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Quantitative Resiliency Analysis of Microgrids

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Outline

- Motivation
- Quantitative Resiliency Definition
- Application
- Matlab model
- SysML Model
- Selected Results
- Discussion
- Conclusions

Motivation

- Resiliency lacks a specific quantitative definition and associated metrics that enable assessment [1]
- This work proposes a definition and shows that Model Based Systems engineering (MBSE), and in particular SysML and Markov models, can be used to assess resiliency

Quantitative Definition of Resiliency

Resiliency is the probability weighted sum of MOPs in each system state

$$R_s = \sum_{k=0}^{n} P_k MOP_k$$

Where

- R_s is the system resiliency measure
- P_k is the probability of being in state k
- MOP_k is the measure of performance for that state (Power generated, Power relative to demand, Total Energy Delivered)

Remarks

The definition can be applied to any system which meets the following conditions

1. Systems can be characterized by states (normal, multiple degraded states, totally disabled states)
2. There is an ascertainable probability of being in each State
   - The probability need not be directly measurable if it can determined on the basis of other measurable parameters
3. Each state has at least one quantifiable Measure of Performance (MOP) which is of interest to the stakeholders

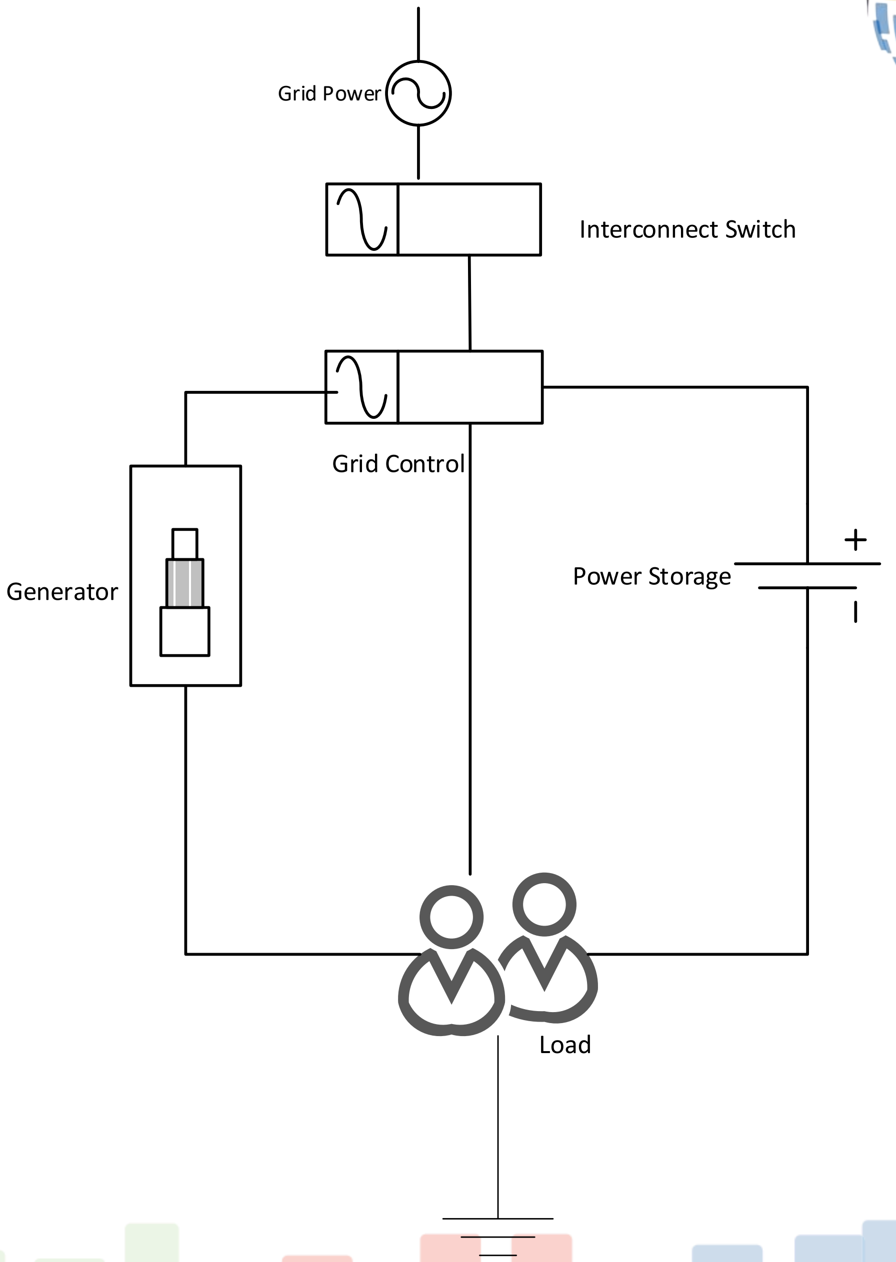
Use of states is consistent with earlier approaches to resilience [4]

Application: Microgrids

- A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that contains loads, distributed energy sources

- Microgrids are a key element in increasing the resiliency of the electrical grid

