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# An Online Dynamic Security Assessment Scheme using Phasor Measurements and Decision Trees

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# Project Team

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# Contents

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- Classification based on Decision Trees
  - Old and new methods
- Proposed online security assessment scheme
  - Offline DT building, periodic DT updating and online security assessment
- Case studies
  - Entergy system

# Decision Trees (DTs)

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- Flowchart representing a classification system or predictive model for an object
- Structured as a sequence of simple questions regarding 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

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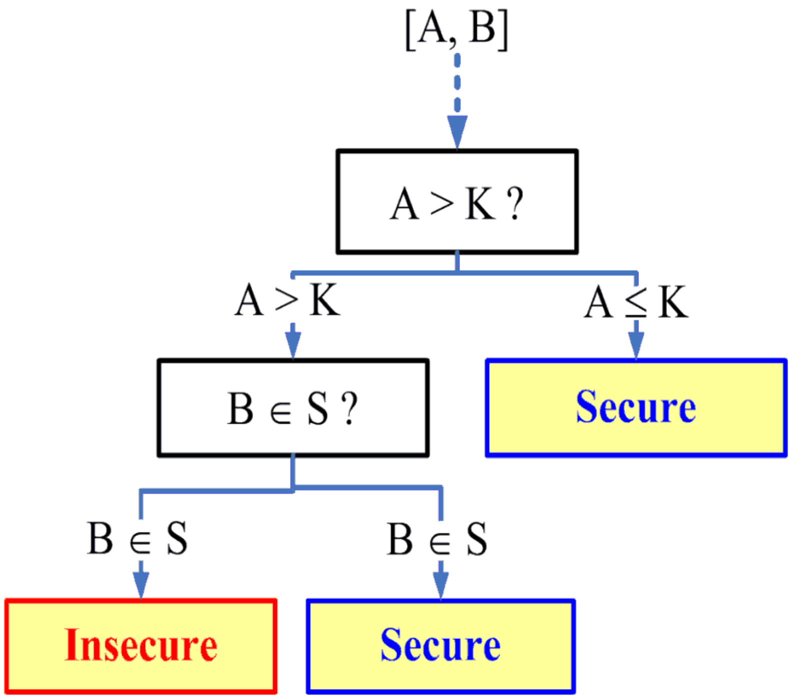
# Example of Classification Tree

- Object is abstracted to a vector of CAs
- 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 DT

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- Preparation:
  - Cases with classifications are separated randomly into a learning set and a test set
  - Predictors are selected from available parameters
- 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
  - Question with highest score is selected and called “Critical Splitting Rule” (CSR)
  - **Parameter used in CSR is CA**

# Building a DT

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  - Other questions are called “competitors”; questions that mimic the action of the CSR are called “surrogates”
  - As the tree grows, nodes become more homogeneous
- DT pruning:
  - 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
- Selecting the best DT
  - Minimizing the misclassification cost
  - Meeting additional requirements (about size, correctness rate, …)

# Critical attributes (CAs)

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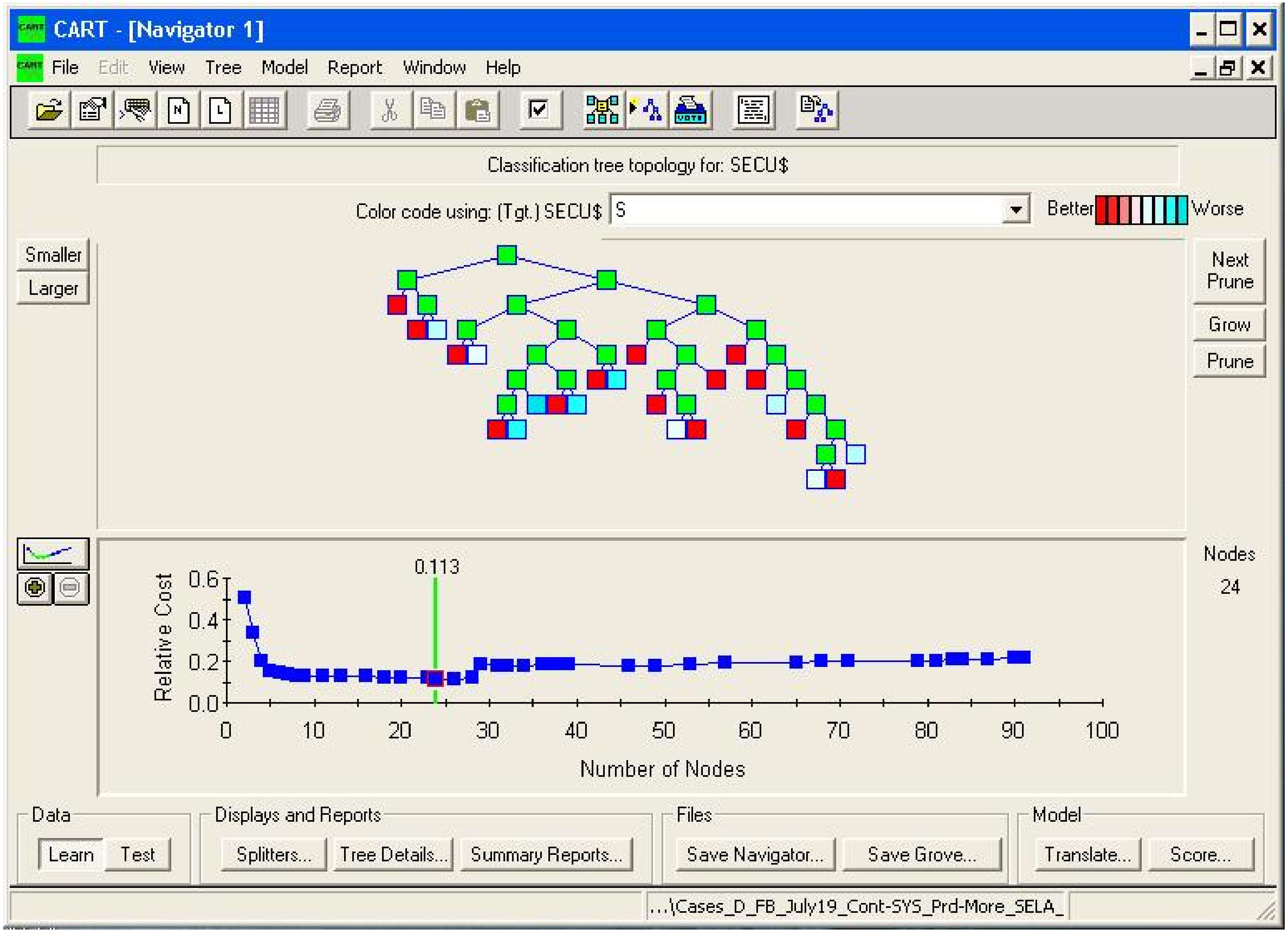
- The CAs are measured simultaneously by the PMUs
- The thresholds of the critical attributes determined by the DTs define an operating nomogram which will guide the operator
- If the OC drives a CA to violate its threshold then arming could be performed
- If the contingency corresponding to the CA threshold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

