Intelligent Fault Diagnosis and Recovery in Power Electronic Systems

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Outline

- Motivation
- Methodology
  - Simple Logic
  - Fuzzy Logic
- Testing Platform
- Model Validation
- Results
- Conclusions and Future Work

Motivation

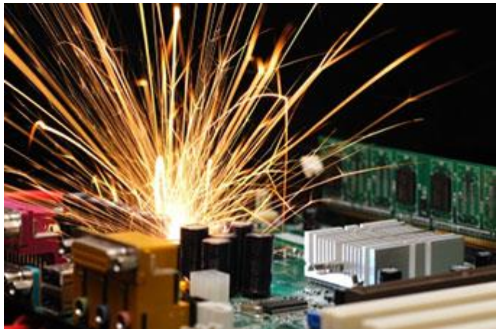
- **Power electronics have penetrated many systems in various fields**
- **Internal and external faults leading to system failures are unavoidable**

Electric ship propulsion system. Source: ship-technology.com

Electric car.
Source: teslamotors.com

Motivation

- The general area of energy systems can have critical applications where loss of energy conversion cannot be tolerated
- Of interest are power electronic systems that can:
  - Recover and self heal
  - Adapt to their surrounding
  - Achieve high reliability
  - Have local intelligent control



Failing capacitor
Source: clemson.edu

IGBT Failure
Source: microwaves101.com

Motivation

- There exist several fault diagnosis methods in energy systems, utilizing:
  - Fuzzy control theory
  - Wavelet theory
  - Random forests and hidden Markov models
  - D-Matrices, etc.

- There is need to tie some of the fault diagnosis ideas with power electronic systems
- There is also need to achieve a recovery strategy

Methodology

- For fault diagnosis, information is needed about the converter under study:
  - Model-based approach
  - Sensor-based approach
  - Combination of both

- Sensors are useful for near-real-time monitoring but:
  - Minimal additional sensors should be introduced for cost purposes
  - Simple and cost-effective sensors are more desirable

Methodology

- Recovery can be achieved using a parallel converter:
  - The parallel converter should not be stressed as the primary converter
  - There is no need to have duplicate controllers, sensors, and circuit boards
  - It is logical to utilize parallel power components in the same converter instead.
  - Safety-critical systems and many other systems accept some cost increase for reliability
  - Parallel components should be offline until engaged to replace a failed component

Methodology

- **Assumptions:**
  - **The system has slow dynamics to achieve a new set point –Many power electronic applications have fast switching dynamics but slow set point changes (e.g. solar micro-inverter)**
  - **There exists basic sensing capability in the system**
  - **Power electronic topology is known, not a black box**
  - **Faults occur in components, failures occur in the system after certain faults. Component faults can be considered as failures at a component level**

Methodology

- ***Define the following:***
- ***M*** **measurements exit for essential voltages and/or currents.**
- ***P*** **quantities are evaluated per measurement**
- **Thus,** ***Q*** **measured quantities where** $Q = M \times P$
- ***N*** **components are susceptible to faults**
- **Each component has** ***K*** **fault conditions**
- **Thus,** ***Y*** **different faults could occur in the system, where** $Y = N \times K$**.**

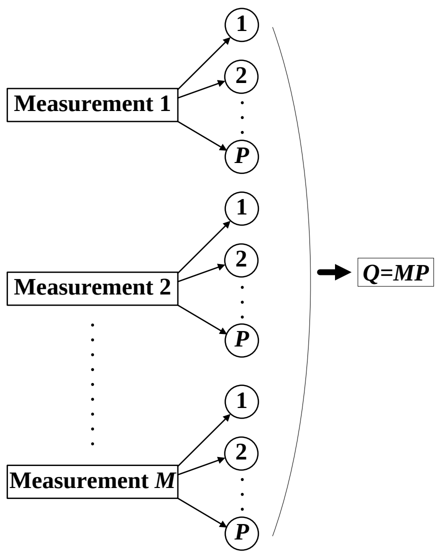
Methodology

Simple Logic

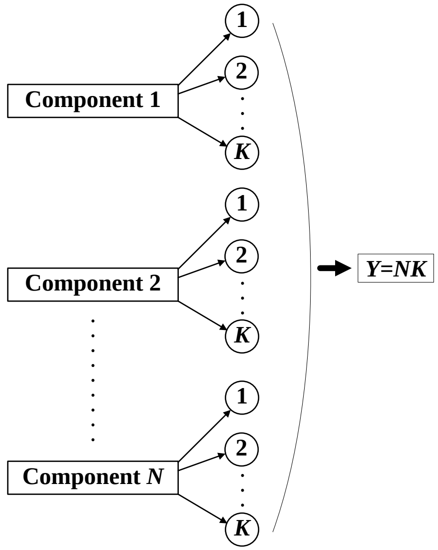
- **A measured quantity is assessed online or in real-time and compared to a pre-determined threshold.**
- **A decision is made by comparing each of the *Q* quantities to its respective threshold.**
  - ***Example: an average voltage changes by a certain % from the expected nominal***
- **Threshold comparison yields a logic result: 1 or 0**
  - **1: *Q* is more than the acceptable threshold**
  - **0: *Q* is less than the acceptable threshold**
- **The decision for *Q* inputs takes the form of a *Q*-bit number: $Z = 2^Q - 1$ combinations per fault.**