- Microgrids have multiple states:
  - Connected (normal state)
  - Island/generator power
  - Island/battery power
  - No power



Application: Microgrid Resiliency (1/2)

Three Measures of Performance (MOPs) of interest to stakeholders

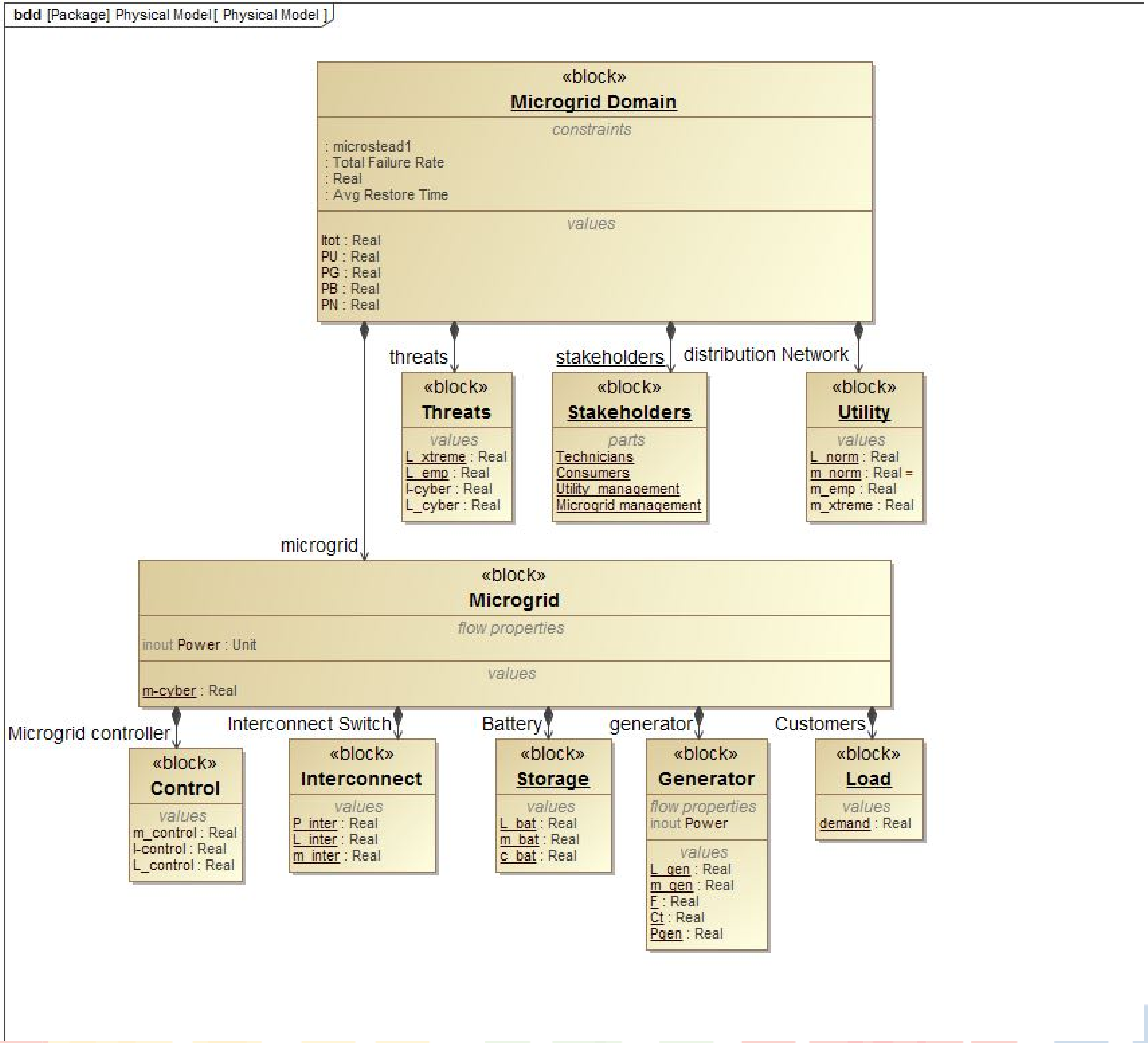
1. Power generation capacity (P_G)
2. Power generation capacity vs. demand (P_D / P_G)
3. Total Energy Provided: ($E_P = A\ P_G\ t$)
    - A=Availability of Power
    - t = Time
    - Energy = Power *Time

Terminology issue: because there are multiple possible MOPs, we refer to each probability weighted sum as a *resiliency measure*,

Example

State	Proba-bility	Measures of Performance (MOPs)			Probability Weighted MOPs		
		Power Genera-tion Capacity (KW)	Capacity vs. Demand	Energy Provided (KWH, 100 hours)	Capacity	Capacity vs. Demand	Energy Provided
Utility Power (U)	0.9581	4000	1	400,000	3832.4	0.9581	383240
Generator Power (G)	0.0261	2400	0.6	240,000	62.64	0.01566	6264
Battery Power (B)	0.0105	2000	0.5	200,000	21	0.00525	2100
No Power (N)	0.0054	0	0	-	0	0	0
Resiliency Measure					***3,916***	***0.9790***	***391,604***

