

Dr. Robert S. Balog ◀

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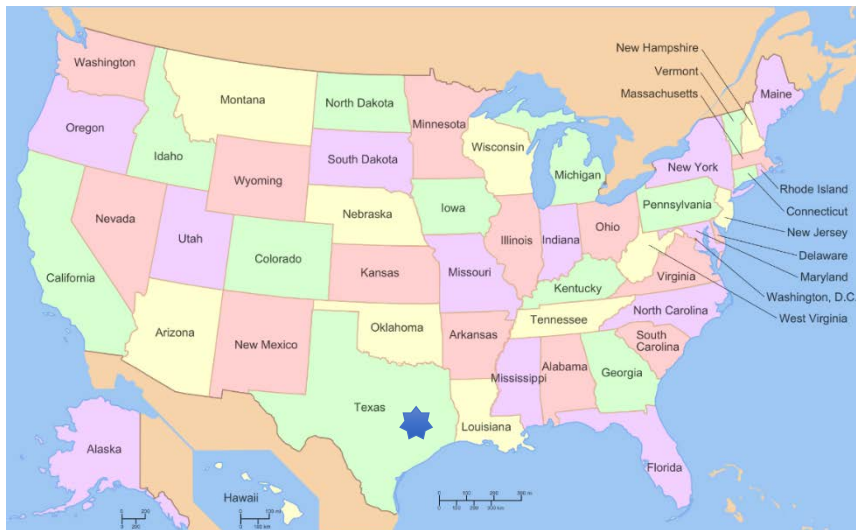
Arc Fault and Flash Detection in Photovoltaic and Building Wiring Systems – Detecting Electrical Safety Problems, Making the Electrical System Safer for the Customer

TECHNICAL SESSION 6

SREDS19 · DOHA, QATAR · DEC. 2, 2019



Texas A&M University



- Established in 1876 as the first public college in Texas
 - Morrill Land-Grants Act
 - Land, Sea, Space grant public institution.
 - Opened as the Agricultural and Mechanical College of Texas
 - Renamed in 1963 and began admitting women
- In 2003, opened branch campus (TAMU-Q) in Doha, Qatar

- Enrolls over 50,000 students in 10 academic colleges.
- Longitude: -96.364, Latitude: 30.589
- Campus area: 5,200 acres (21 km²)
- Time Zone: Central Time (UTC – 6:00)
- Today's weather forecast:
 - College Station: 61F (16C) high, 38F (3C) low
 - Qatar: 79F (26C) high, 64F (18C) low



TAMU Electric Power & Power Electronics

Faculty:

- Robert Balog (Power Electronics)
- Kate Davis (Power Systems)
- Miroslav Begovic (Power Systems)
- Karen Butler-Purry (Power Systems)
- Mehrdad Ehsani (Power Electronics)
- Prasad Enjeti (Power Electronics)
- Garng Huang (Power Systems)
- Mladen Kezunovic (Power Systems)
- Tom Overbye (Power Systems)
- B. Don Russell (Power Systems)
- Chanan Singh (Power Systems)
- Hamid Toliyat (Power Electronics)
- Le Xie (Power Systems)

Research Laboratories:

- Renewable Energy & Advanced Power Electronics Research (REAPER) Laboratory
- Electric Machines and Power Electronics (EMPE) Laboratory
- Power Electronics and Clean Power Research Laboratory
- Power Electronics & Motor Drives Laboratory
- Power Engineering Laboratory
- Power System Automation Laboratory
- Power System Control and Protection Laboratory

Total Tenure/Tenure Track Faculty in USA: 13

Power Systems and Power Electronics Classes

Graduate courses

- ECEN 611 General Theory of Electromechanical Motion Devices
- ECEN 612 Comp. Aided Design of Electromech. Motion Devices
- ECEN 613 Rectifier and Inverter Circuits
- ECEN 614 Power System State Estimation
- ECEN 615 Methods of Electric Power Systems Analysis
- ECEN 616 Power System Electromagnetic Transients
- ECEN 630 Analysis of Power Electronic Systems
- ECEN 632 Motor Drive Dynamics
- ECEN 643 Electric Power System Reliability
- ECEN 666 Power System Faults and Protective Relaying
- ECEN 667 Power System Stability
- ECEN 668 High Voltage Direct Current Transmission
- ECEN 677 Control of Electric Power Systems
- ECEN 679 Computer Relays for Electric Power Systems
- ECEN 686 Electric and Hybrid Vehicles
- ECEN 710 DC-DC Converters
- ECEN 711 Sustainable Engineering and Vehicle Engineering
- ECEN 712 Power Electronics for Photovoltaic Energy Systems ★

- ECEN 715 Physical and Economical Operations of Sustainable Energy Systems
- ECEN 738 Power Electronics ★
- ECEN 741 Electric Motor Drives
- ECEN 442 DSP-Based Electromechanical Motion Control

Undergraduate courses

- ECEN 338 Electromechanical Energy Conversion
- ECEN 340 Electrical Energy Conversion
- ECEN 438 Power Electronic ★
- ECEN 441 Electric Motor Drives
- ECEN 442 DSP-Based Electromechanical Motion Control
- ECEN 459 Power System Fault Analysis and Protection
- ECEN 460 Power System Operation and Control

enrolls 160 students
every fall semester

★ Courses
I teach

About the Speaker

- Associate Professor (with tenure), Texas A&M University, College Station USA, **joint appointment** with **Texas A&M University at Qatar (since 2015)**
- 1996, BS. Electrical Engineering, Rutgers University USA
- 2006, Ph.D. Power Electronics, University of Illinois, Urbana-Champaign USA

Experience:

- Research / R&D experience in power electronics since 1996 (**PV since 2001**).
- 3 yrs *industry* developing microinverter and power electronics systems for residential systems (**SolarBridge Technologies, acquired by SunPower 2014, Enphase 2018**), secured initial \$6MM venture capital
- 3 yrs *industry* developing lighting controls (**Lutron Electronics**)
- Consulting: **U.S. Army CERL**, various companies; int'l: **Turkey, Qatar, Turkmenistan**
- **18 issued U.S. patents** (17 directly related to PV systems) + addt'l pending
- 160+ IEEE internationally peer-reviewed conference and journal articles in power electronics
- 1 book, 2 book chapters
- **Technical Program Chair 2016 IEEE Energy Conversion Congress and Exposition**
- Voting member of **PV standards groups: UL 1741 and UL 1699B**

Select Awards:

- 2019 Elected as Senior Member, National Academy of Inventors
- 2018-2019 Distinguished Lecturer, IEEE Power Electronics Society
- 2017 Texas A&M Engineering Patent Award
- 2011 Rutgers Distinguished Engineer Award
- 2011 Admitted into the Hungarian Academy of Science (external body)
- 2007 Elevated to Senior Member, IEEE Power Electronics Society



Past Technology Transfer Projects

- SolarBridge™ PV microinverter – University of Illinois startup
 - SmartSpark Energy Systems, became SolarBridge (2008)
 - raised a total of [\\$105.1M](#) in funding in [7](#) rounds
 - 2014 acquired by SunPower (NASDAQ: SPWR)
 - In 2018, 80% of it's residential PV modules sold had a microinverter attached
 - 2018 sold to Enphase (NASDAQ: ENPH)
- SolarAgs™ myPVhouse™ smartphone app
 - NSF project to DOE Sunshot Catalyst accelerator (2015)
 - Functional MVP pitched to VCs in Galvanize, San Francisco USA.
 - Feb 2019, Aurora Solar (myPVhouse™ competitor) secured \$20M in VC financing