Methodology

Simple Logic



Measurements and related quantities

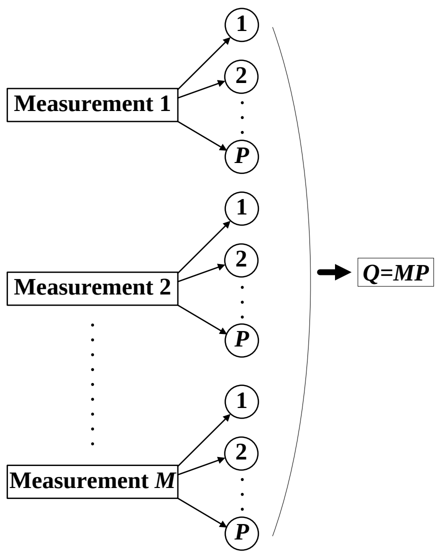


Components' fault conditions

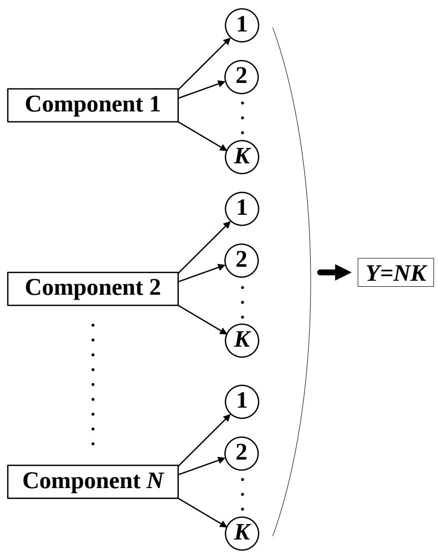
	f_{11}	…	f_{1K}	f_{21}	…	f_{2K}		f_{N1}	…	f_{NK}
q_{11}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
⋮	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{1P}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{21}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
⋮	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	…	c_{ij}	c_{ij}	c_{ij}
q_{1P}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{M1}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
⋮	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{MP}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}

Methodology

Simple Logic



Measurements and related quantities



Components' fault conditions

		L		D_2		S_2		C		S_B		$S_{B'}$	
		O	S	O	S	O	S	O	S	O	S	O	S
I_L	RMS	1	0	0	1	1	1	1	1	0	1	1	1
	MEAN	1	0	0	1	1	1	1	1	1	1	1	1
	THD	1	1	1	1	1	1	1	1	1	0	1	1
V_{S2}	RMS	1	0	1	0	0	1	1	0	0	0	0	0
	MEAN	1	0	0	0	0	1	0	0	0	0	0	0
	THD	1	1	1	1	1	1	1	1	1	0	1	1
V_C	RMS	1	0	1	1	1	1	1	1	0	1	0	1
	MEAN	1	1	1	1	1	1	1	1	1	1	1	1
	THD	0	0	1	1	0	1	1	0	1	1	1	1
V_B	RMS	1	0	1	0	1	1	1	1	1	1	1	0
	MEAN	1	0	1	1	1	1	0	1	0	1	0	0
	THD	0	0	0	1	0	0	1	1	1	1	1	0
$V_{B'}$	RMS	1	0	1	0	1	1	1	1	1	0	1	1
	MEAN	1	0	1	1	1	1	0	1	0	0	0	1
	THD	0	0	0	1	0	0	1	1	1	0	1	1

Methodology

Simple Logic

- **If two rows are identical, then one of the measured quantities can be eliminated (redundant information)**
- **If two or more columns are identical → two or more faults should both be reported**

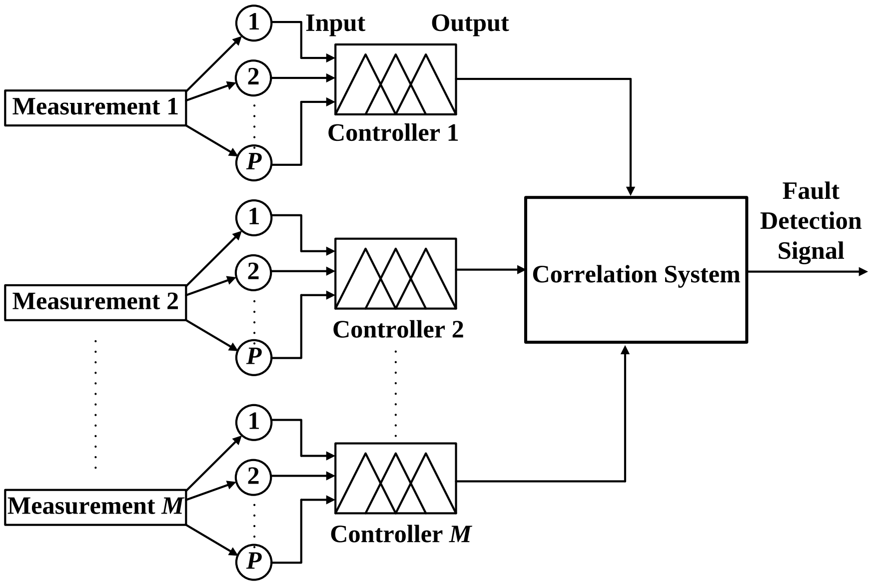
	f_{11}		f_{1K}	f_{21}		f_{2K}		f_{N1}		f_{NK}
q_{11}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{1P}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{21}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{1P}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{M1}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}
q_{MP}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}		c_{ij}	c_{ij}	c_{ij}