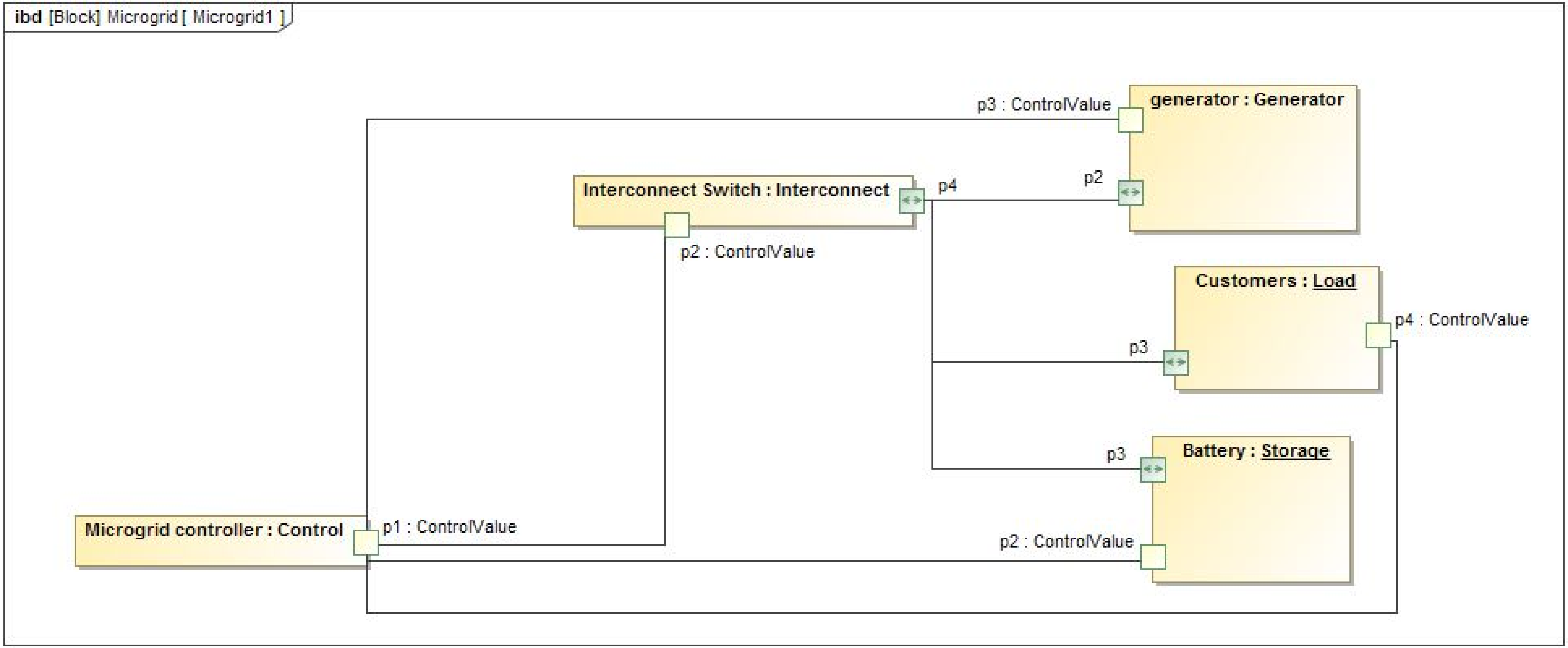
SysML Block Definition diagram



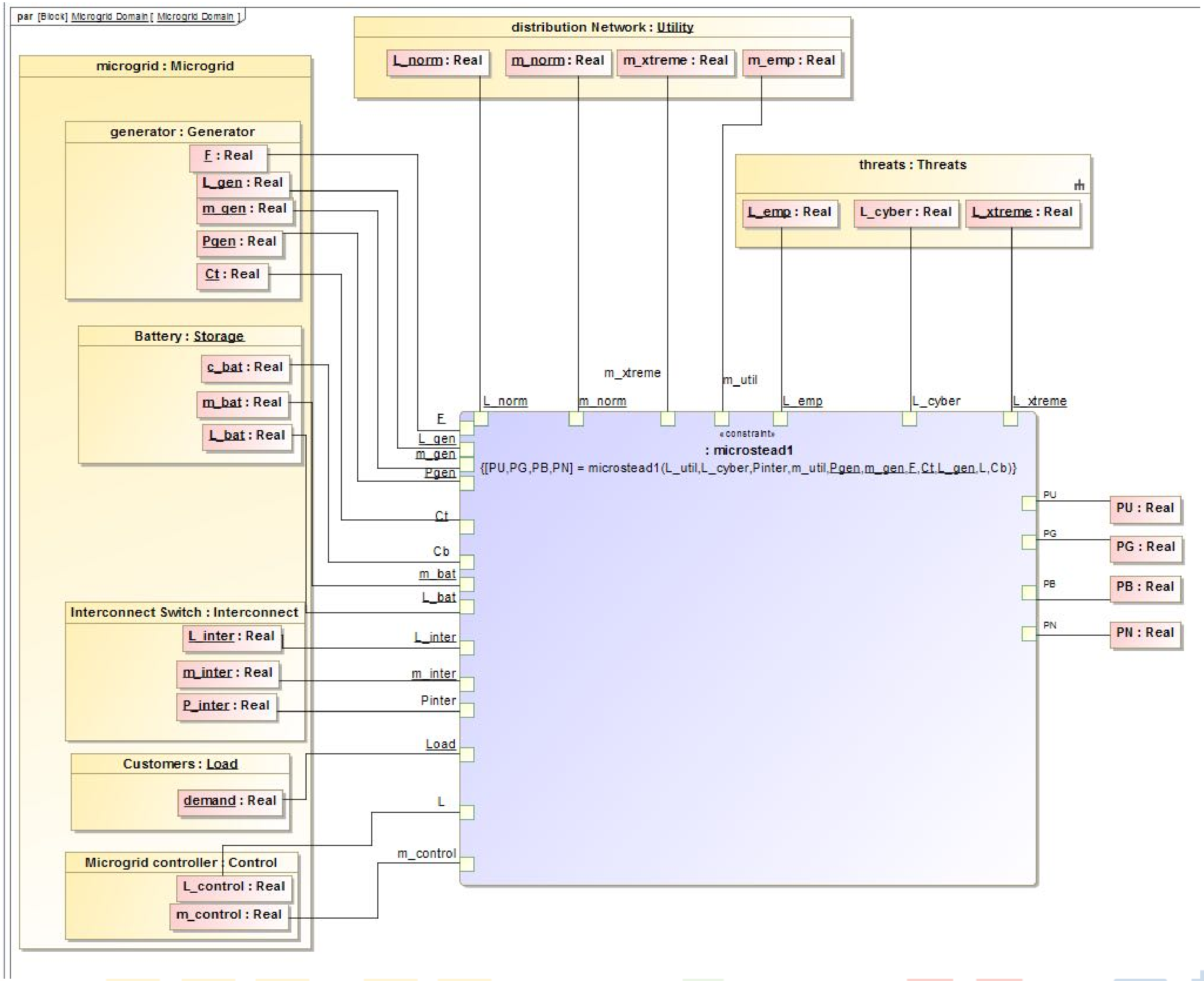
Microgrid Blocks

Block	Description
Consumers	Customers of the microgrid (electrical power users)
Microgrid Domain	Domain of the microgrid including components, stakeholders, and threats
Microgrid	A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that contains loads, distributed energy sourc
Threats	Phenomena (natural or anthropogenic) that can degrade or destroy the availability of power to consumers
Stakeholders	stakeholders in the microgrid (consumers, technicians, utility management, microgrid management)
Storage	Electrical energy storage (battery) characterized by a capacity (watt-hours)
Generators	System elements that convert other forms of energy into electrical power with the load (diesel generators, gas turbines, solar arrays, windmills)
Utility	The external grid to which the microgrid is connected
Interconnect switch	A device which connects the microgrid to the utility
Load	Aggregate of power consumers on microgrid measured in watts