# Software: CART 5.0 of Salford Systems



# Performance Parameters

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- Main parameters defined by the CART methodology:
  - $R^{ts}$ --- Misclassification cost (a key criterion for the best DT)

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

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

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

  - $c(i|j)$ --- Cost of misclassifying a class-*j* case as class-*i*
    - Key parameters to control $CR_i^{ts}$: $c(i|j)$ ↑**makes** $CR_j^{ts}$ ↑**and** $CR_i^{ts}$↓
  - $N^{ts}$ --- Number of test cases
  - $N_{ij}^{ts}$ --- Number of the class-*j* cases predicted as class-*i*

# Methods on classification

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- Old method
  - Classification is based on only the terminal node
  - Unreliable for unpredicted system conditions since some CSRs lose validity
- New method
  - Basic idea: CSRs at **earlier nodes** of each path are more reliable and important
  - Classification is based on the **entire path**
  - This approach results in more adaptive and reliable classification results

# New Method on Classification

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- Appropriate weights are assigned to nodes of the path
- An insecurity score is calculated and compared to a threshold to decide security

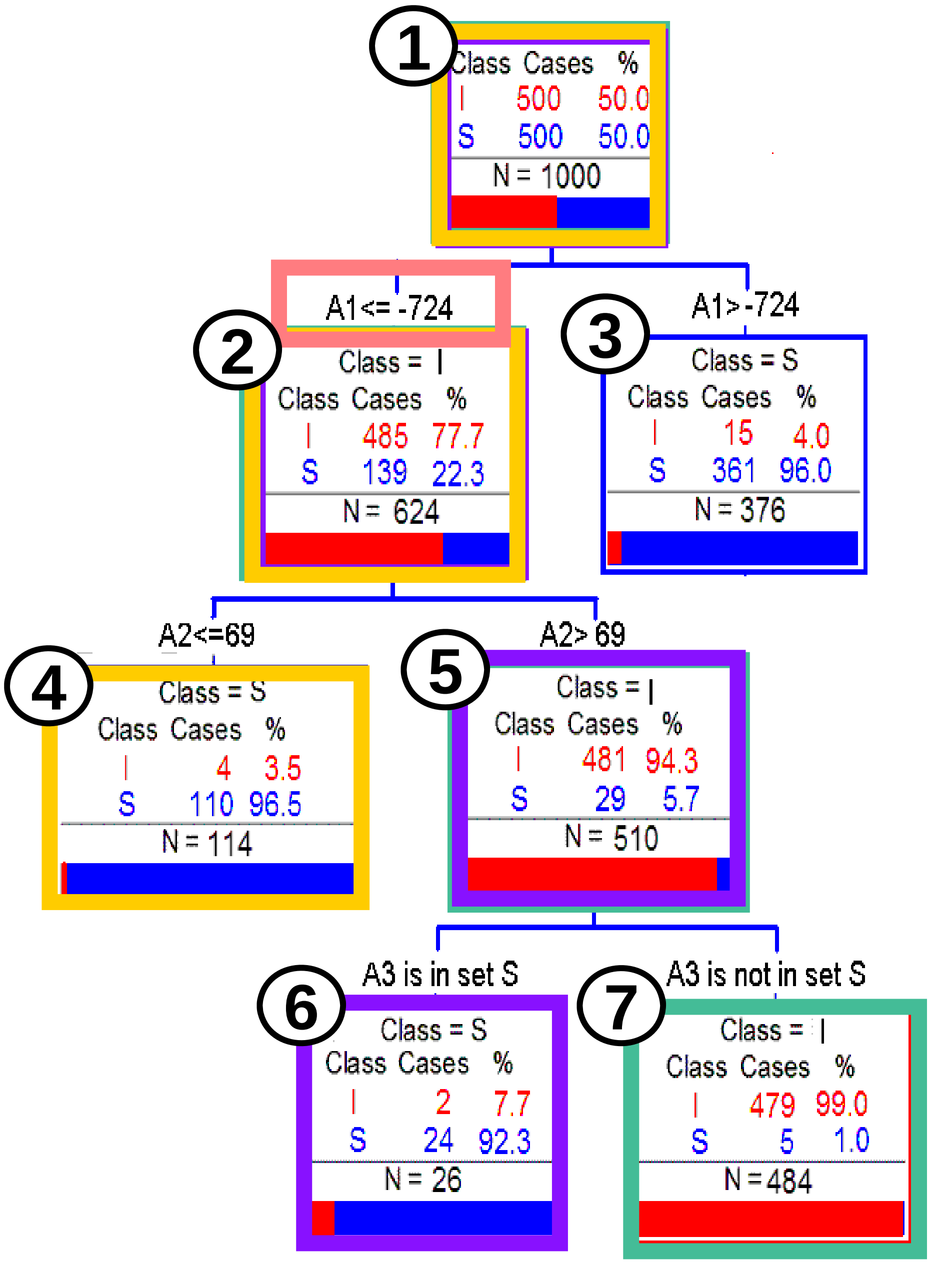
$$S = \sum_{j=1}^{K}\left(\lambda_j \cdot \sum_{i=1}^{L}\omega_i \cdot p_{ij}\right) \Bigg/ \left(\sum_{i=1}^{L}\omega_i \cdot \sum_{j=1}^{K}\lambda_j\right)$$

  - $\boldsymbol{p_{ij}}$ ---- percentage of the insecure learning cases of class *j* in node *i*
  - $\omega_i$ and $\lambda_j$ ---- weights assigned to node *i* and class *j*

- Key class of insecurity is class *j* maximizing $\lambda_j \cdot \sum_{i=1}^{L}\omega_i \cdot p_{ij}$
- Key insecure nodes are those with large $\boldsymbol{\omega_i \cdot p_{ij}}$ , whose CSRs and CAs are helpful for designing preventive control

