

# Impact of PHEVs on Reliability of Electric Grid

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March 2009

**Workscope** (supported by DOE/PNNL and MPSC/DTE)

- **Develop stochastic models for grid reliability and availability assessment.**
- **Evaluate maximum PHEV penetration allowed based on loading capacity and reliability.**
- **Suggest improvements in equipment maintenance practices and reconfiguration strategies to optimize grid operations.**



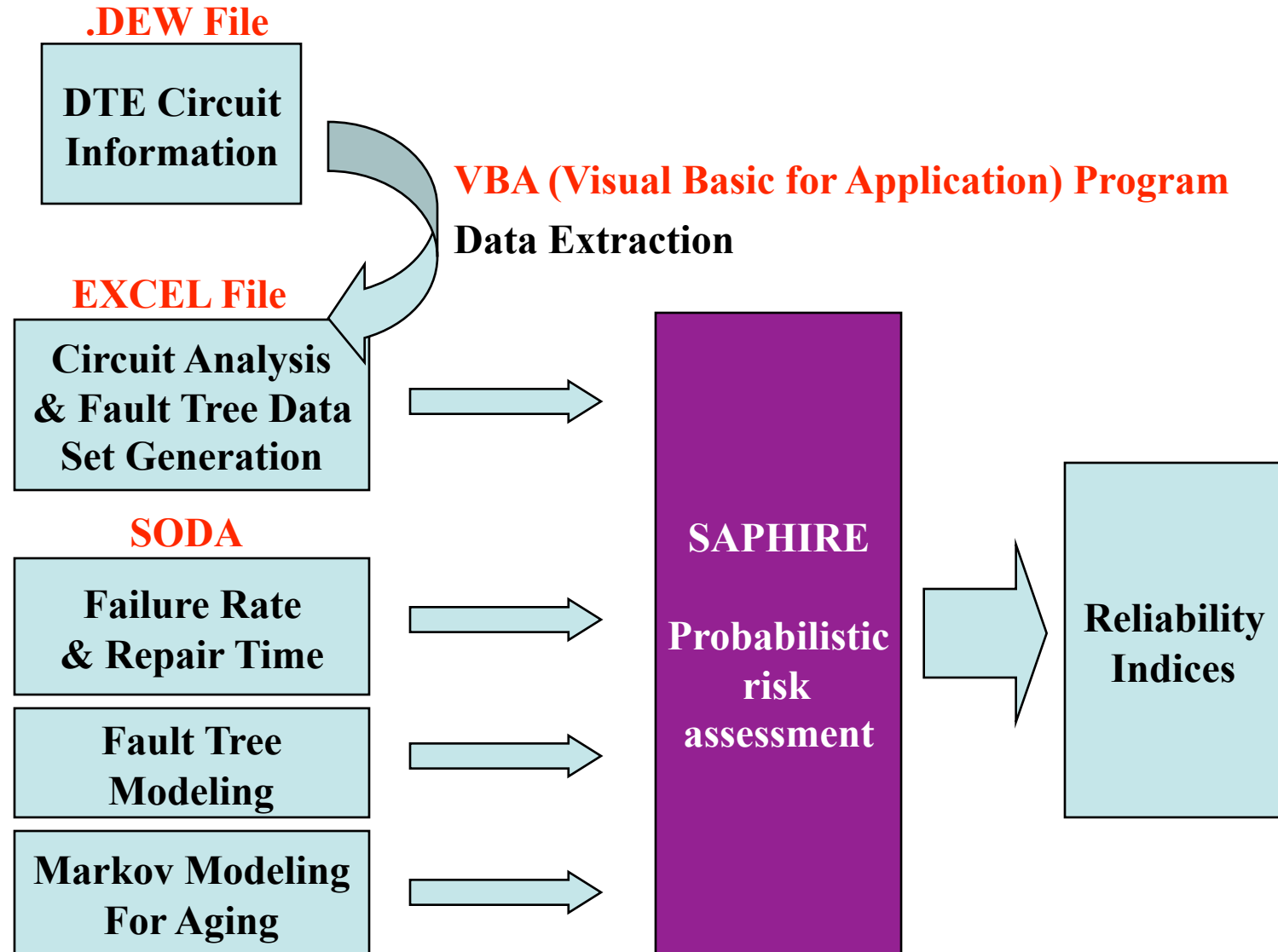
# Outline

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- Overall reliability model
- Markov model for unavailability with repair
- Evaluation of DTE System Outage and Data Analysis (SODA) files
- Load dependence of transformer reliability
- Concluding remarks