SysML Internal Block diagram



Parametric Diagram

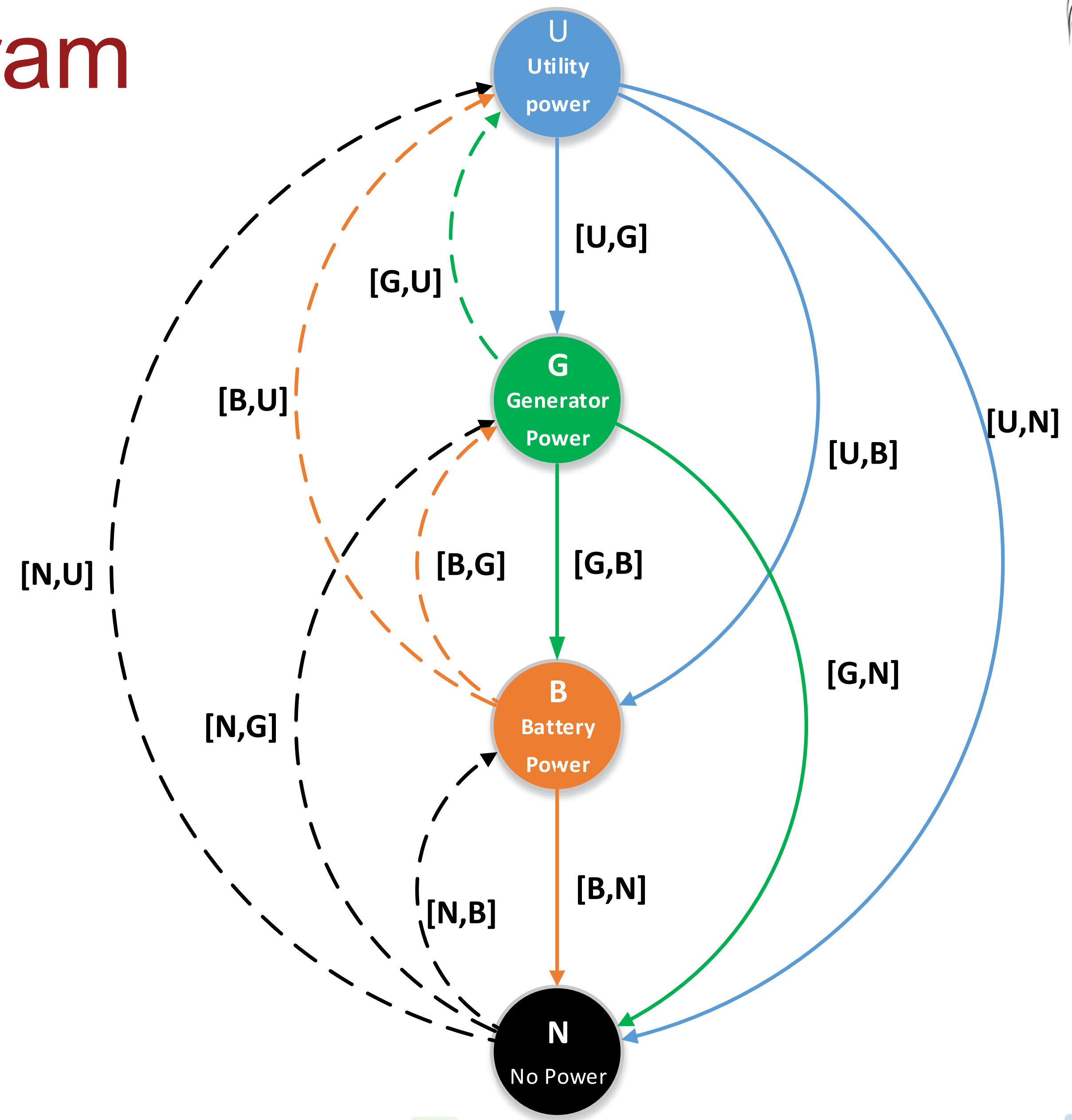


Mathematical Model Assumptions

- Resilient Component behavior
  - Any component can fail
  - Any component can be subject to a cyberattack
  - Failed components can be restored
- Microgrid behavior
  - Interconnect switch necessary to isolate microgrid from the main grid
  - Diesel Generators have a limited fuel supply
  - Batteries have a limited capacity which is subject to a demand
  - Demand is variable and controllable within the power grid
- Mathematics
  - Times between failures and recovery times are distribution exponentially
  - Component failures are independent of each other

State Transition Diagram

Steady State Markov Model solution provides the percentage of time that the system is in each state (state residence probability)



Input Variables in the Model

Name	Owning Block	Meaning
Ct	Generator	Capacity of fuel tank in liters
F	Generator	Fuel consumption rate for diesel generator set (liters per hour)
L_gen	Generator	diesel generator set failure rate
m_gen	Generator	repair rate for generator
Pgen	Generator	Probability of successful generator startup
L_inter	Interconnet	Failure rate of interconnect switch
m_inter	Interconnet	repair rate of the interconnect switch
Pinter	Interconnet	Probability of successful interconnect switching to island mode upon interruption of utility power
demand	Load	Demand of load (in watts)
c_bat	Storage	Capacity of battery
L_bat	Storage	Failure rate of battery (or other electrical energy storage device)
m_bat	Storage	Repair rate of battery (or other electrical energy storage device)
L_emp	threats	Occurrence rate of electromagnetic pulses (EMP) sufficient to disable the utility
L_xtreme	threats	Occurrence rate of extreme weather conditions (aggregate)
m-cyber	threats	recovery rate from microgrid cyberattack
L_norm	Utility	Failure rate (interruption rate) of the grid
m_norm	Utility	Weighted average recovery time of common repairs, extreme weather repairs, EMP, and cyber reapirs
L_gen	Generator	diesel generator set failure rate
m_gen	Generator	diesel generator set restoration rate
Pgen	Generator	probability of successful diesel generator start on demand

Variables used in this analysis

Input	Meaning	Value	Units
L_util	Utility outage frequency	0.001	per hour
L_cyber	Utility cyberattack rate	0.0001	per hour
Pinter	Probabiltiy of successful interconnect switch	0.999	none
m_util	Utility restoration rate	0.05	per hour
Pgen	Probability of successful generator start	0.99	none
L_gen	Generator failure rate	0.001	per hour
m_gen	Generator restoration rate	0.025	per hour
F	Fuel consumption rate in liters per hour	1000	liters per hour
Ct	capacity of fuel tank	2.40E+05	liters
L_bat	battry failure rate	0.001	per hour
m_bat	battery repair rate	0.025	per hour
Load	demand on battery in Watts	1000	per hour
Cb	battery capacity in watt hours	20000	Watts