About My Research Program

power conversation at the grid edge™

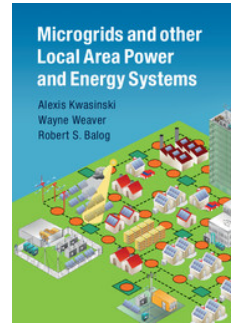
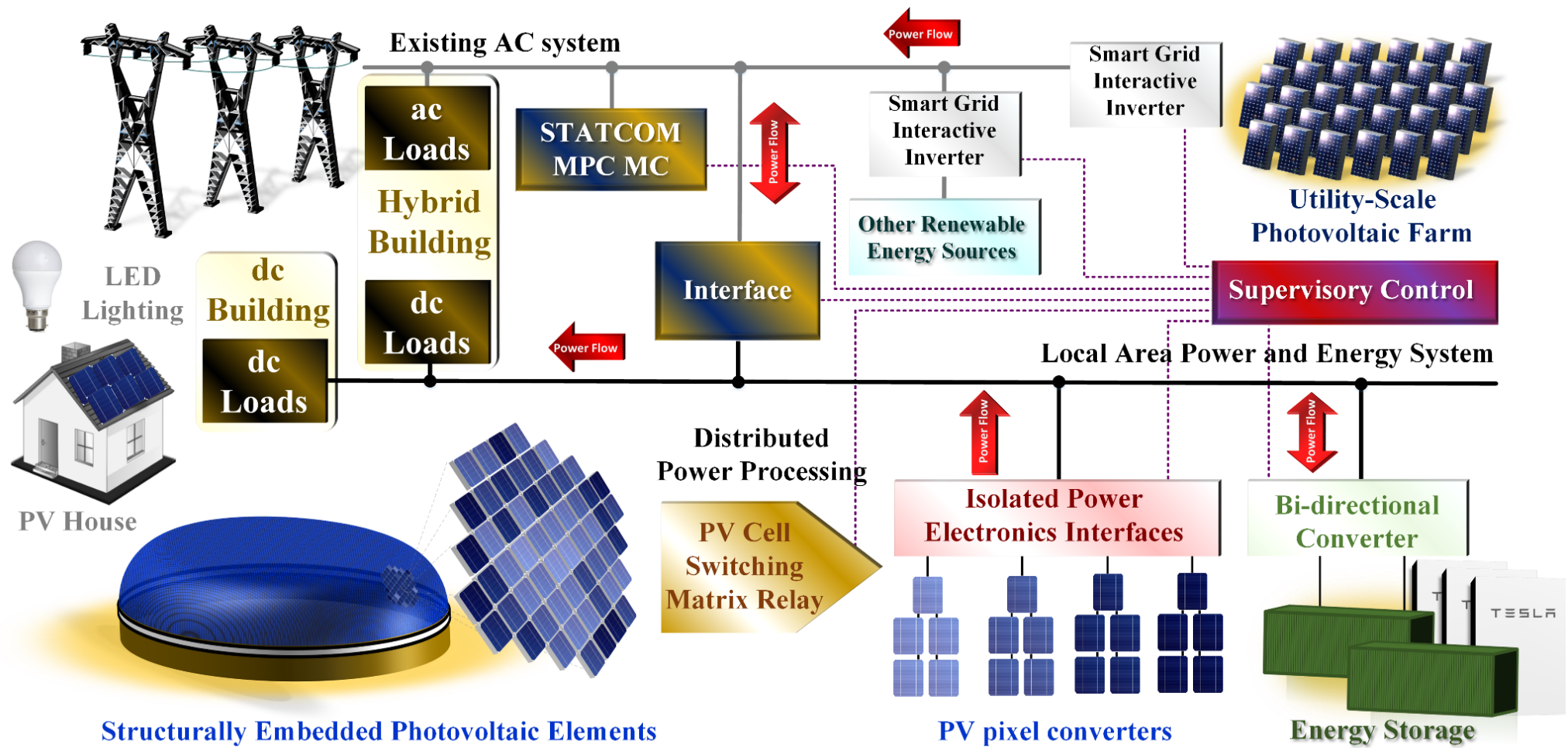
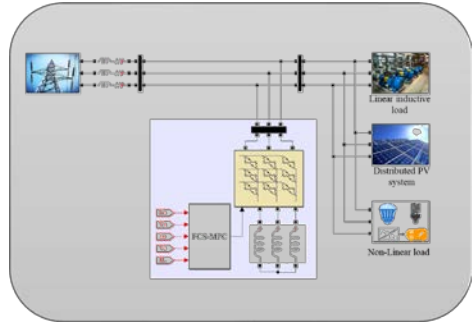
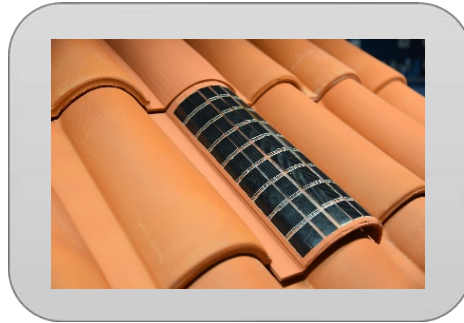


Illustration credit: Morcos Metry

Selected Research Portfolio



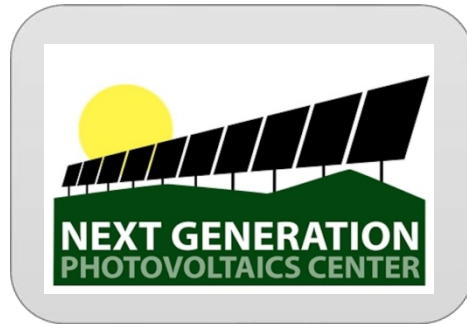
Fault tolerant, capacitor-less power quality compensator for electrical distribution systems



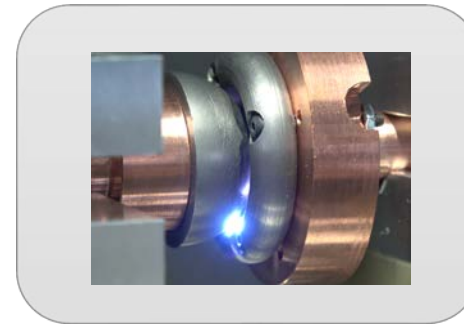
Smart PV Skin for grid-connected, non-planar photovoltaic systems



ARC fault detection for DC systems (PV / battery storage)



National Science Foundation Industry/University Cooperative Research Center for Photovoltaics



Automated arc generator testbed

Photovoltaic Energy Systems Potential

Development / Progress for environment and economy



Disaster / Setback



Walmart roof fire, USA

Fires Attributable to PV Make Headlines

NEW Solar Panel Mounting with S-5 PVKIT™ & ProteaBracket™
ProteaBracket can be used for rail or direct attach™ with new and improved S-5 PVKIT 2.0

Netherlands begins inquiry into fire accidents involving rooftop PV

The investigation will be carried out by the Netherlands Organisation for Applied Scientific Research on behalf of the national enterprise agency and at the request of PV association Holland Solar and Unetovnl, the country's installers' association.



A series of incidents involving fires on Dutch rooftops with PV systems may have been caused by the summer's extreme temperatures, according to speculation.
Image: Flickr, Marufish

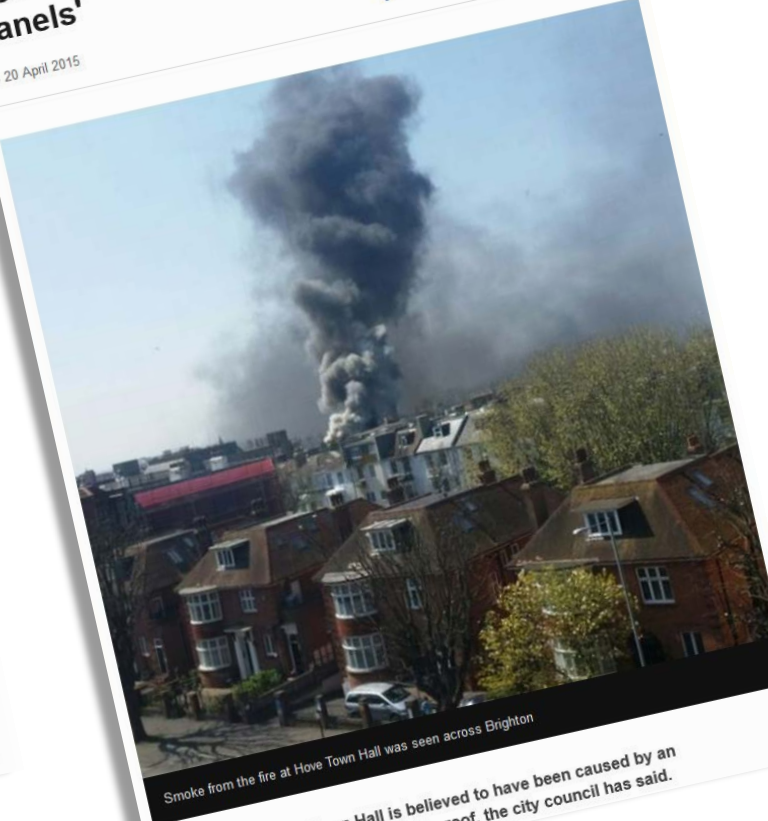
Solar PV fires predominantly caused by installer error, government report concludes



A recent fire in Bow Wharf was largely blamed on faulty solar panels, despite London Fire Brigade stating an investigation was still to be carried out. Image: Twitter/Andrew Bannister.

