”

Publication

PSERC

- R. Diao, K. Sun, V. Vittal, R. O'Keefe, M. Richardson, N. Bhatt, D. Stratford, and S. Sarawagi, "Decision Tree Based Online Voltage Security Assessment Using PMU Measurements," Paper accepted for publication in the IEEE Transactions on Power Systems (December 2008).

THANK YOU!

Questions?