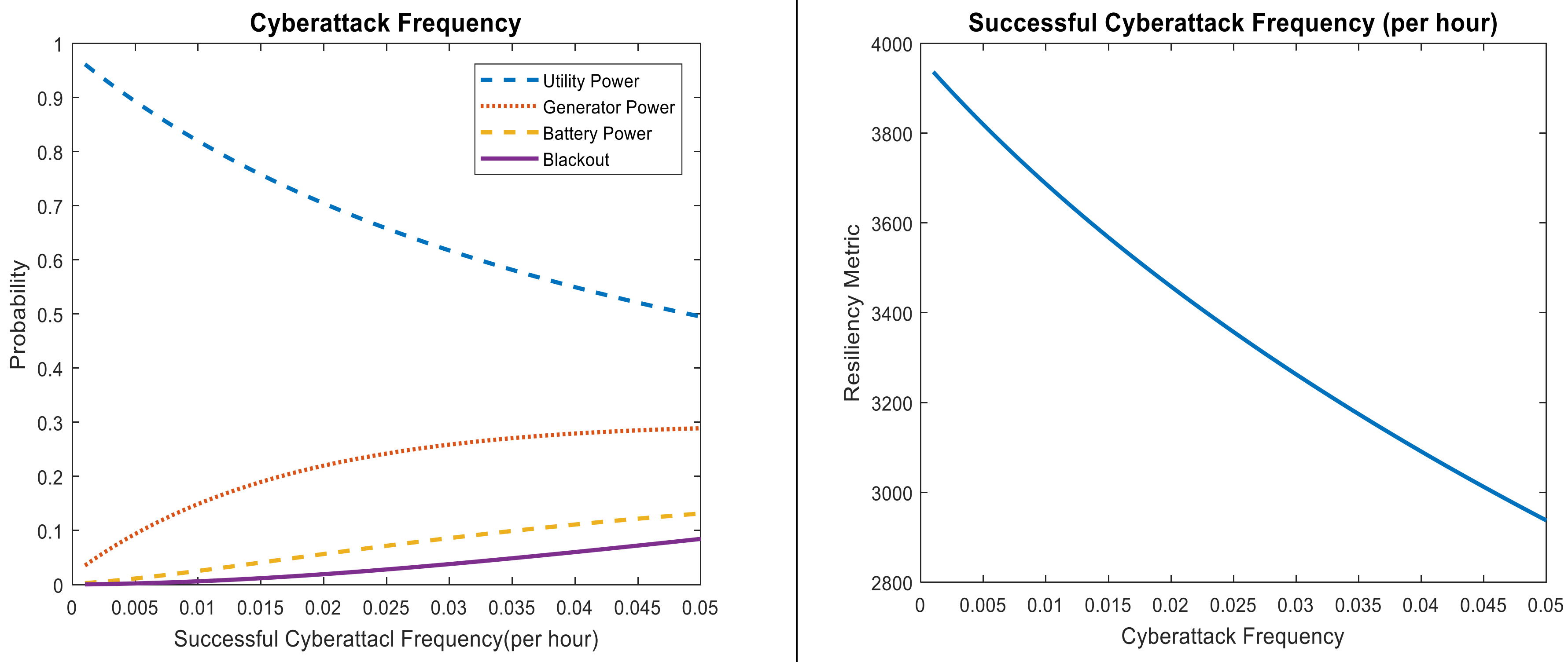
Matlab Function for Constraint Block Microstead1

```
function [PU1, PG1, PB1, PN1, PU2, PG2, PB2, PN2] = microstead1( L_util, L_cyber, Pinter,
m_util, Pgen, L_gen, m_gen,  L_bat, m_bat, F, Ct, Load, Cb)
%Function Microstead1
%M. Hecht  10/24/2017
% Steady State solution Microgrid
%Transition Expressions
E11=-L_util-L_cyber*Pinter -Pinter*Pgen*(L_util+L_cyber);
E21=Pinter*Pgen*(L_util+L_cyber);
E22= -Pgen*(L_cyber+F/Ct+L_gen)-L_gen*(1-Pgen)-m_util;
E31=Pinter*(1-Pgen)*(L_util+L_cyber);
E32=Pgen*(L_cyber+F/Ct+L_gen);
E33=-L_cyber-L_bat-Load/Cb-m_gen;
E41=L_util*(1-Pinter);
E42=L_gen*(1-Pgen);
E43=L_cyber+L_bat+Load/Cb;
E44=-m_util-m_bat-m_gen;

T1=[ 1           1       1       1;
    E11         m_util  m_util  m_util;
    E21         E22     m_gen   m_gen;
    E41         E42     E43     E44];

P=[1 0 0 0 ]';
b1=inv(T1)*P;
PU1=b1(1);
PG1=b1(2);
PB1=b1(3);
PN1=b1(4);
end
```