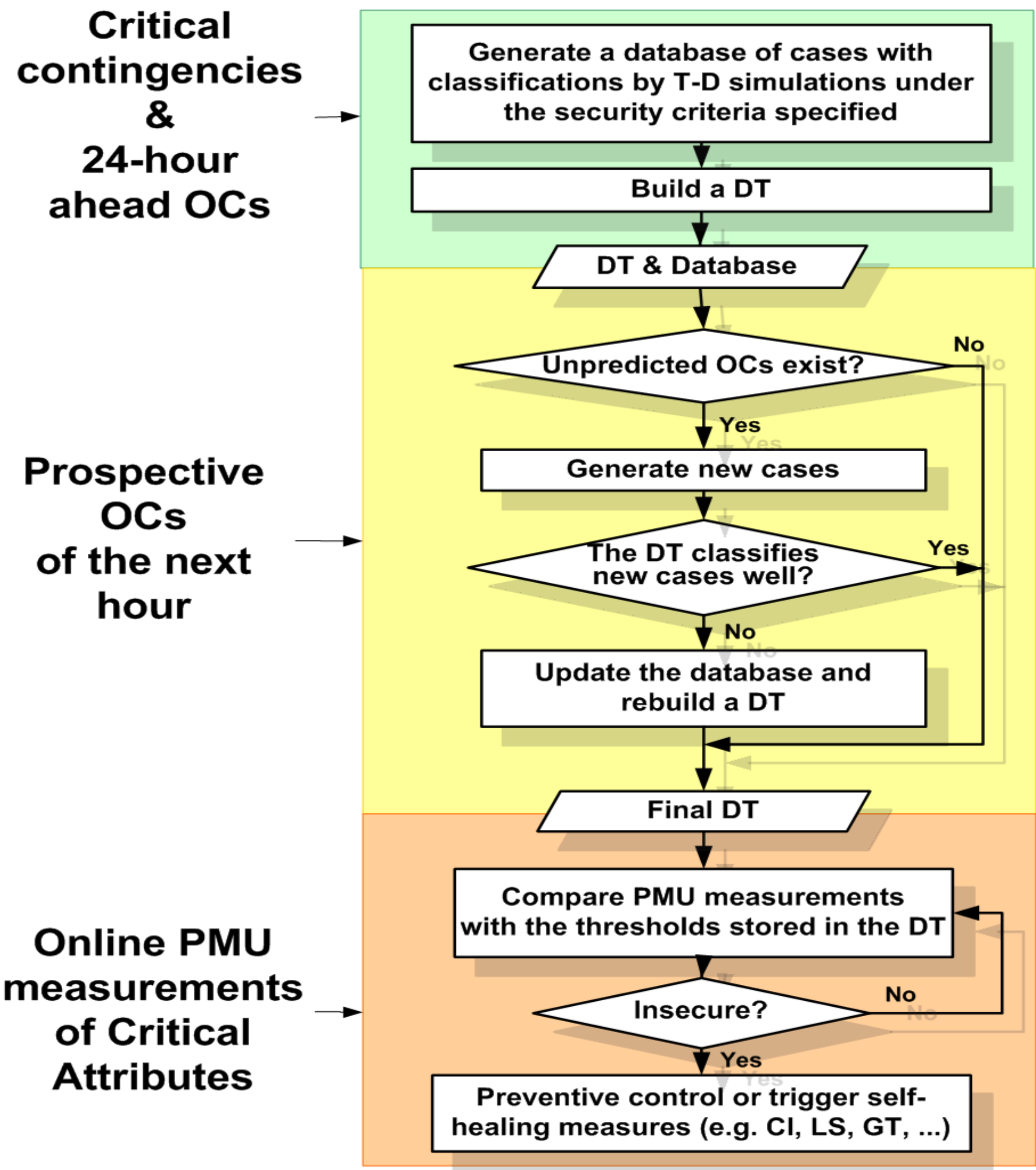
# Example

- Old approach:
  - Only terminal node #7 is insecure
- New approach:
  - Paths 1-2-5-7, 1-2-5-6 and 1-2-4 may have high insecurity scores
  - For path 1-2-4, node 2 is critical
  - “A1<=724” indicates a critical cause of insecurity



# Proposed scheme

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



# Offline DT building

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- Database of cases is built offline:
  - Projected operating conditions in the next 24 hours are considered
  - A list of probable contingencies is selected
  - Simulation result for each contingency along with measurements is stored as a case of the database

# Sample database

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| | Class | Predictor 1 | Predictor 2 | Predictor 3 | Predictor 4 | … |
|---|---|---|---|---|---|---|
| | Security | Fault bus | P_1_2 (MW) | A_3_5 (degree) | P_2_4 (MW) | … |
| Case 1 | Secure | #2 | 130 | 5.2 | 745 | … |
| Case 2 | Insecure | #4 | 209 | 6.1 | 680 | … |
| Case 3 | Secure | #5 | -5 | 4.9 | 699 | … |
| Case 4 | Insecure | #11 | -12 | 5.9 | 720 | … |
| … | … | … | … | … | … | … |

# Building a good DT

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- Select predictors from critical variables arising from NERC reliability standards
- Build a DT using CART
- Replace each CSR by a good competitor to see if a better DT is generated.
- Relocate fault-dependent and -independent CSRs  by appropriately penalizing predictors (e.g. using fault-dependent CSRs at only the first or only the last splitting)

# Periodic DT updating

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- Carried out on an hourly basis or as needed
- Projected operating conditions (OCs) for the next hour or for the update period considered are obtained from short term load forecast
- If there is significant change then simulations are carried out for the new operating points
- The existing DT is tested on these new results

# Periodic DT updating

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- If the DT performs well then it is left unchanged
- Otherwise a new DT is built using the old and new cases

# Online security assessment

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- The simultaneous measurements obtained in real time are fed to the DT
- Use of PMUs ensures that measurements are synchronized
- Related paths are identified and scored
- Each path corresponds to a group of contingencies
- If a path is insecure, the following are determined:
  - Insecure cases from the contingency list considered
  - Critical class of insecurity
  - Critical insecure nodes of the path