Hove town hall fire 'caused by solar panels'

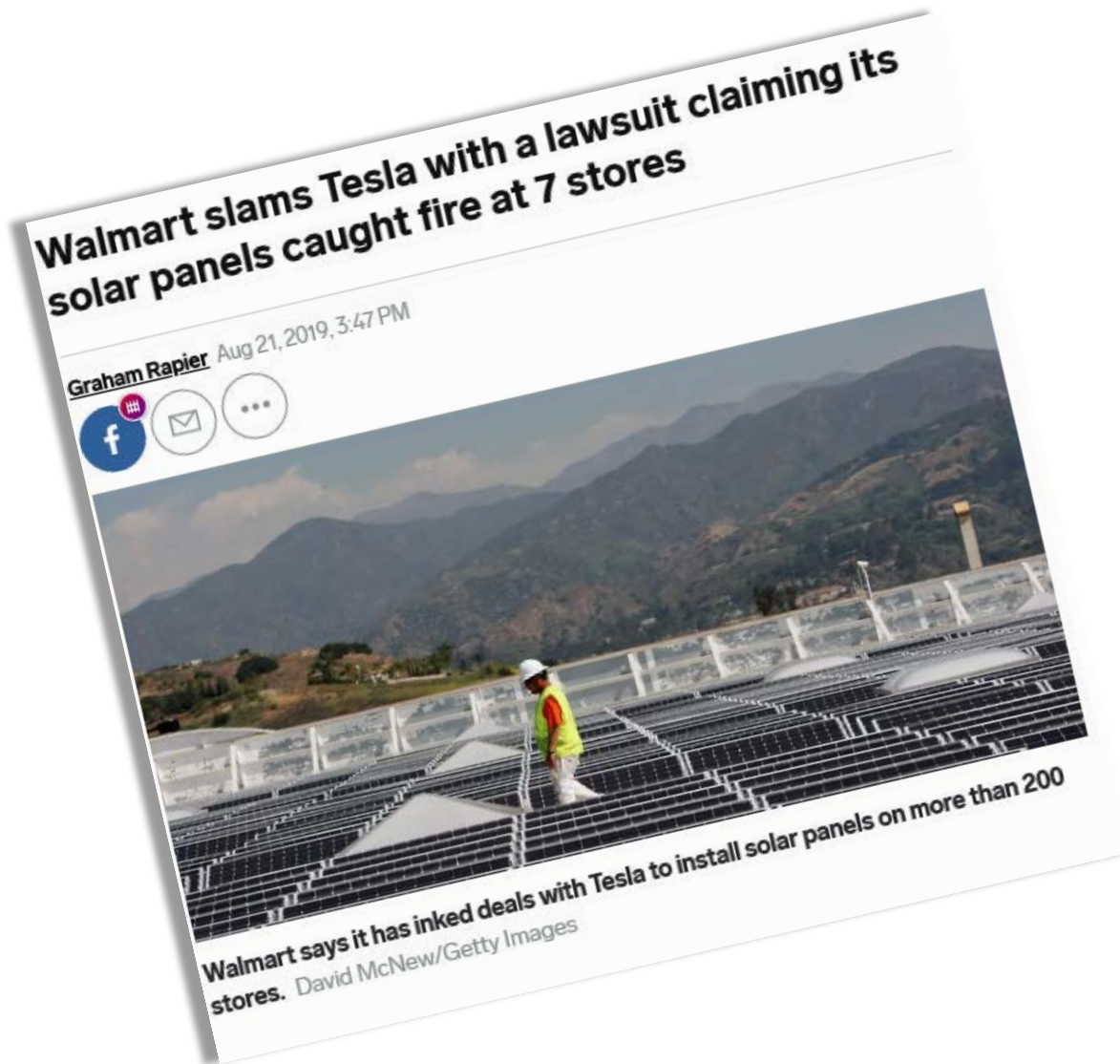
© 20 April 2015



Smoke from the fire at Hove Town Hall was seen across Brighton

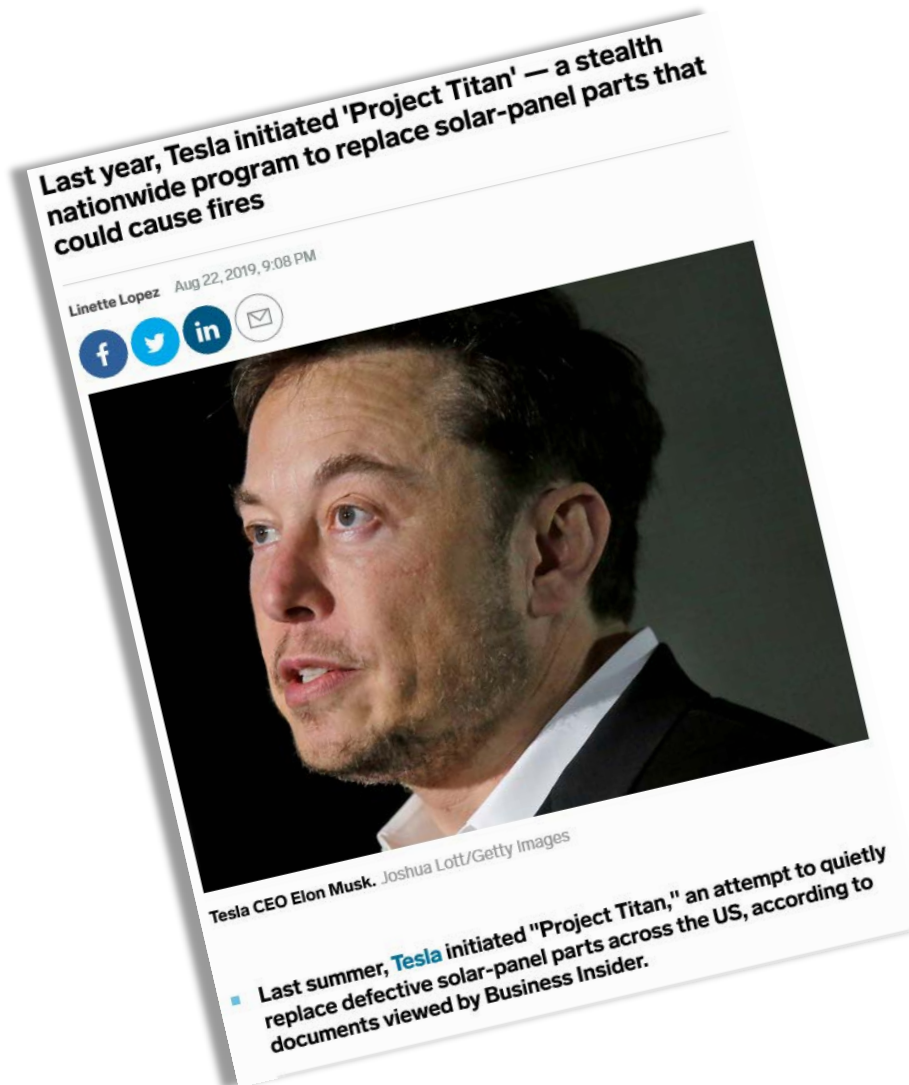
A large fire at Hove Town Hall is believed to have been caused by an electrical fault in solar panels on the roof, the city council has said.