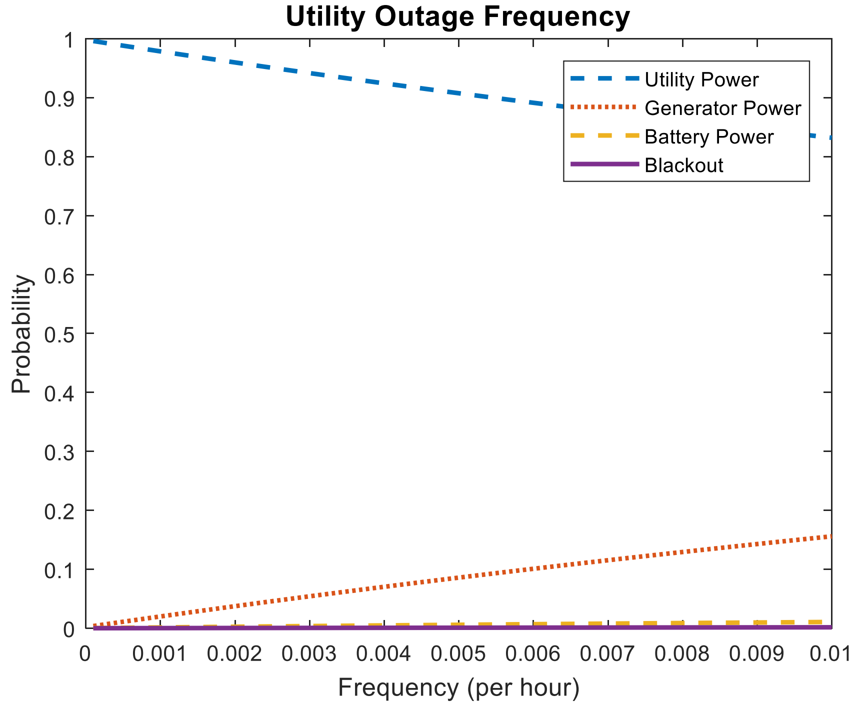
Selected Results:
1. Sensitivity Study on Successful Cyberattack Rate