- **Advantage: simple implementation**
- **Disadvantage: threshold wait time and sensitivity to threshold selection**

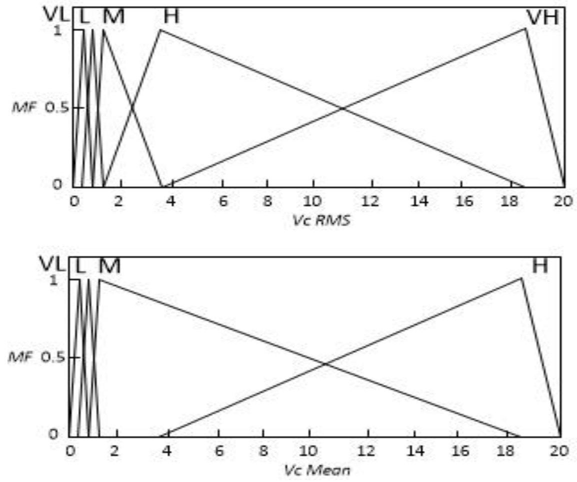
Methodology
Fuzzy Logic

- Measured quantities vary with time and waiting for a threshold might not be practical
- Membership functions can be defined for ranges of various quantities
- Decisions can be made on "how close" is the combination of various quantities to a specific fault condition
- Advantage: faster response, more intelligent decision making
- Disadvantage: model-based and requires significant setup time