Economic Impact of PV Fires



- Walmart has more than 240 stores with Tesla-supplied solar-energy systems.
- "As of November 2018, no fewer than seven Walmart stores had experienced fires due to Tesla's solar system," August 2019 lawsuit.
- Walmart suit alleged "chaotic installation practices" and for lacking "adequate quality-control checks or supervision protocols."
- Settlement reached November 6th

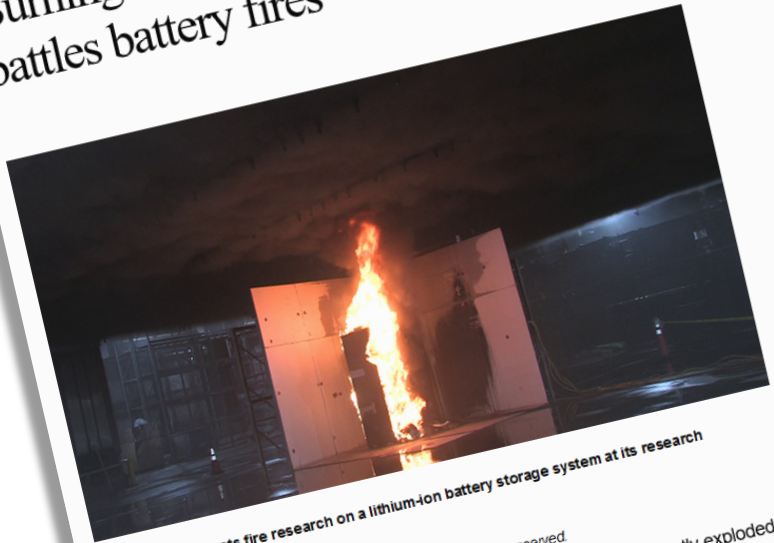
Damage Control



- The problem isn't necessarily specific to the PV cells or module technology.
- Connectors, which existed in the market for many years, seemed to be the main contributor to Tesla's woes.
- Tesla's secret "Project Titan" to replace faulty equipment.
- A better / safer PV cell is not sufficient. Entire supply chain is involved in the root hazard.

Fires Also Occur in Batteries

Burning concern: Energy storage industry battles battery fires



FM Global conducts fire research on a lithium-ion battery storage system at its research center in West Gloucester, Rhode Island.

Source: © 2019 FM Global. Reprinted with permission. All rights reserved.

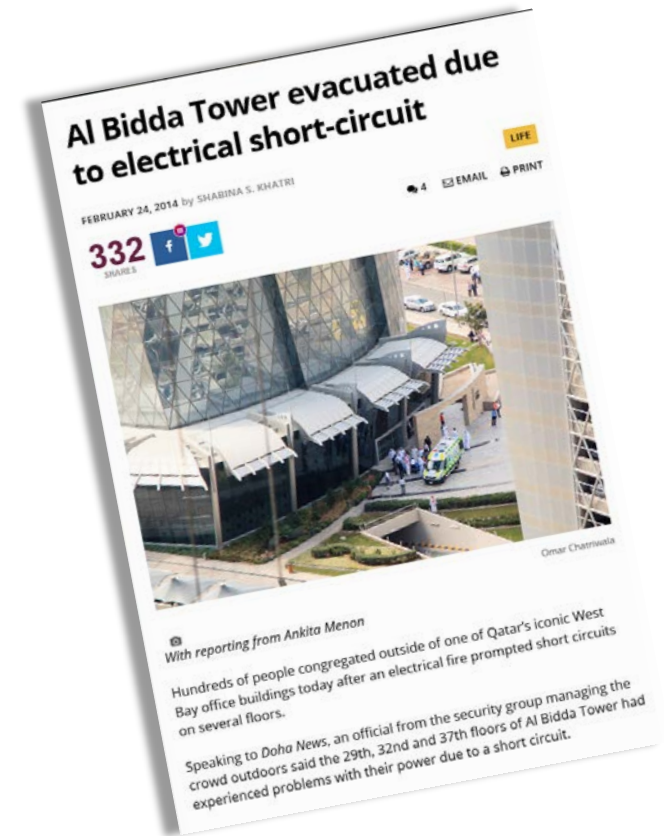
When a 2-MW battery array in Surprise, Ariz. caught fire and subsequently exploded on April 19, it highlighted a troubling reality for the nascent energy storage industry: the sector's momentum, marked by record numbers of deployments, falling prices and expanding state mandates and incentives, could be derailed by a series of well-publicized and, in some cases, little-known incidents involving runaway fires.

- From May 2 last year to Jan. 22, **21 ESS fires** were reported in S. Korea
- Fires linked to lithium-ion batteries also have hit [Europe](#) and [Australia](#).
- LG Chem's energy solutions business **lost \$124 million, in the first quarter of 2019**, following seven straight quarters of profits.

An ESS is a large stack of rechargeable batteries. It is often used for storing cheap off-peak electricity or coupled with solar, wind or other intermittent power generators.

Qatar Also Suffers From Electrical Hazards

Faulty equipment, improper installation, flooding ...
all contribute to the hazards

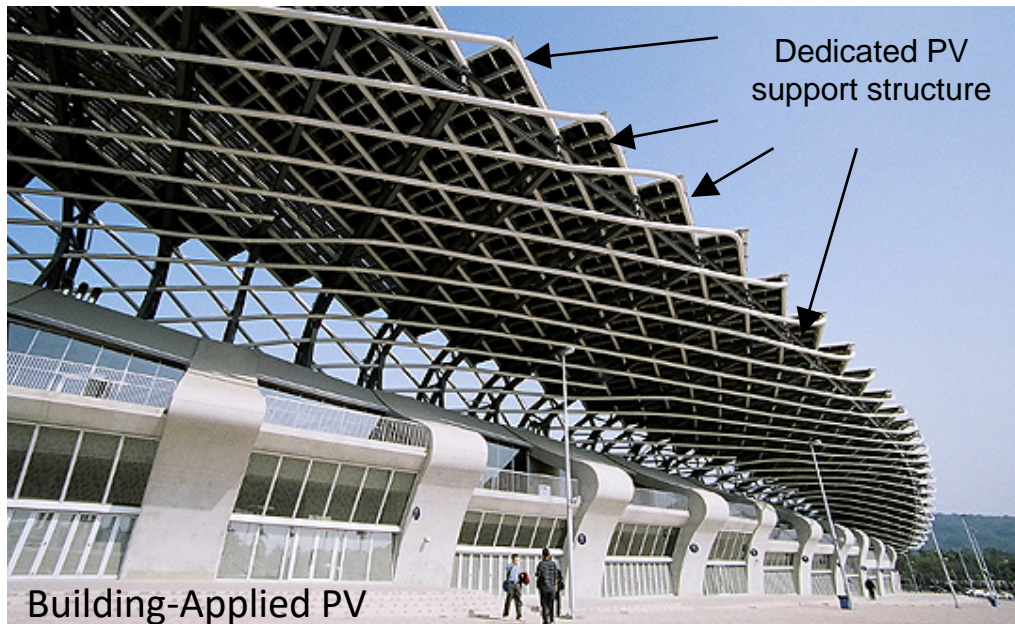


We should anticipate, from examples elsewhere, that as Qatar develops more distributed energy resources, the probability of incidents increases.