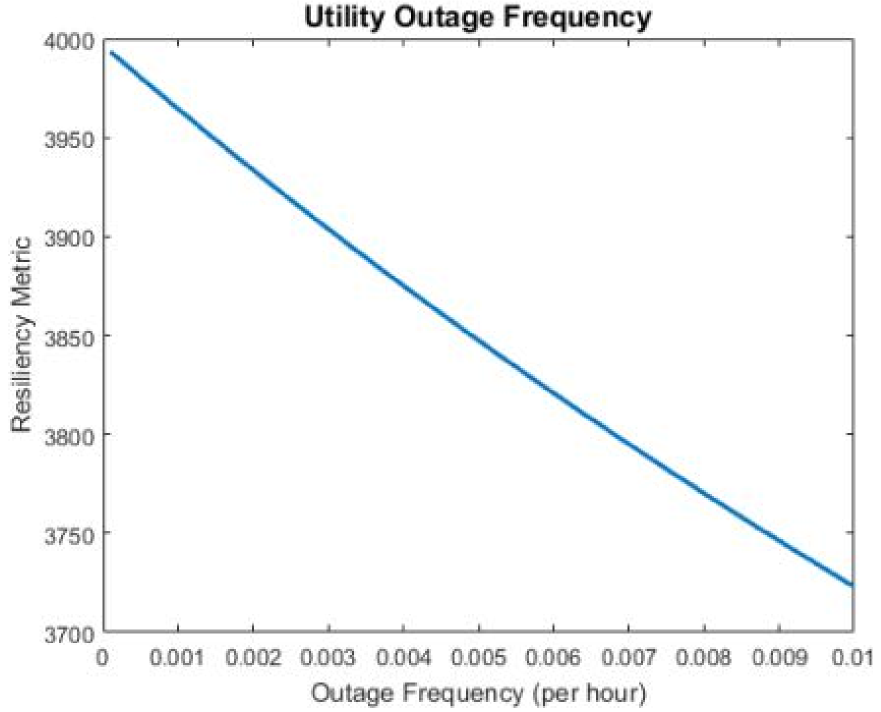
(a) State Probabilities

(b) Resiliency Metric

Selected Results:
2. Sensitivity Study on Utility Power Outage Rate

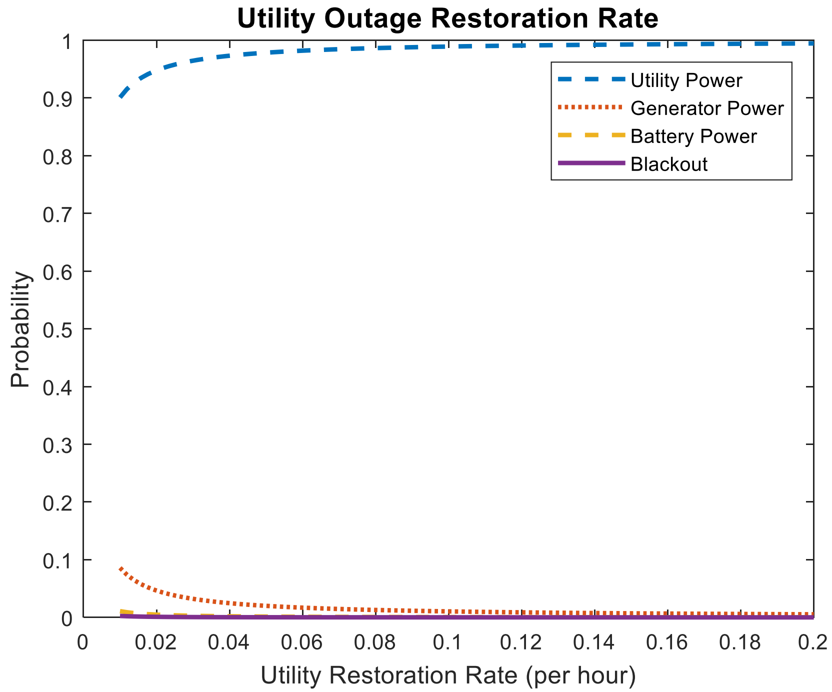


(a) State Probabilities

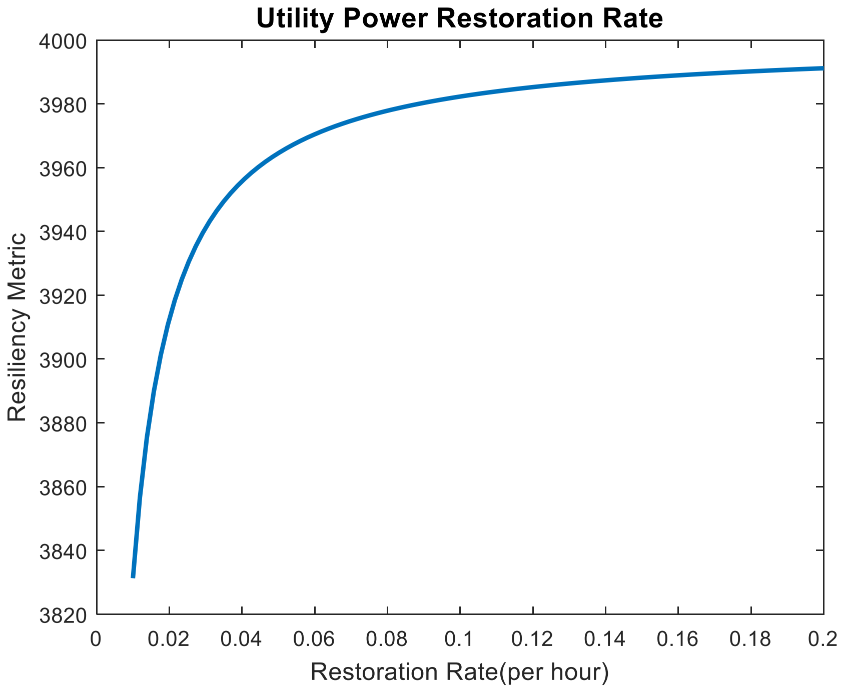


(b) Resiliency Metric

Selected Results:
2. Sensitivity Study on Utility Restoration Rate



(a) State Probabilities



(b) Resiliency Metric

Discussion

- Usefulness: conclusions that can be reached using this model
  - Successful cyberattack rate is the most significant parameter
  - Utilities should strive to keep their average restoration time after an outage to 10 hours (below that, not much significant benefit; above that , disproportionate benefit)
- Limitations:
  - Considers only continuous time events, not discrete events such as battery discharged, diesel storage tanks refilled, etc.
  - Model has only one load and one generator
  - Assumption of exponential assumption (doesn’t model running out of fuel or a battery being drained of energy)
  - Load shedding not considered
  - Input parameter values are not verified
  - The specific analytical model and results are shown for the purposes of illustration of this point. Not intended to be generalized to other systems
- All Models are Wrong, Some Models are Useful

Current Status and Future Work

- Resiliency model has been incorporated into INCOSE Critical Infrastructure Protection and Recovery (CIPR) Working Group reference model (in collaboration with S. Friedenthal)
- Next Steps
  - Refine models to account for extreme events and EMP with separate parameters
  - Add models for solar arrays and gas turbines