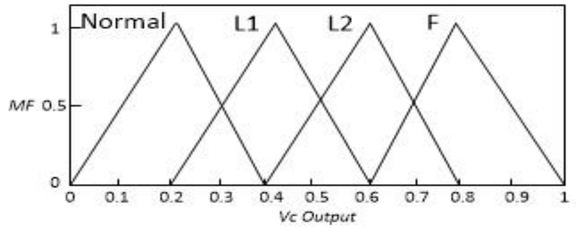
Methodology
Fuzzy Logic



Fuzzy Logic System



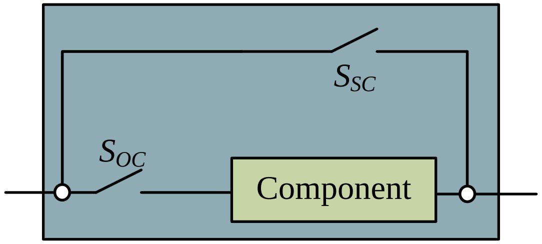
Input membership function

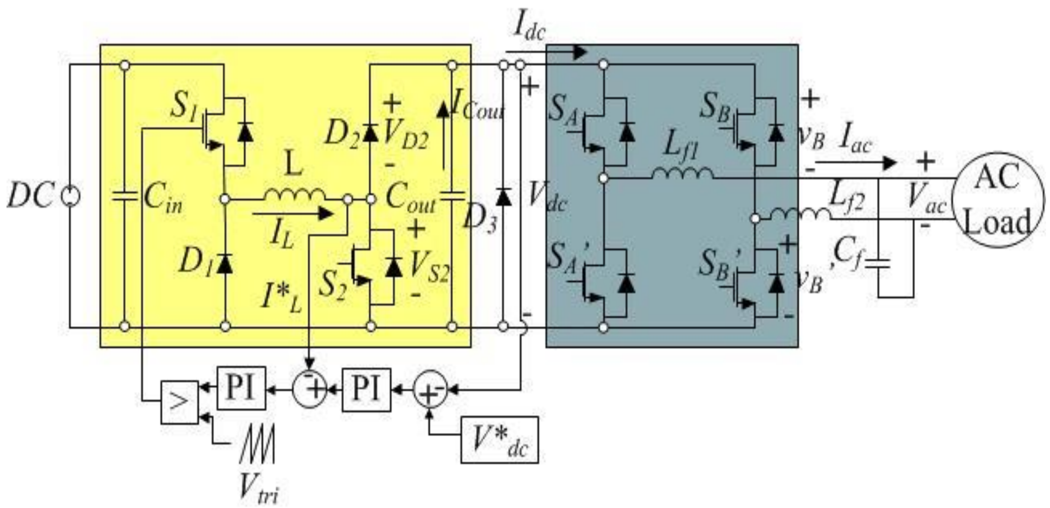


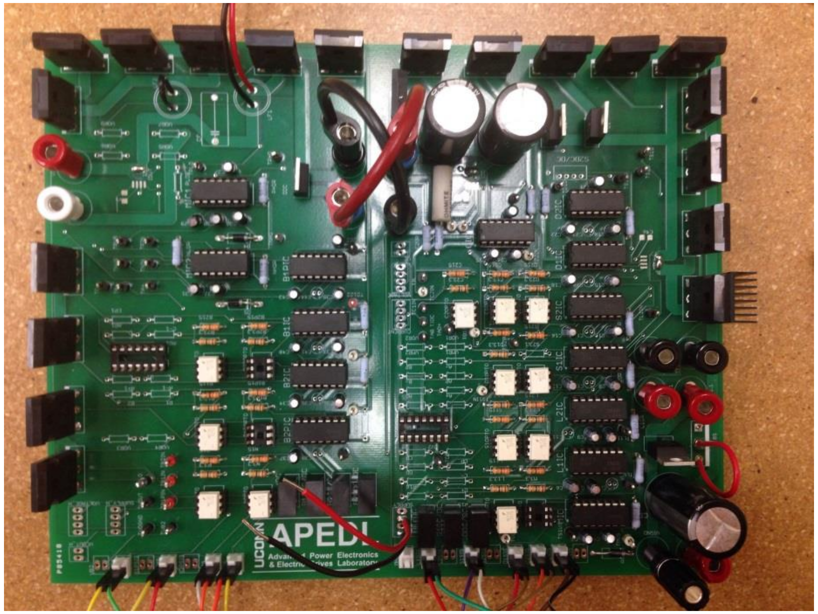
Output membership function

Testing Platform

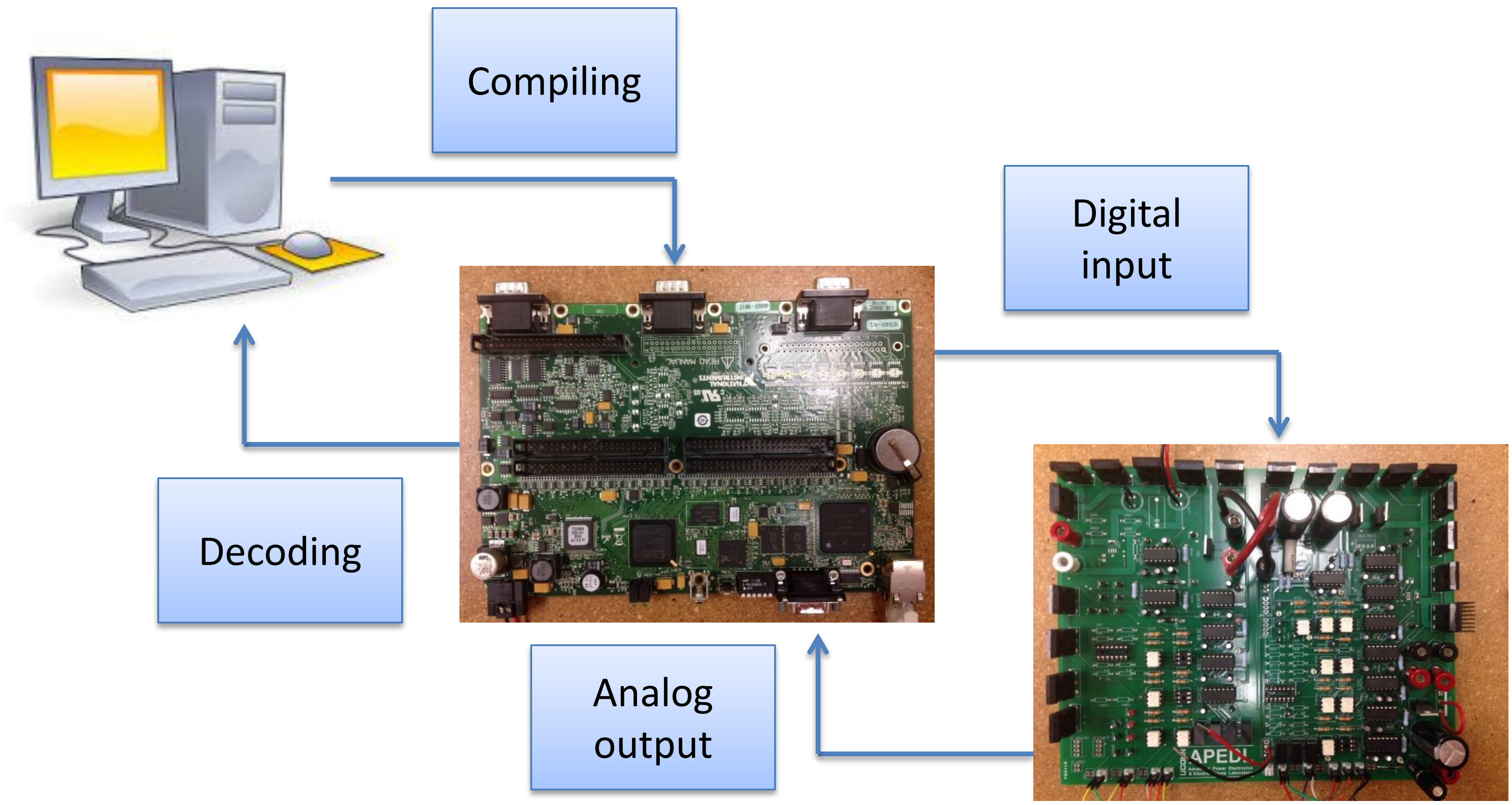
- **Solar PV micro-inverter**
- **Includes DC/DC and DC/AC stages**
- **Open- and short-circuit faults are mimicked using series and parallel switches**