# Overall Reliability Model



# Markov Model for Unavailability with Repair

- System with two states with failure rate  $\lambda$  and repair rate  $\mu$ :

$P_1(t)$  = probability that system is in operational state

$P_2(t)$  = probability that system is under repair

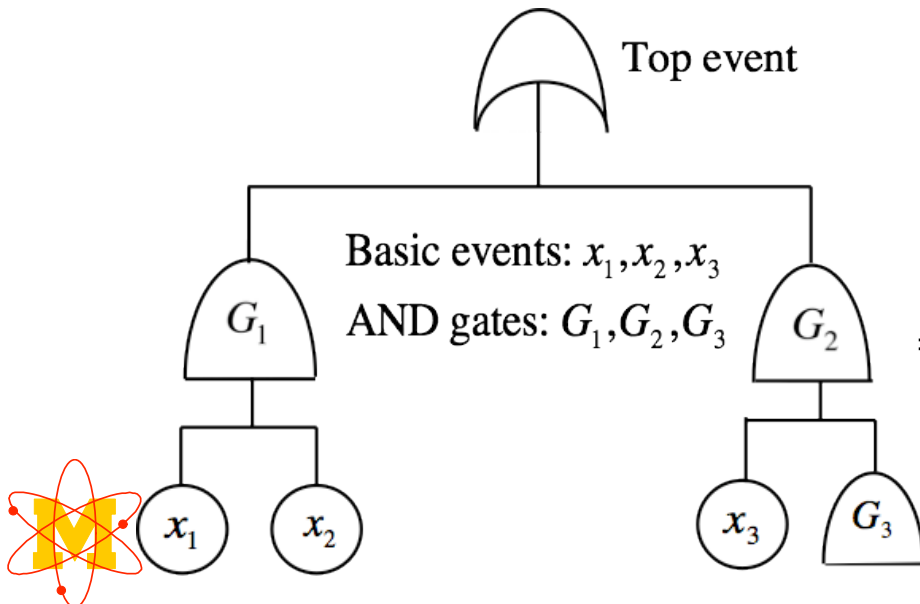
$$\frac{d}{dt} \begin{pmatrix} P_1(t) \\ P_2(t) \end{pmatrix} = \begin{pmatrix} -\lambda & \mu \\ \lambda & -\mu \end{pmatrix} \begin{pmatrix} P_1(t) \\ P_2(t) \end{pmatrix} \Rightarrow \text{Unavailability: } P_2(\infty) = \frac{\lambda}{\lambda + \mu} \approx \lambda \cdot \text{MTTR}$$

- Top event in a fault tree = OR gate comprising AND gates or basic failure events.

Probability of AND gate  $G_i$

$$P(G_i) = \prod_{j=1}^J \left( \frac{\lambda}{\lambda + \mu} \right)_j$$

$$\Rightarrow \text{top event probability} = \sum_{i=1}^I \prod_{j=1}^J \left( \frac{\lambda}{\lambda + \mu} \right)_j$$



# System Outage and Data Analysis (SODA)

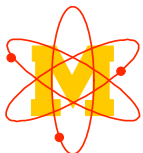
- Load-based statistics
  - Load interrupt, Load-mins
- Customer-based statistics (2005-2008 Ann Arbor circuits)

$$CAIDI = \frac{\text{\#Customer-Minutes Outaged}}{\text{\# Customers Outaged}}$$

$$SAIDI = \frac{\text{\#Customer-Minutes Outaged}}{\text{\# Customers Served}}$$

$$SAIFI = \frac{\text{\#Customer Outaged}}{\text{\# Customers Served}}$$

- Outage Events (2005-2008)
  - Cause
    - Equipment break / malfunction (41%)
    - Trees/wind (27%), lightning (7%),
    - Others (25%)
  - Effect
    - Blown fuse overhead (28%)
    - Open in line (60%), others (12%)

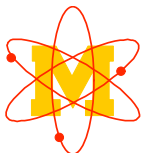


# Benchmarking Reliability Calculations with DTE data

Component	Repair Time [hours]	Outage Contribution % (time)
Transformer	12.8	19.1
Fuse	4.7	21.5
Recloser	6.0	0.5
Underground cable	6.3	2.3
Overhead line	5.4	18.7
Capacitor	4.0	0.04

$$\text{Repair Time (hours)} = \frac{\text{\#Customer-hours Interrupted}}{\text{\# Customers Interrupted}}$$

$$\text{Outage Contribution \%} = \frac{\text{Component Outage Time (hours per year)}}{\text{Total Outage Time (hours per year)}}$$