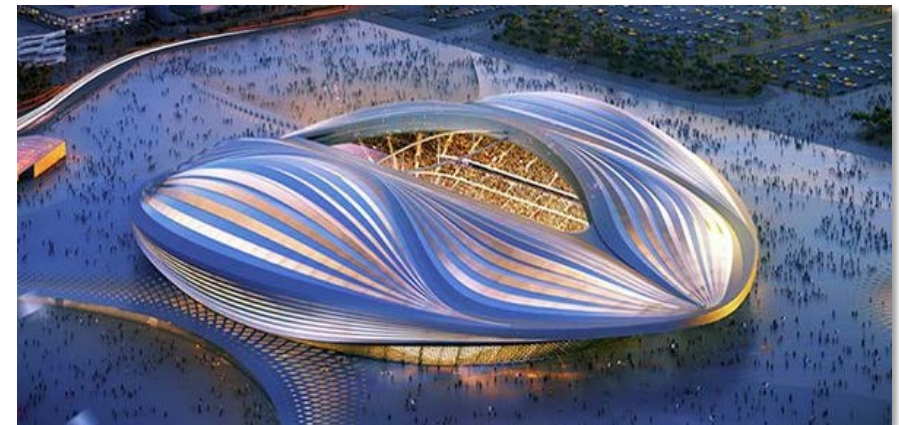
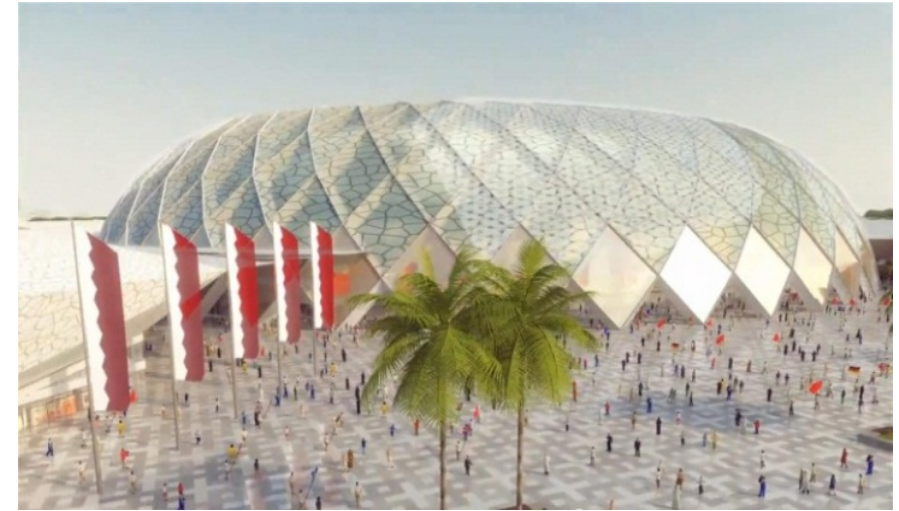
Hazards Are Unavoidable

- Building-Integrated PV is aesthetically pleasing.
- Electrical circuits are in proximity to building materials.
- We can't see the wiring to inspect for safety, like a frayed wire, or observe a problem, like an arc.

 Ban the hazard, or develop ways to minimize the impact ?



Conceptual designs for Qatar Stadiums



Minimize Risk

- The hazard may be unavoidable.
- Commoditization means more companies manufacturing *essentially equivalent* parts.
- Where is the liability?
OEM / Installer / Systems Integrator / Architect / Engineer
- The risk can be addressed through monitoring / detection technology.
- Standards like National Electric Code and UL1699B specify arc detection safety equipment.

Fire at the Shanghai Hongkou soccer stadium in Shanghai, China March 28, 2017



Arc Fault Hazard in PV Systems

- **Arc faults cause fires, shock hazard, and system failures in photovoltaic (PV) and other direct-current (DC) systems such as a energy storage systems, microgrid.**
- The number of PV system fires is increasing each year. (Because more PV is installed)
- The problem of arc faults exists for small-scale residential systems as well as **large-scale utility systems** and can pose significant threats to human safety.
- Significant concerns about **safety**



What About Utility-Scale PV

agniSOLAR THE WAY FOR EVERYONE | OUR STORY | SOLUTIONS | PRODUCTS | GALLERY | CONTACT | BLOGS | SOLAR SHOP | LOGIN

NOVEMBER 13, 2018

Floating Solar Energy Transforming India Into a Greener Nation

The green solar energy is the next alternative source of energy that is being explored at an immense pace. With the search for alternative energy sources at its peak, solar energy has clearly come out as the winner amongst the other options like wind and water. The need for the search of an alternative source is all the more accelerated due to the fact that the environment needs an urgent re look, for the sake of its survival. With the waning ozone layer and adverse effect on the health of the flora and fauna alike, the need for a green energy source seems like the only plausible survival mantra for the future. Solar energy provided the way out a long time back. However, to counter the cons of solar panels in terms of the space they occupy on land, technological advancement made floating solar panels a possibility, which has been widely accepted across the globe.

Solar power is being harnessed not just for household use but also for commercial purposes. When it comes to utility-scale production, the power generation demand far exceeds household demands. This is where the alternative of floating solar energy source comes into play since such a huge production will be made possible only by a solar plant. That would be a huge space to install the plant. The resolution to this dilemma came with floating solar plant. So what is a floating solar energy plant?

Solar floating Energy Installations

These are solar plants, installed on barges, marine vessels or even over the dams. Since the photovoltaic cells or the solar panels are on water bodies and are therefore floating they are called the floating energy installations.

One of the most asked questions is how do these heavy solar panels float? The floating solar panels are of the same material as the ones made for the rooftop solar panels. However, they are mounted on material which have buoyancy and hence remains afloat.

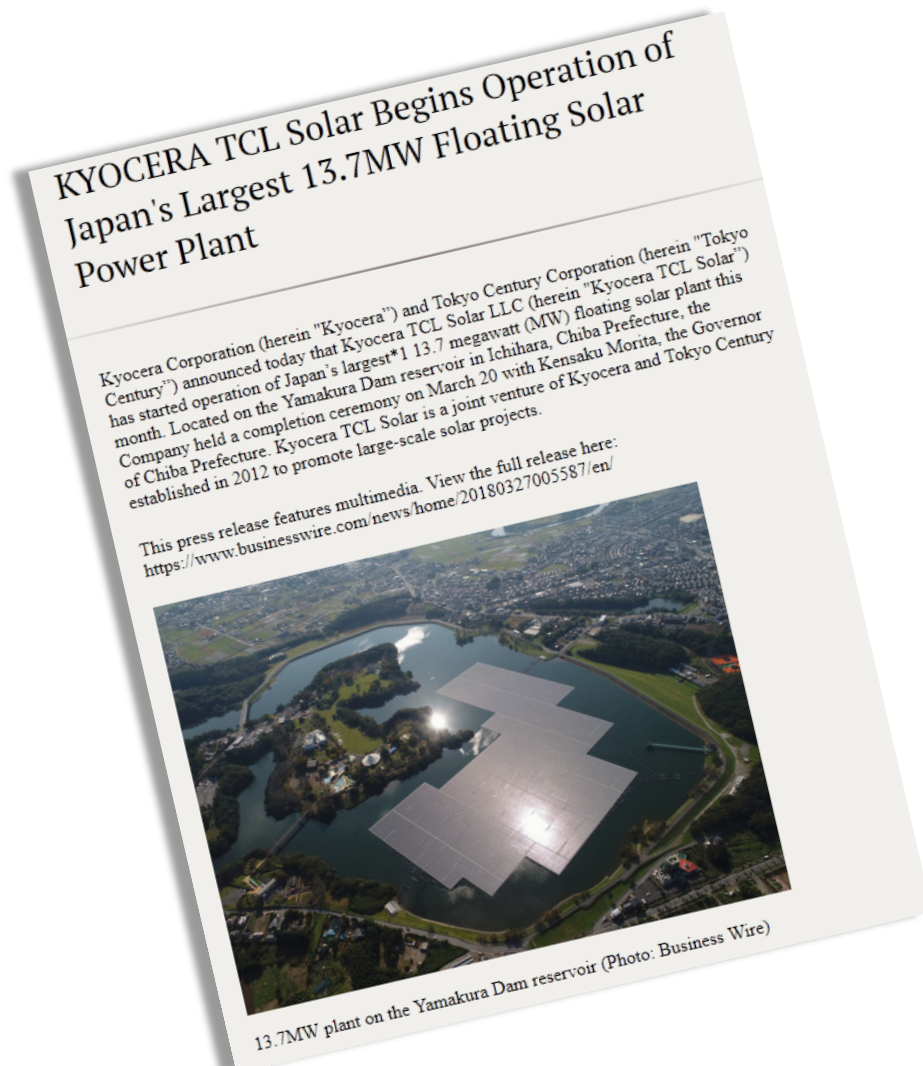
KYOCERA TCL Solar Begins Operation of Japan's Largest 13.7MW Floating Solar Power Plant

Kyocera Corporation (herein "Kyocera") and Tokyo Century Corporation (herein "Tokyo Century") announced today that Kyocera TCL Solar LLC (herein "Kyocera TCL Solar") has started operation of Japan's largest* 13.7 megawatt (MW) floating solar plant this month. Located on the Yamakura Dam reservoir in Ichihara, Chiba Prefecture, the Company held a completion ceremony on March 20 with Kensaku Morita, the Governor of Chiba Prefecture. Kyocera TCL Solar is a joint venture of Kyocera and Tokyo Century established in 2012 to promote large-scale solar projects.