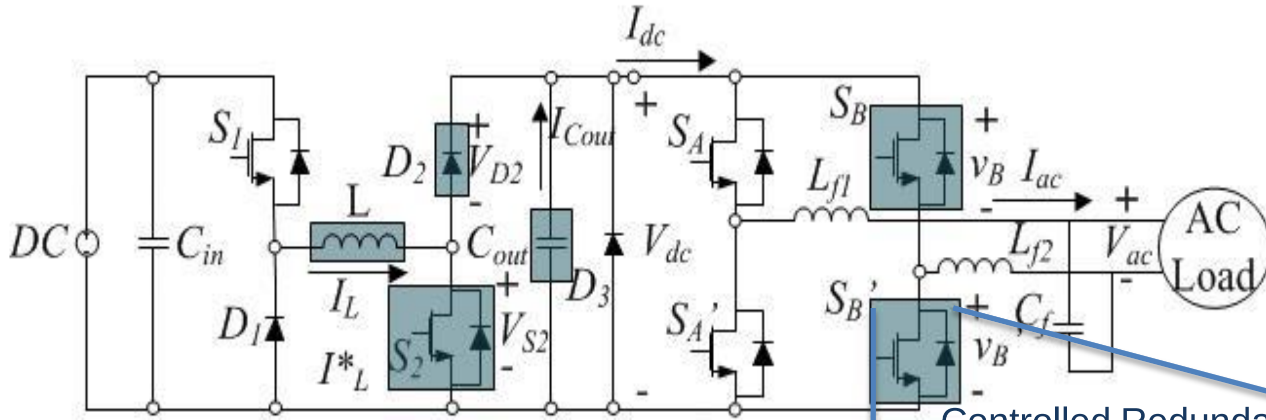


Testing Platform

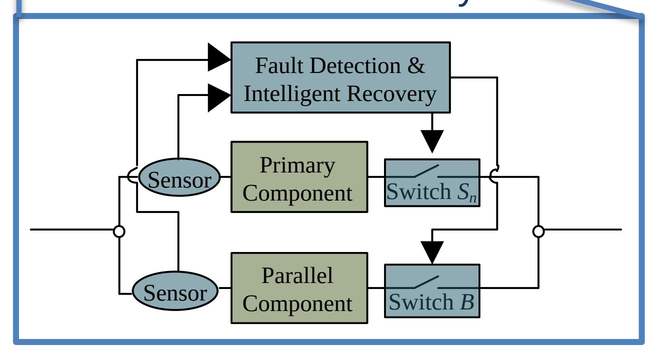


Testing Platform

- **Redundant power components are introduced in highlighted components**



Controlled Redundancy

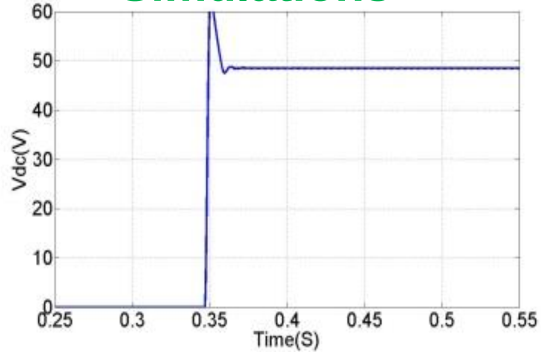


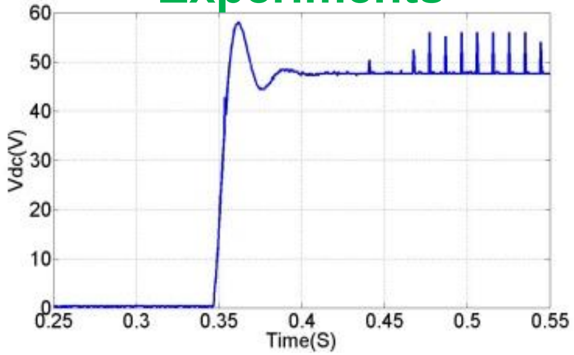
- **Redundant components are engaged using a decision made by the fault diagnosis algorithm**

Model Validation

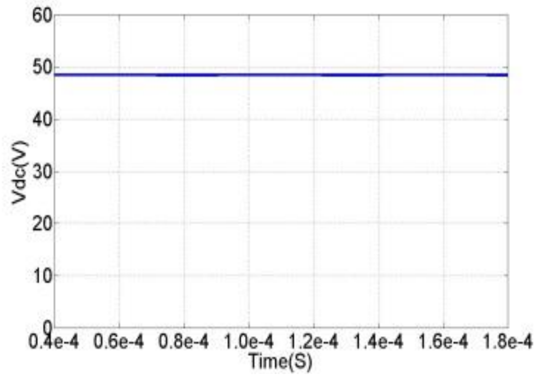
Converter (Plant) with Open-Loop Control