# Implementation on Entergy System

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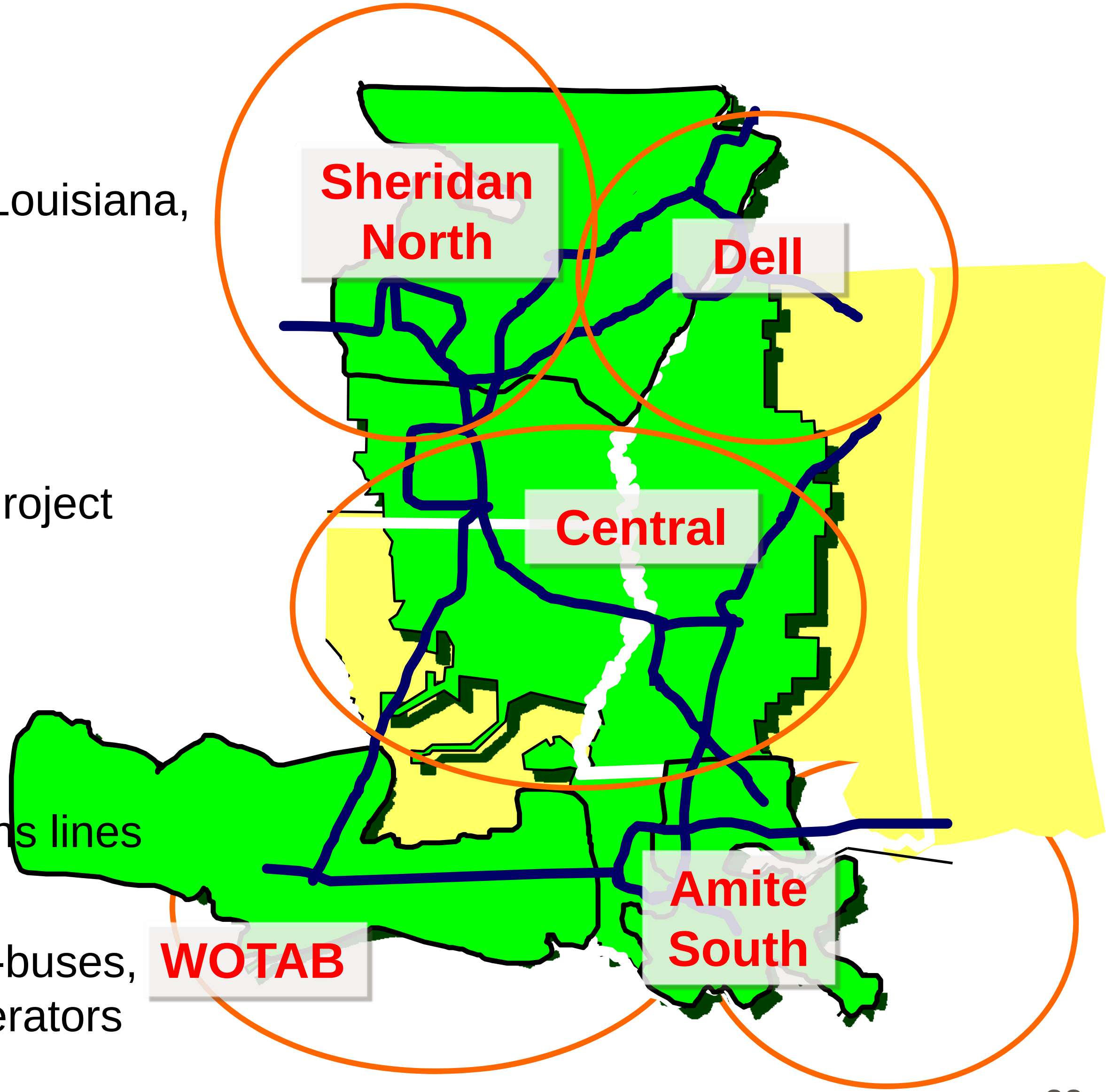
- Entergy Corp.
  - Investor owned utility
  - Service area: Arkansas, Louisiana, Mississippi, and Texas.
  - Capacity: 30,000 MW
  - 2.6 million customers
  - Involved in the Eastern Interconnection Phasor Project (EIPP).
  - 9 PMUs were installed
- Power system
  - Five control areas
  - Over 15,000 miles of trans lines
  - 1450 substations
  - Operational model: 2100-buses, 2600-lines, and 240-generators



# Implementation on Entergy System

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Based on the Entergy operation model:

- Make a day-ahead database of cases – Key step to capture characteristics of the system as it evolves
  - Predict day-ahead OCs
  - Select a list of contingencies based on operator experience
  - Specify security criteria
  - Conduct time domain simulations
- Build the day-ahead DT for each Entergy zone:
  - Sheridan North
  - Dell
  - Central
  - WOTAB
  - Amite South

# Case Studies: Amite South on 7/19/2006 without a 500kV line to WOTAB

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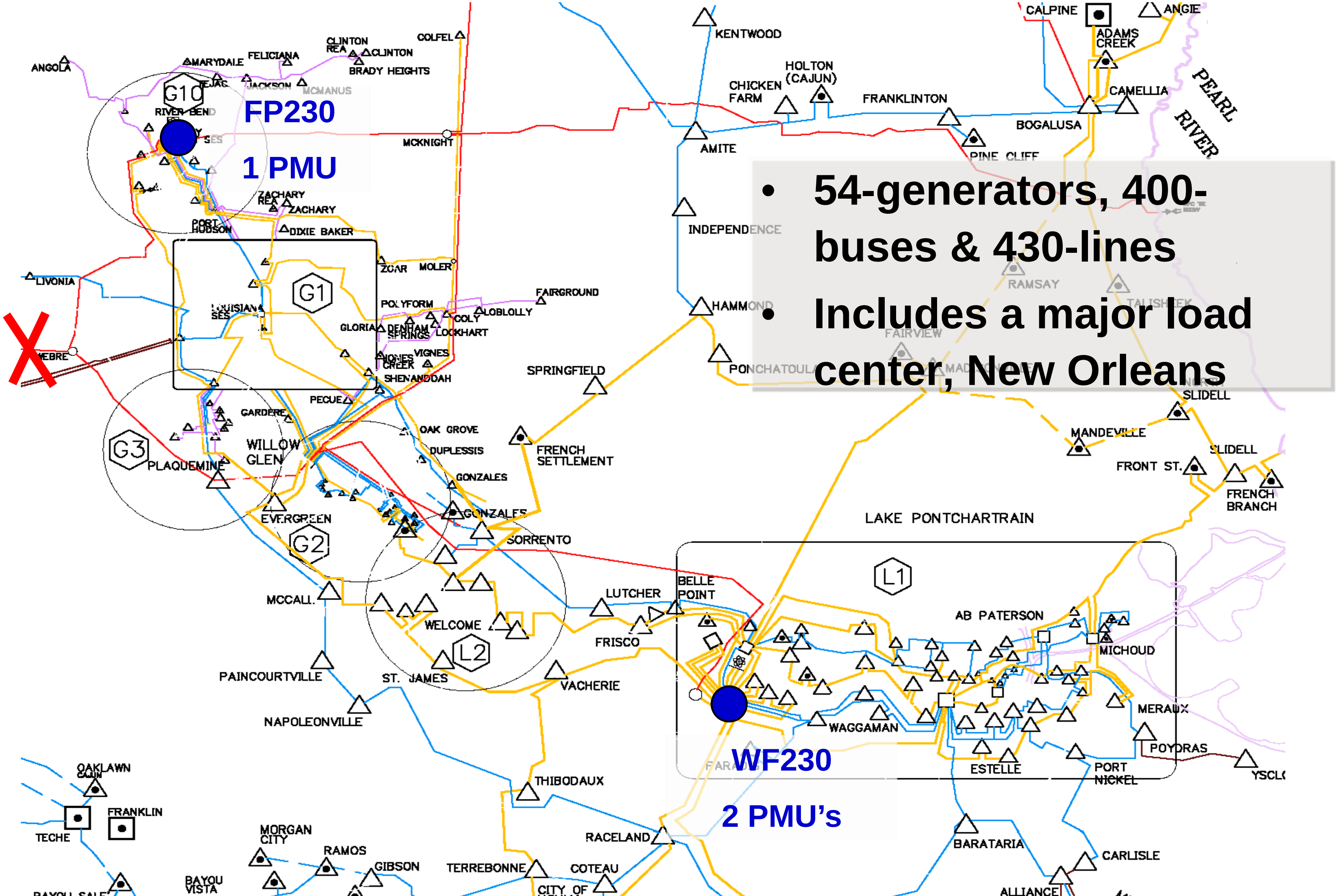