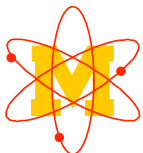
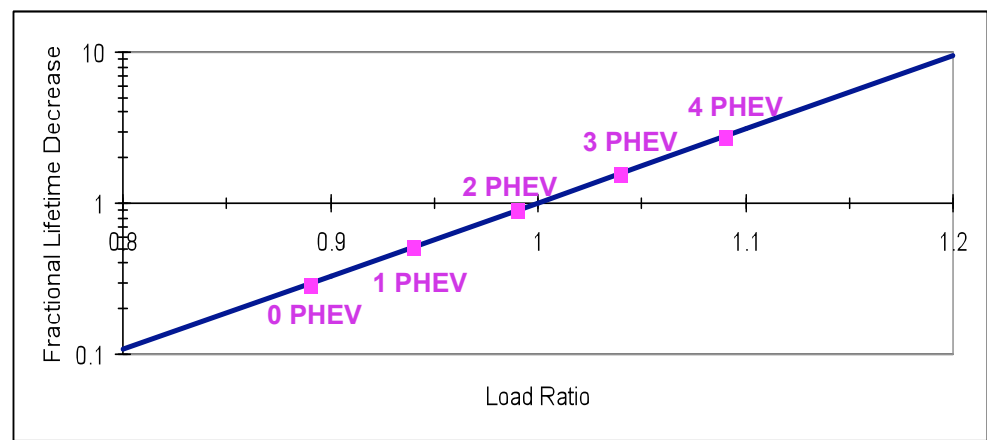
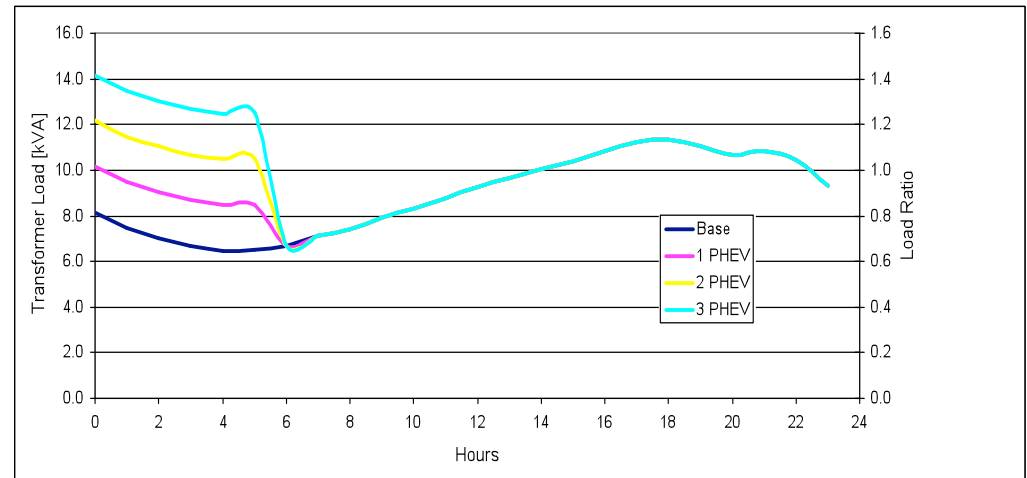


**No Damage or Malfunction 28.67%, Other 9.19%**

# Transformer Reliability With Load Dependence

- Load profile of a 10 kVA transformer serving 2 residential customers for an average summer day
- Charging rate is 2 kW over 6 hours per PHEV
- PHEVs are assumed to be charged during off peak hours
- Each PHEV increases transformer load ratio  $L$  by 0.5
- Fractional lifetime *decrease*  $\Delta\tau$  increases exponentially as  $L$  increases:

$$\ln \Delta\tau \propto L$$



# Concluding remarks

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- Preliminary analysis of DTE field data shows SAIFI = 2 for 152 Ann Arbor circuits vs. fault tree prediction of 0.2 for 70 circuits.
- Actual field data include weather related outages, accounting for 60% of all outages.  
SAIFI adjusted for equipment failures = 0.8.
- Could rebalance generic failure data based on DTE field data.
- Transformer aging accelerates exponentially as PHEV related load increases.
- Need to improve fault tree model with repair involving multiple component failures.
- Need to develop dynamic event tree model accounting for load variations on circuit reliability.