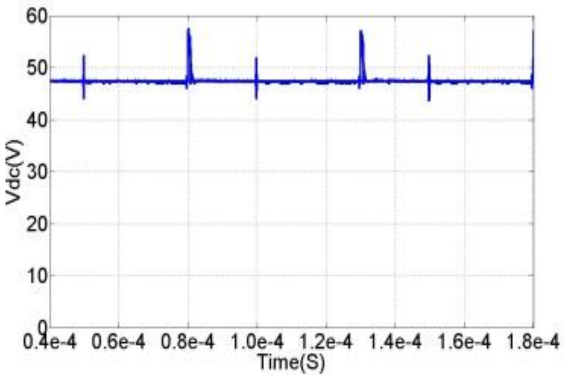
Simulations | **Experiments**





DC/DC converter nominal output voltage



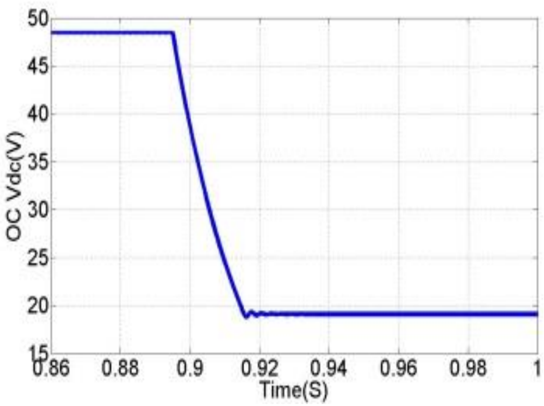


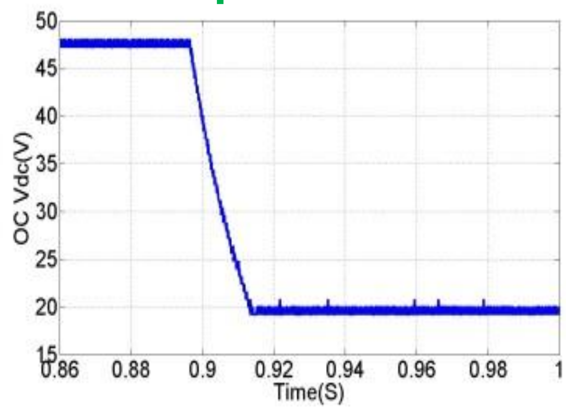
Steady-state of DC/DC converter nominal output voltage

Model Validation

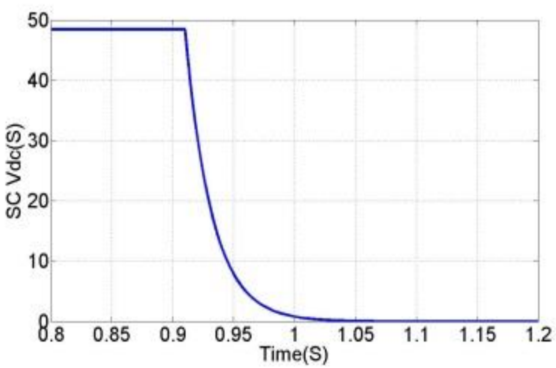
Converter (Plant) with Open-Loop Control