- 54-generators, 400-buses & 430-lines
- Includes a major load center, New Orleans

# Creating the Database

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- Generate 56 typical OCs for 7/19/2006
  - From high-load (26.6GW) and low-load (17.8GW) power flow profiles
- Select 280 “n-1” contingencies:
  - 3-phase faults on 230~500kV buses
- Check security criteria for TSAT simulation results:
  - *Transient stability:* stability margin>5% (estimated by TSAT’s power swing based algorithm)
  - *Low damping*: damping ratios>3% for 0.25~1.0Hz modes

# Creating the Database

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- 15680 cases are generated
  - 355 (2.3%) cases violate the transient stability criterion
  - 2501 (16.0%) cases violate the low-damping criterion
- Simulation time:
  - Each case takes 5~10s for its T-D simulation in TSAT
  - Cases for each OC takes 30~50 minutes.
  - Parallel processing can reduce the total time for 15680 cases
- Two databases are generated respectively for each of the two criteria
  - Database-1 for transient stability: 355 cases are insecure; the others are secure
  - Database-2 for low damping: 2501 cases are insecure; the others are secure

# DT building

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- Predictors chosen as:
  - FB: Fault bus
  - P_i_j: MW flows measurable by PMUs
  - A_i_j: Differences between the voltage angles measurable by PMUs
- The first group of predictors:
  - Only consider 3 existing PMUs:
    - At WF230 looking at NM230
    - At WF230 looking at WF500
    - At FP230 looking at FP500
- The second group of predictors:
  - 3 existing PMUs
  - Additional candidate measurements from PMUs:
    - At all 500kV buses looking at connected branches

# DT Building

- Test and learning sets:
  - Test set: random 20% cases
  - Learning set: the other 80% cases
- Low damping: power flow distribution is more critical
  - “FB” (fault bus) is only used at the last splitting
  - c(I|S) : c(S|I) =7.5
  - $DT^{SS}_1$ based on existing PMUs
  - $DT^{SS}_2$ based on existing and candidate PMUs
- Transient stability: fault location is more critical
  - Without limitation of using FB
  - c(I|S) : c(S|I) =40
  - $DT^{TS}_1$ based on existing PMUs
  - $DT^{TS}_2$ based on existing and candidate PMUs

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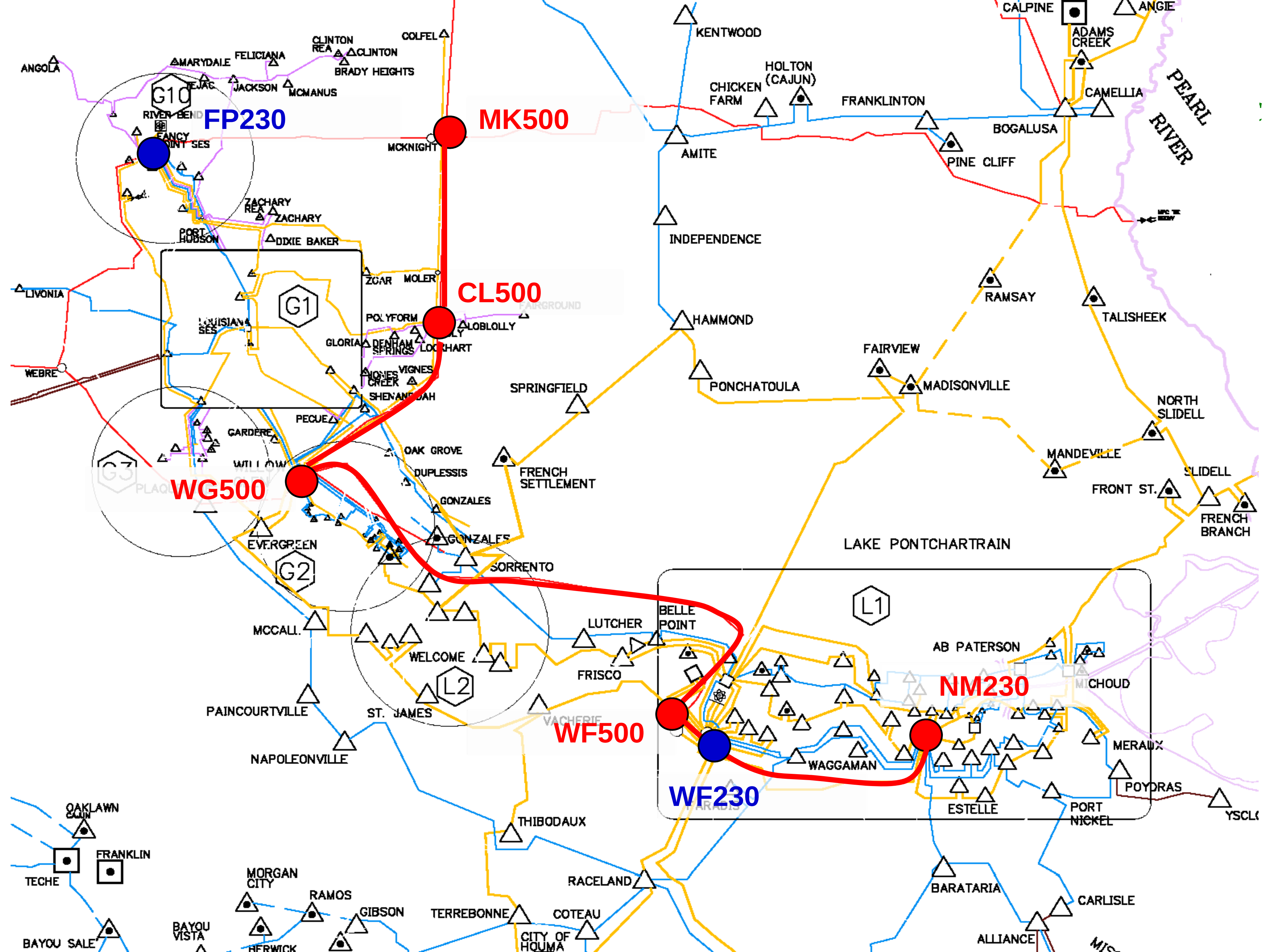
# DT Performance (Old Method)