This press release features multimedia. View the full release here:
<https://www.businesswire.com/news/home/20180327005587/en/>

13.7MW plant on the Yamakura Dam reservoir (Photo: Business Wire)

Japan's 13.7 MW Floating PV



- The Chiba Yamakura Floating Mega Solar Power Plant
- The plant output of about 13.7MW
- Constructed on the surface of "Yamakura Dam," a pond in Ichihara City, Chiba Prefecture, Japan
- Started operation in March 2018

Destroyed by Typhoon Faxai



- The Chiba Yamakura Floating Mega Solar Power Plant
- The plant output of about 13.7MW
- Constructed on the surface of "Yamakura Dam," a pond in Ichihara City, Chiba Prefecture, Japan
- Started operation in March 2018
- **September 9, 2019 -- No injuries, but about 77% of the 50,904 solar panels were damaged by the winds and fire**

Arc Fault Hazard – A “Hidden” Cost



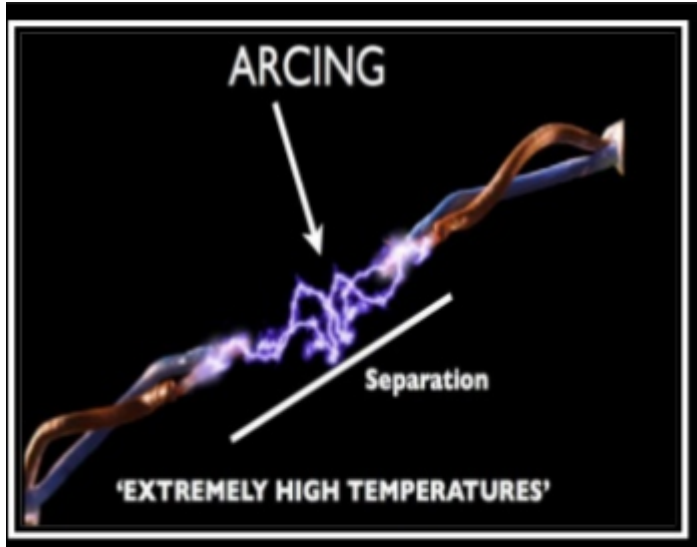
\$\$\$



- Annually (USA) over 28,000 residential electrical fires: 360 deaths, 1,000 injuries, and \$995 million in damage.
- Residential as well as large-scale utility systems
- Liability and insurance implications
- Impact upon widespread adoption of photovoltaic energy
 - Al Jazeera: “*PV system causes dairy farm to catch fire in Doha*”
- PV arc fault detection is now required as part of NEC and UL1699B

Sept. 2, 2013 Dietz & Watson Warehouse Fire, NJ USA

What is an Arc



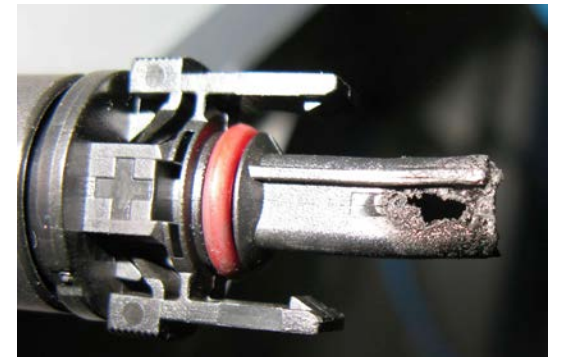
*An Arcing Fault is the flow of current through the air between phase conductors or phase conductors and neutral or ground. Concentrated radiant energy is released at the point of arcing in a small amount of time resulting in **Extremely High Temperature**.*

- The plasma that forms within the arc is extremely hot and can exceed 35,000°F (19,400°C).
- This is hot enough to vaporize metal, leading to what is known as an arc blast in high-power systems.
- The power in PV system may not be high enough to cause a shockwave, like in ac systems.
- But the high temperatures can ignite combustible materials.



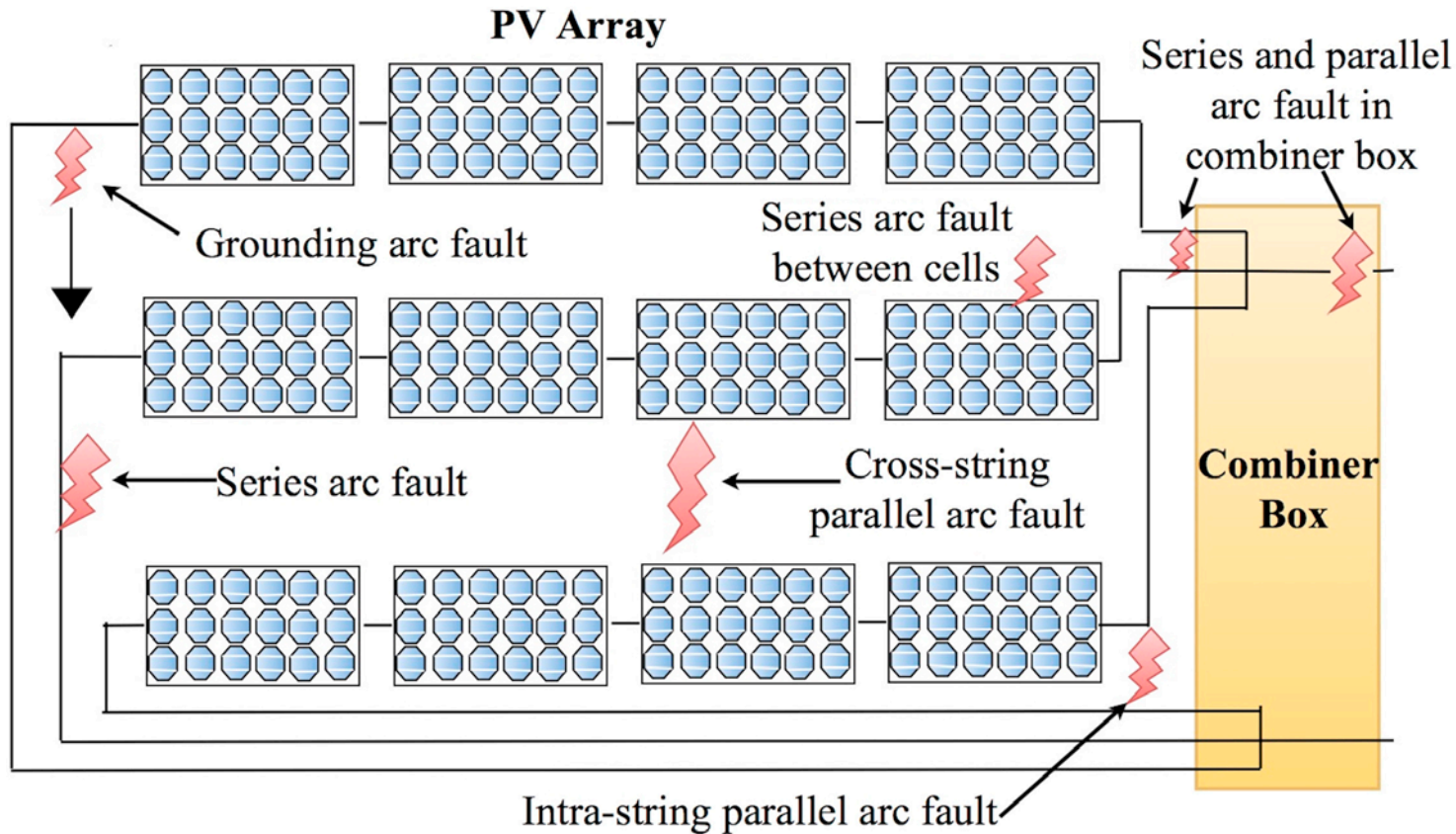
Code and Standards

- 2011 NEC required all **roof-top** PV system greater than 80V to have series arc fault detectors.
- 2014 NEC required all PV system greater than 80V to have series arc fault detectors.
- UL-1699B standard requires every Arc Fault Circuit Interrupter (AFCI) or Arc Fault Detector (AFD) pass the arc test with the power of 300–900 W.
- AFCI and AFD must respond within 2s.
- At the string level, could be a 100 W arc fault.