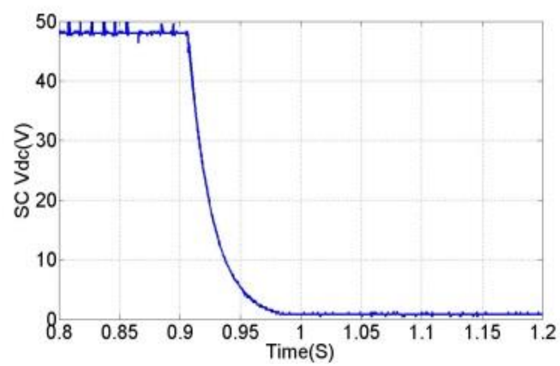
Simulations | **Experiments**





MOSFET OC condition



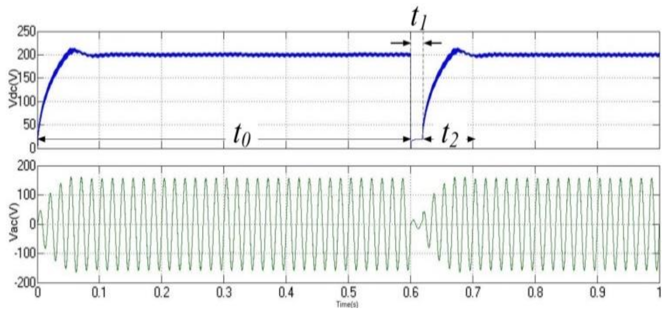


MOSFET SC condition

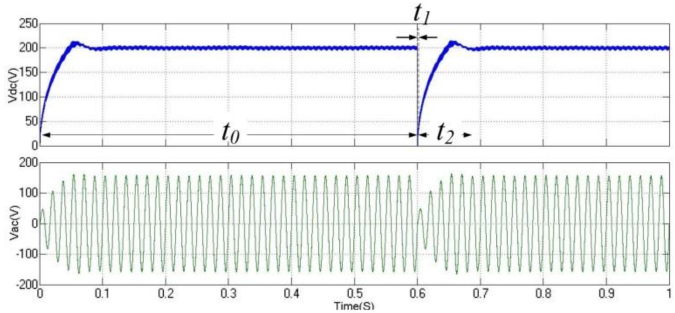
Results

Simple Logic

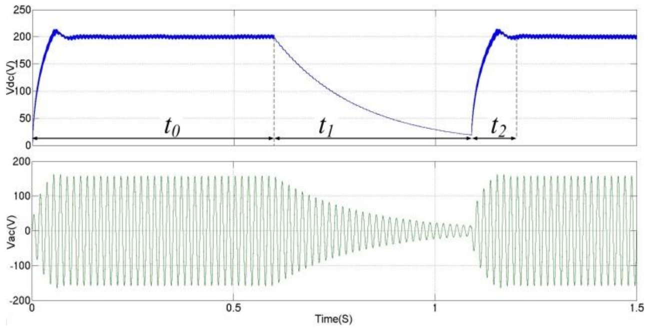
Fuzzy Logic



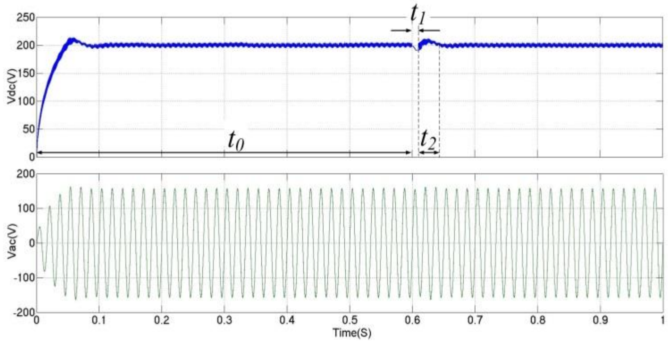
C_{out} SC



C_{out} SC



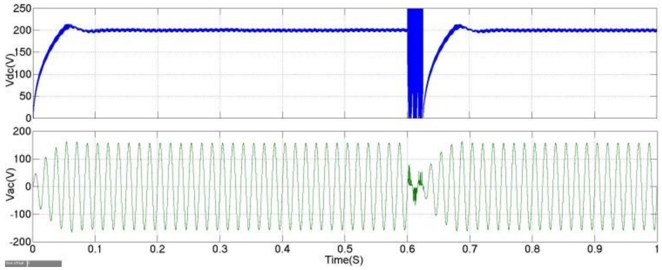
S_2 OC



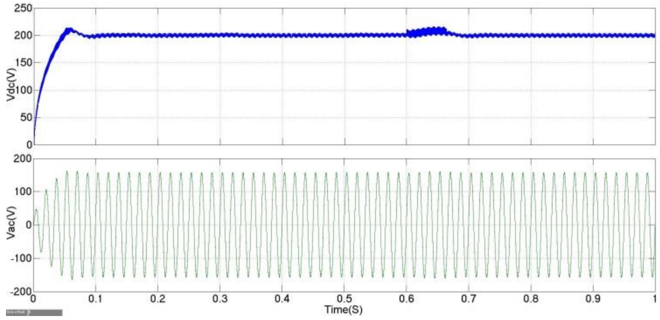
S_2 OC

Results

Simple Logic

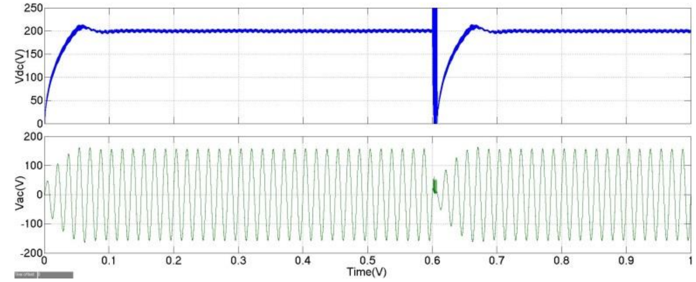


C_{out} OC

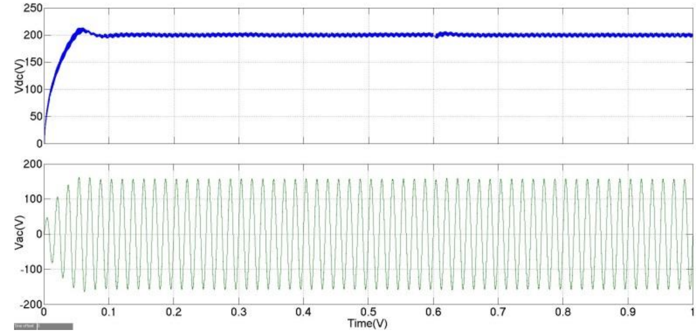


L SC

Fuzzy Logic



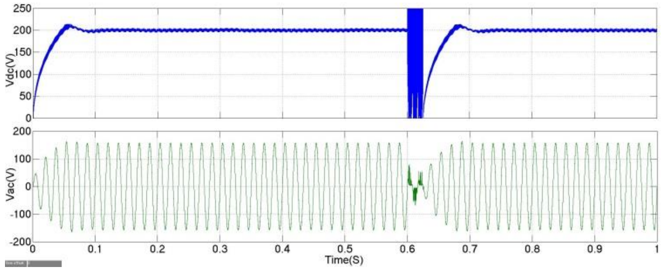
C_{out} OC



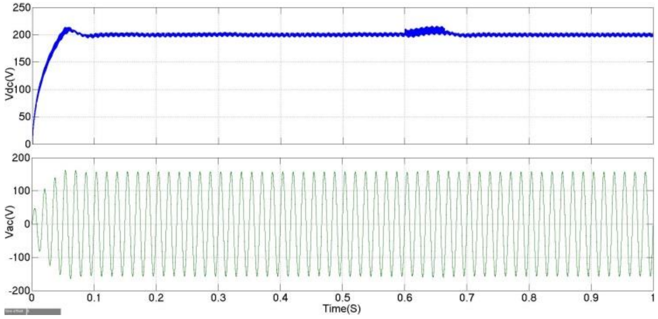
L SC

Results

Simple Logic

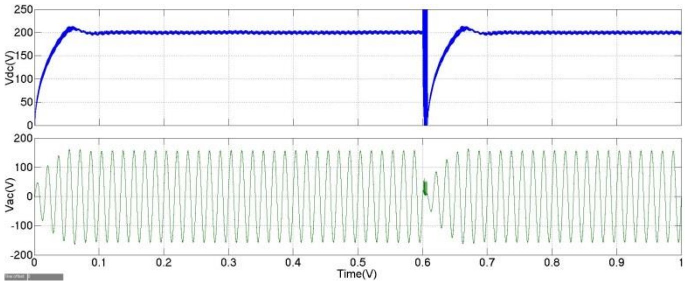


C_{out} OC

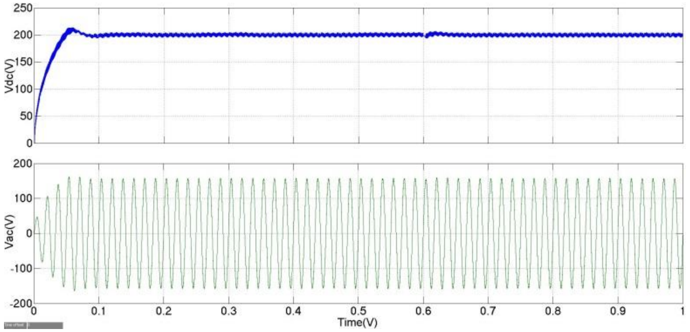


L SC

Fuzzy Logic



C_{out} OC



L SC

Results

Simple Logic

	Fault Occurrence Time t_0 (s)	Fault Detection Time t_1-t_0(s)	Fault Recovery Time t_2-t_1(s)
L OC	0.6	0.4875	0.0424
D_2 OC	0.6	1.1878	0.0639
S_2 OC	0.6	0.4897	0.0441
C_{out} OC	0.6	0.0255	0.0643
S_B OC	0.6	0.0472	0.0161