| DTs | Size | $R^{ts} \pm \Delta R^{ts}$ | $CR_I^{ts}$(%) | $CR_S^{ts}$(%) |
|---|---|---|---|---|
| $DT^{ss}_1$ | 31 | 0.113±0.006 | 96.7 | 91.1 |
| $DT^{ss}_2$ | 31 | 0.100±0.005 | 97.9 | 91.0 |
| $DT^{ts}_1$ | 17 | 0.072±0.005 | 97.3 | 95.3 |
| $DT^{ts}_2$ | 17 | 0.070±0.005 | 97.3 | 95.5 |

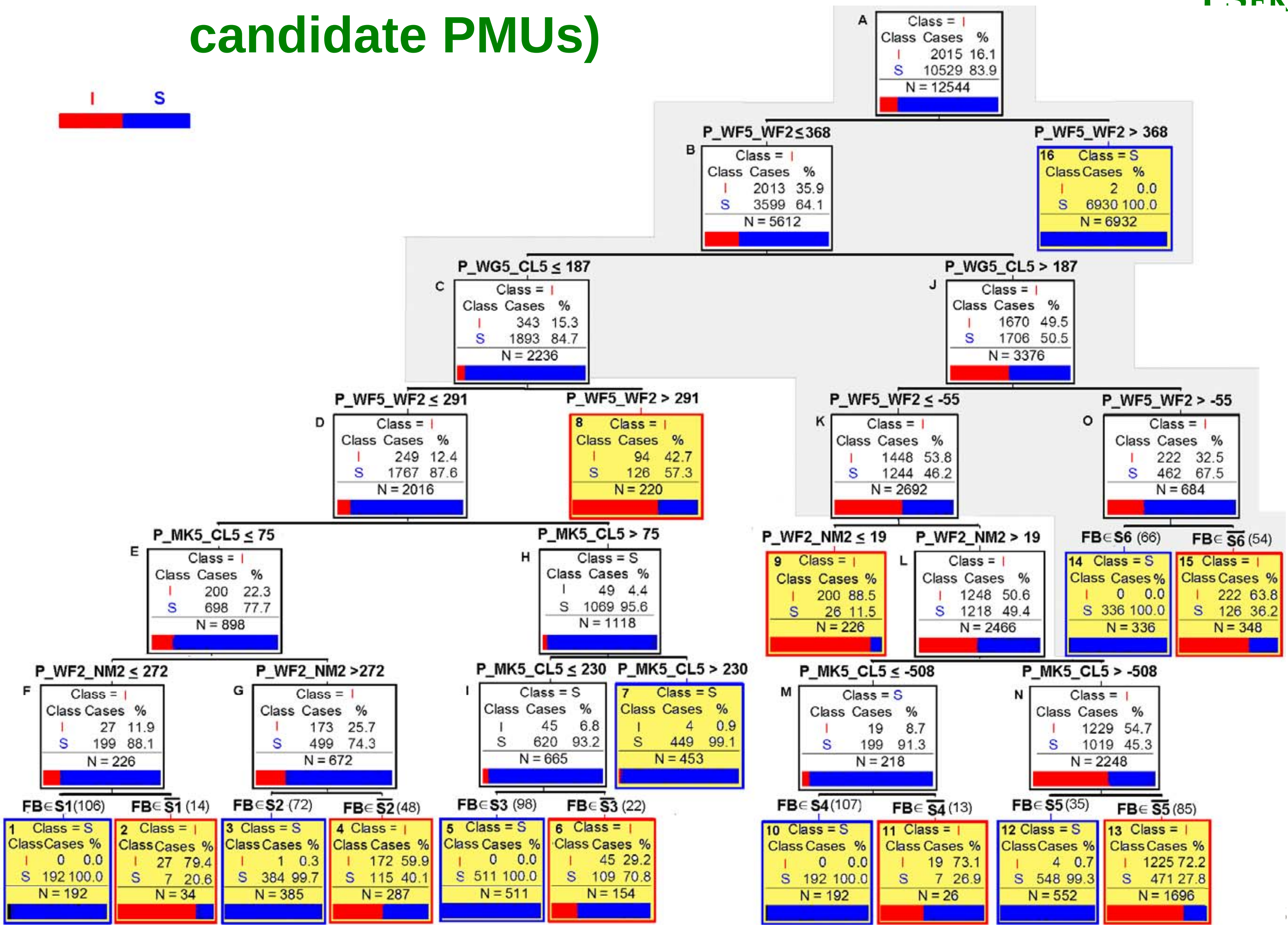
# DT Comparison

- $DT^{TS}_1$ *vs.* $DT^{TS}_2$
  - Equally good (0.072±0.005≈0.070±0.005)
  - $DT^{TS}_2$ picked up MW flows of 3 branches
    - **WF500 – WF230, WF230 – NM230**, and WG500 – CL500
- $DT^{SS}_1$ *vs.* $DT^{SS}_2$
  - $DT^{SS}_2$ is better (0.100±0.005 < 0.113±0.006)
  - $DT^{SS}_2$ picked up MW flows of 4 branches:
    - **WF500 – WF230, WF230 – NM230,** WG500 – CL500, and CL500 – MK500
- A key transmission path is identified:
  - WF500 – WF230 – NM230 – WG500 – CL500 – MK500
  - May consider adding a new PMU at CL500 to measure MW flows of WG500 – CL500 – MK500