Classifications of Arc Types

Long cable runs, many connectors



- **Series:** occurs when a connection is pulled-apart while carrying current.
- **Parallel:** occurs when insulation fails between two conductors of opposite polarity in the same circuit
- **Ground:** occurs when insulation of one conductor fails and the conductor contacts grounded metal.

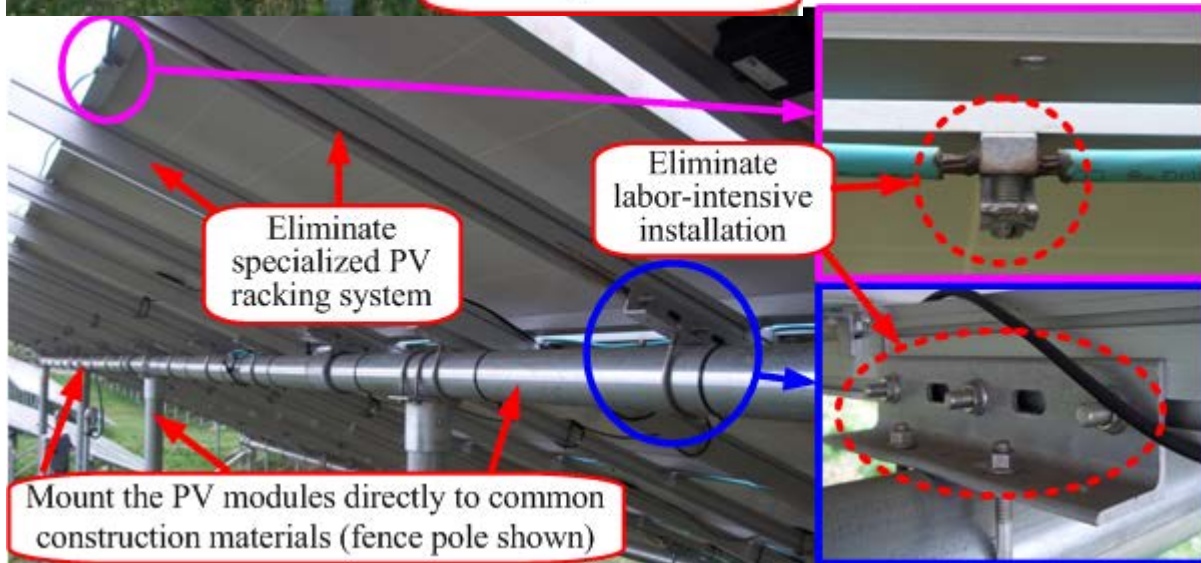
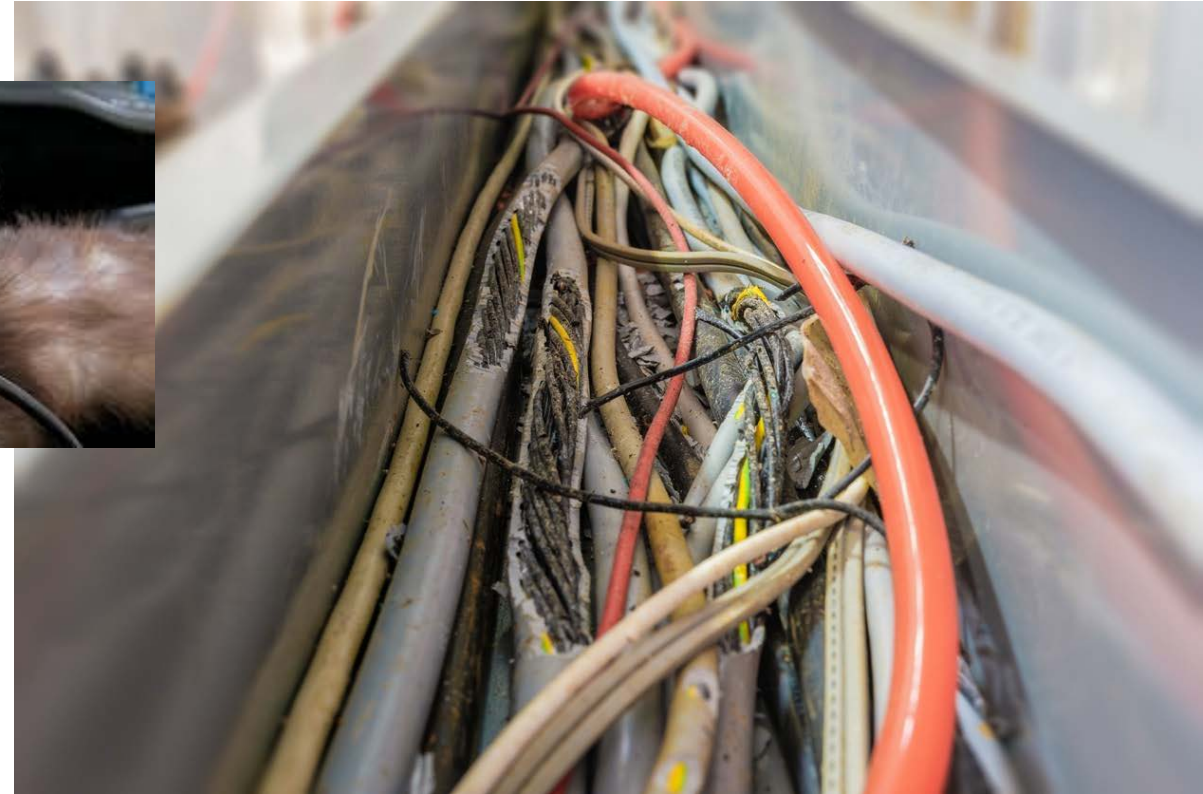
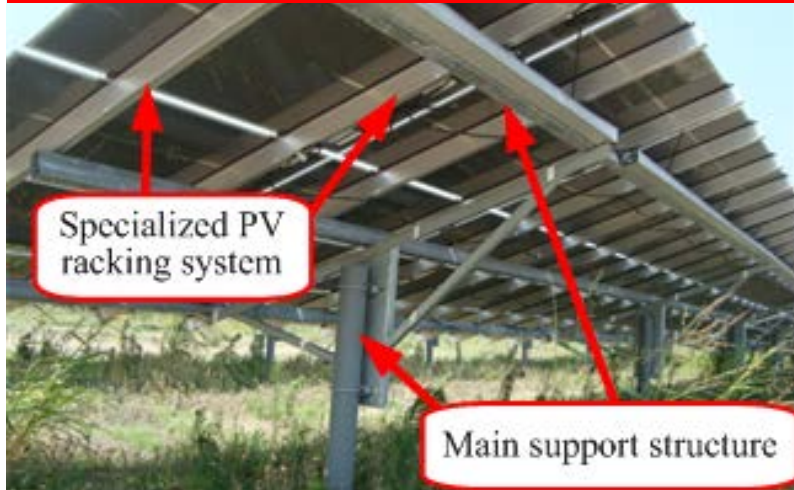
Possible Arc Fault Causes

- Connections in junction boxes can degrade over time.
- Screw type terminal connections can come loose due to changes in temperature.
- Improper stripping length can result in wire insulation being captured in terminals.
- Improper crimping of DC terminals results loose connections.
- DC connectors not fully mated.
- Animals chewing through wires or wiring that has come loose and rubbed against the array racking. This can also show up as a ground fault.
- PV modules are cracked or damaged.