  - Add multiple loads and generators to state transition diagrams
  - Investigate use of discrete event simulators

Conclusions

- Quantitative Metrics for Resiliency Can Be Defined
  - Necessary to evaluate current designs, alternatives, and tradeoffs
  - Example was shown for Microgrid measure of performance
  - Can be extended to any other system where MOPs can be defined for degraded states
- MBSE can incorporate resiliency analyses
  - Models can provide the metrics
  - Such models can enable design decisions

References

[1] National Academies of Sciences, Engineering, and Medicine , *Enhancing the Resilience of the Nation's Electricity System* , available online at http://www.nap.edu/, p. 10 (2017)

[2] Object Management Group, “System Modeling Language”, www.sysml.org, specification available at http://sysml.org/sysml-specifications/ (2015)

[3] , Alberto Avritzer, Daniel S. Menasch Javier Alonso, Leandro Aguiar, and Sara G. Alvarez, "WAP: Models and Metrics for the Assessment of Critical-Infrastructure-Targeted Malware Campaigns," in International Symposium on Software Reliability Engineering, Gaithersburg, MD, (2015).

[4] Scott Jackson, Stephen Cook, and Timothy L. J. Ferris, “A Generic State-Machine Model of System Resilience”, *Insight* Magazine, April, 2015, pp. 14-18

[5] *Resilience Engineering* in System Engineering Book of Knowledge version 1.8, http://sebokwiki.org/wiki/System_Resilience, Systems Engineering Research Center (SERC), the International Council on Systems Engineering (INCOSE), and the Institute of Electrical and Electronics Engineers Computer Society (IEEE-CS) March 2017

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