MK500
CL500
WG500
WF500
NM230
FP230
WF230
G10
G1
G2
G3
L1
L2
LAKE PONTCHARTRAIN
PEARL RIVER
ANGOLA
MARYDALE
FELICIANA
CLINTON REA
CLINTON
COLFEL
BRADY HEIGHTS
JACKSON
MCMANUS
RIVER BEND
FANCY POINT SES
MCKNIGHT
ZACHARY REA
ZACHARY
PORT HUDSON
DIXIE BAKER
ZOAR
MOLER
POLYFORM
LOBLOLLY
LOUISIANA SES
GLORIA
DENHAM SPRINGS
LOCKHART
JONES CREEK
VIGNES
SHENANDOAH
PECUE
GARDERE
OAK GROVE
DUPLESSIS
GONZALES
SORRENTO
EVERGREEN
MCCALL
WELCOME
ST. JAMES
PAINCOURTVILLE
NAPOLEONVILLE
THIBODAUX
LIVONIA
WEBRE
KENTWOOD
HOLTON (CAJUN)
CHICKEN FARM
FRANKLINTON
AMITE
INDEPENDENCE
HAMMOND
PONCHATOULA
SPRINGFIELD
FRENCH SETTLEMENT
LUTCHER
FRISCO
BELLE POINT
CALPINE
ANGIE
ADAMS CREEK
CAMELLIA
BOGALUSA
PINE CLIFF
RAMSAY
TALISHEEK
FAIRVIEW
MADISONVILLE
NORTH SLIDELL
MANDEVILLE
SLIDELL
FRONT ST.
FRENCH BRANCH
AB PATERSON
MICHOUD
WAGGAMAN
MERAUX
POYDRAS
ESTELLE
PORT NICKEL
BARATARIA
CARLISLE
ALLIANCE
RACELAND
TERREBONNE
COTEAU
CITY OF HOUMA
OAKLAWN CAJUN
TECHE
FRANKLIN
MORGAN CITY
RAMOS
GIBSON
BAYOU VISTA
BERWICK
BAYOU SALE

# $DT^{SS}_2$ (Based on existing and candidate PMUs)

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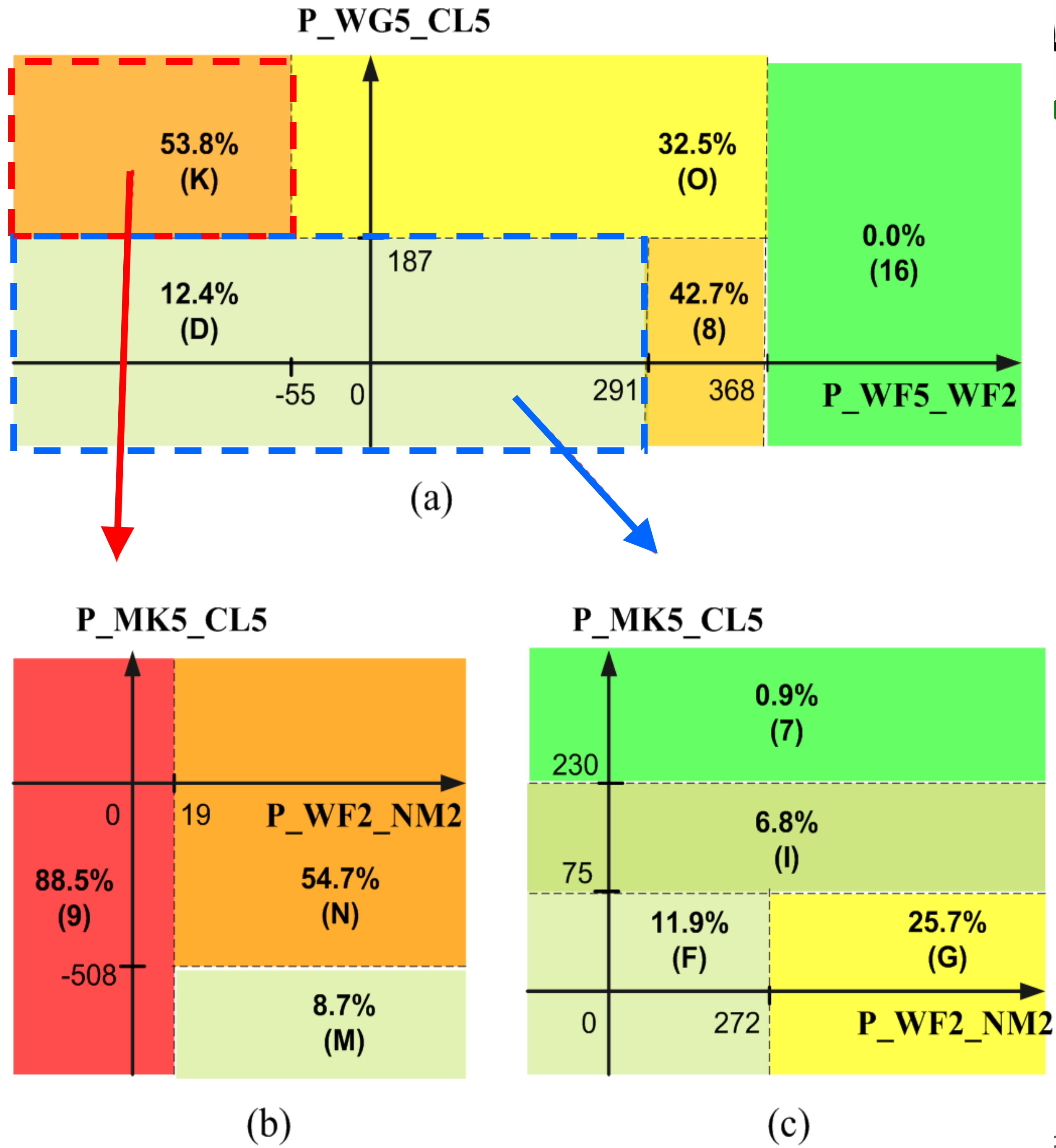
# Nomograms from $DT^{SS}_2$



# DT Reliability Against OC Perturbations

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- 24 OCs on 7/26/2006 (a week later)
  - Entergy load: 16.1~24.1GW
  - 15 lines change in/out status
  - Generation distribution among generators is different
- Same “n-1” contingencies
  - 6672 cases: 942 (14.1%) low damping cases