$S_{B'}$ OC	0.6	0.0394	0.0159
L SC	0.6	0.0660	0.0056
D_2 SC	0.6	0.0167	0.0636
S_2 SC	0.6	0.9835	0.2377
C_{out} SC	0.6	0.0195	0.0631
S_B SC	0.6	0.0165	0.0618
$S_{B'}$ SC	0.6	0.0165	0.0629

Fuzzy Logic

Method	Fault Occurrence Time t_0 (s)	Fault Detection Time t_1-t_0(s)	Fault Recovery Time t_2-t_1(s)
L OC	0.6	0.0080	0.0450
D_2 OC	0.6	0.0100	0.0300
S_2 OC	0.6	0.0088	0.0312
C_{out} OC	0.6	0.0080	0.0643
S_B OC	0.6	0.0130	0.0070
$S_{B'}$ OC	0.6	0.0130	0.0070
L SC	0.6	0.0035	0.0065
D_2 SC	0.6	0.0083	0.0717
S_2 SC	0.6	0.0067	0.0133
C_{out} SC	0.6	0.0066	0.0631
S_B SC	0.6	0.0165	0.0618
$S_{B'}$ SC	0.6	0.0165	0.0629

Conclusions & Future Work

- Both methods show ability to accurately diagnose faults and engage redundancy
- Faster diagnosis time is achieved with the more intelligent fuzzy logic, at the cost of setup time
- Recovery time is independent of the diagnosis method as it depends on the system response
- A special case is when the fault is detected while the system is still close to nominal operation
- Implementation on an FPGA is currently in progress

Questions?