# New Method

| Path | Terminal Node Cases (%) | Class by Old Method | Insecurity Score (%) | Class by New Method | 7/26/2006 Cases (S / I ) |
|---|---|---|---|---|---|
| A-B-C-D-E-F-**1** | 1.5 | S | 25.3 | S | 0 / 0 |
| A-B-C-D-E-F-**2** | 0.3 | I | 25.9 | S | 0 / 0 |
| A-B-C-D-E-G-**3** | 3.1 | S | 25.2 | S | 0 / 0 |
| A-B-C-D-E-G-**4** | 2.3 | I | 26.9 | S | 0 / 0 |
| A-B-C-D-H-I-**5** | 4.4 | S | 22.2 | S | 216 / **2** |
| A-B-C-D-H-I-**6** | 1.2 | I | 23.3 | S | 58 / **2** |
| A-B-C-D-H-**7** | 3.6 | S | 23.2 | S | 556 / 0 |
| A-B-C-**8** | 1.8 | I | 30.4 | S | 555 / **1** |
| A-B-J-K-**9** | 1.8 | I | 44.8 | I | 57 / **221** |
| A-B-J-K-L-M-**10** | 1.5 | S | 44.0 | I | 0 / 0 |
| A-B-J-K-L-M-**11** | 0.2 | I | 44.6 | I | 0 / 0 |
| A-B-J-K-L-N-**12** | 4.4 | S | 44.9 | I | 344 / **64** |
| A-B-J-K-L-N-**13** | 13.5 | I | 48.8 | I | 610 / **650** |
| A-B-J-O-**14** | 2.7 | S | 39.0 | S | 0 / 0 |
| A-B-J-O-**15** | 2.8 | I | 41.2 | I | 0 / 0 |
| A-**16** | 55.3 | S | 0.0 | I | 3334 / **2** |

**Paths with insecurity scores>40% are regarded as "insecure"**

# New Method Vs. Old Method

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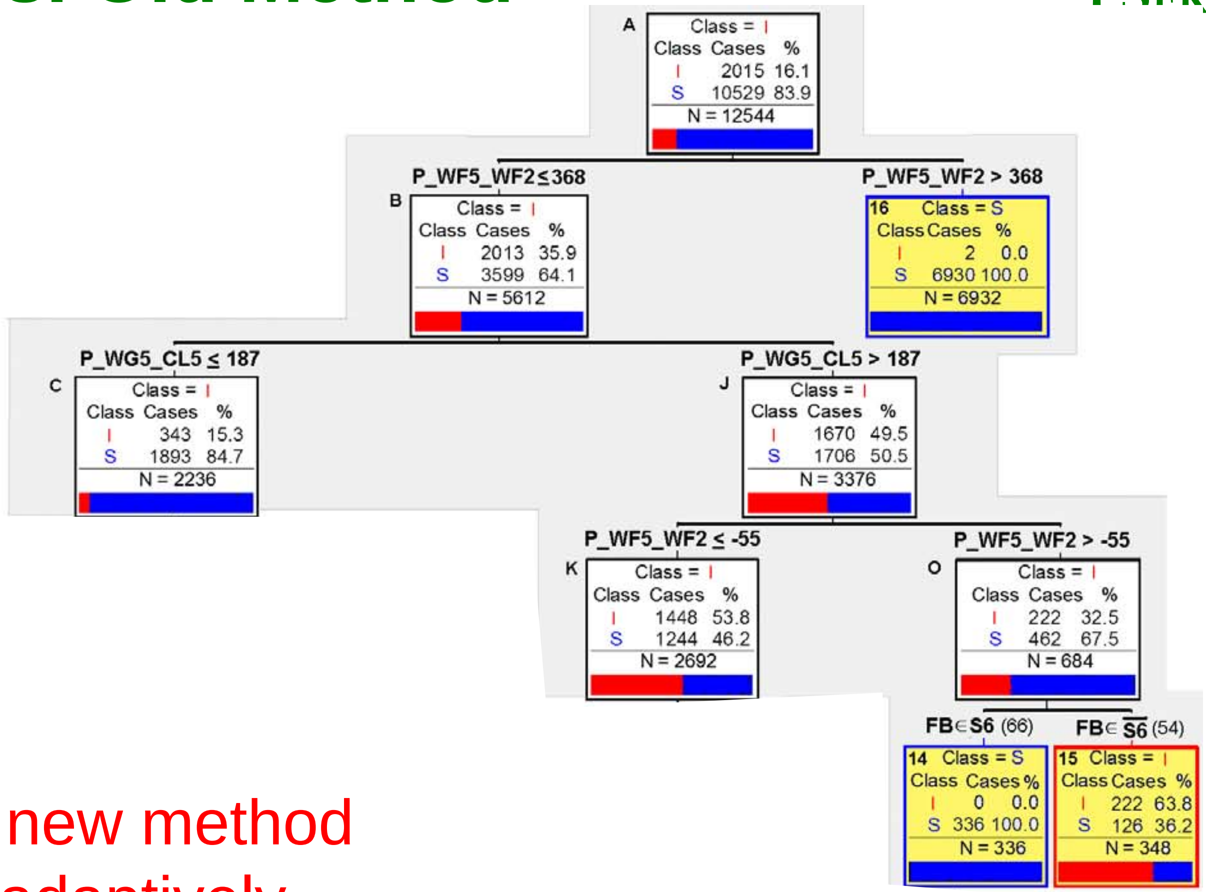
| Correctness Rates (Misclassified Cases) | | |
|---|---|---|
| | Insecure cases | Secure cases |
| Old | 92.8% ( 68 /942) | 77.7% ( 1278 /5730) |
| New | 99.3% ( 7 /942) | 82.4% ( 1008 /5730) |

# New Method Vs. Old Method


The new method self-adaptively picks up a key part of $DT^{SS}_2$

# New Method

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- The new method endows a DT with self-adaptability under nondeterministic conditions by using weights $\omega_i$ to reasonably emphasize a portion (sub-tree)
- Basically, a lower limit for insecurity scores leads to a higher accuracy for insecure cases
- The nodes closer to the root need higher weights when perturbations of OCs increase

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# Preventive Control

- The key Critical Attributes of a path are important indicators of security
- The Critical Splitting Rules indicate options  for preventive control
- Nomograms are helpful for grasping secure and insecure regions
- The intention would be to transfer the system from an insecure state to a known secure state according to the database

# Conclusions

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- An online dynamic security assessment scheme using PMUs and DTs is proposed for the Entergy system
- A new paths-based method is proposed and compared with the terminal nodes-based old method.
- Case studies for the Amite South area demonstrate:
  - The proposed scheme can identify key security indicators and give accurate online dynamic security predictions
  - Can reliably predict unseen operating conditions

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**Thank you.**

**Any questions?**