Many Opportunities for Electrical Arcs

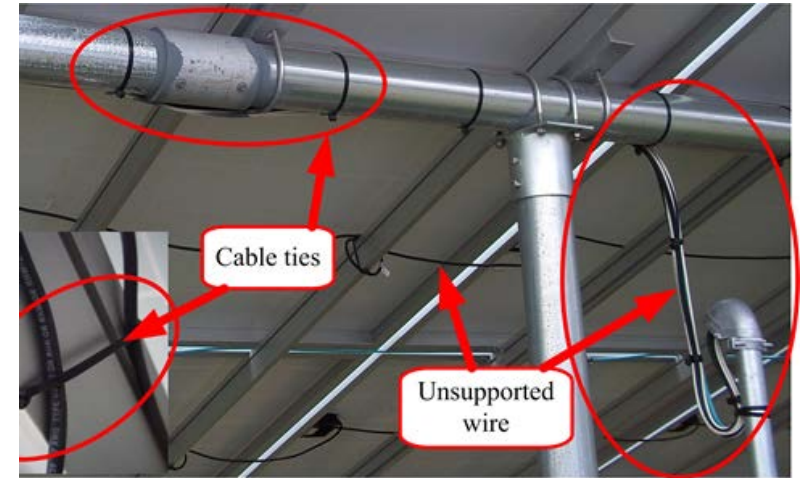
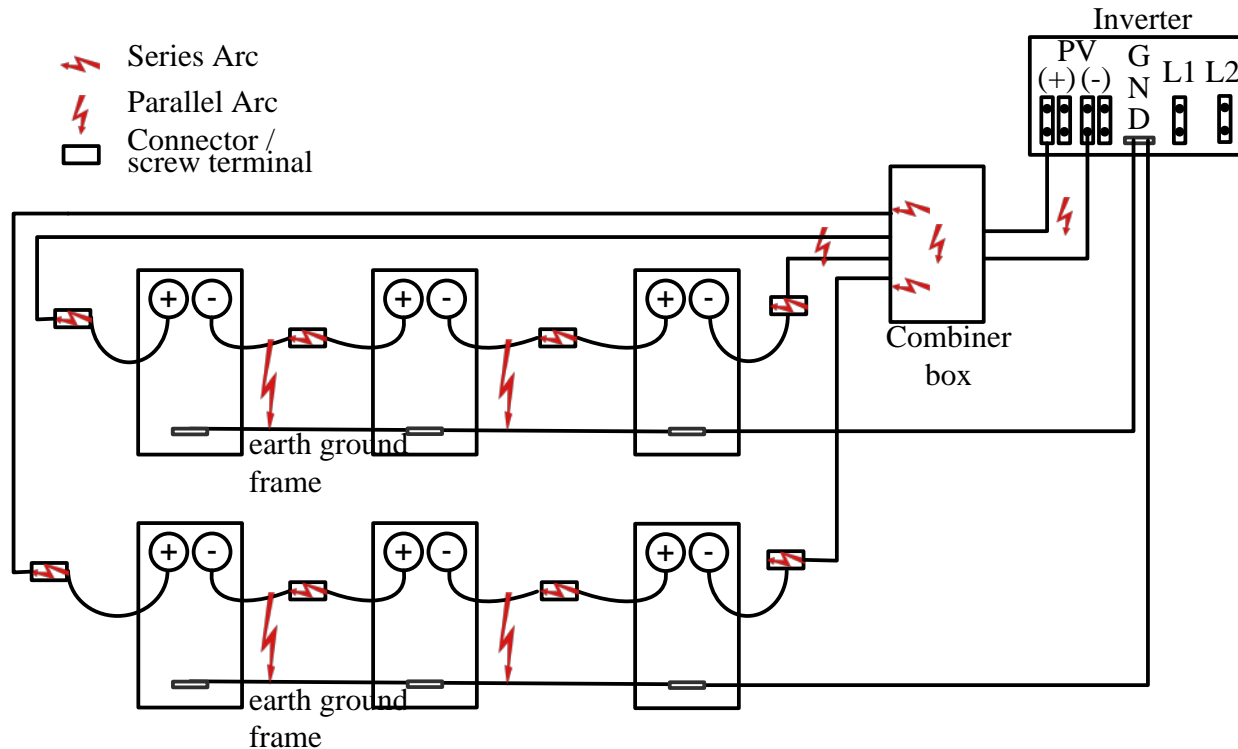
Rutgers University Livingston 8MW Solar Farm



Out in the open, PV systems can become home for rodents.
Potential for series, parallel, or ground arc

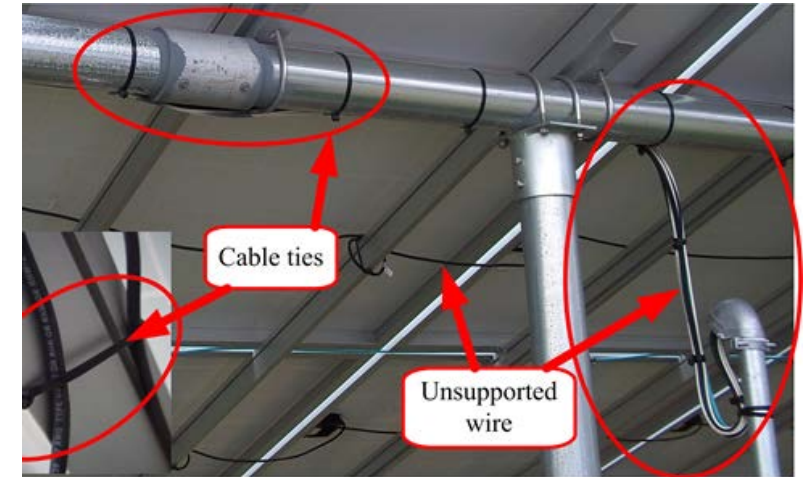
Possible Locations for Arc Fault Occurrence

DC electrical arcs in PV systems can be caused by loose electrical connections or abrasion of conductors secured to the mounting frame due to thermal expansion, vibration, nesting rodents, or failure within the PV modules.



Environmental Component Degradation

Texas A&M College Station Rooftop Array



Video is after years of Texas summers

Consider the effects on degradation when exposed to the high heat and intense sun of Qatar.

PV Arc Faults Can Persist, Undetected



Glowing arc fault in the dc wiring at the combiner box

- PV systems do not have the capability to provide large short-circuit current that helps to clear a fault in ac-systems.
- Instead, arcs continue to burn.

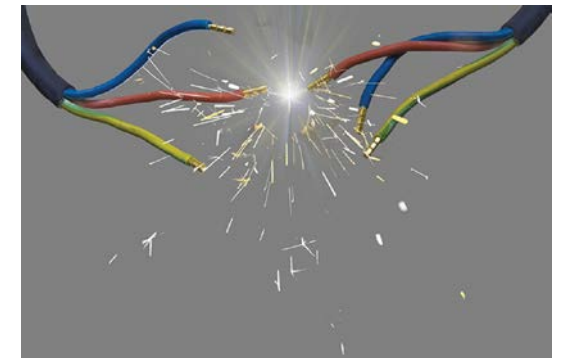
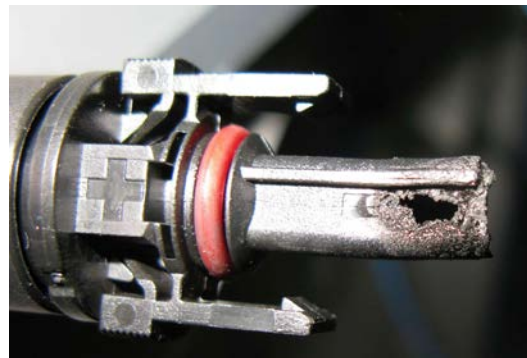


Arc Flash Detection



“The best arc-fault is the one that never happens”
— Jay Johnson, Sandia National Laboratories

- How to ensure it doesn't happen?
- Detect the “spark plug” effect
- Low energy arc flashes are often the precursors to sustained arcing as they deposit carbon traces making it more likely for the next arc to occur



Arc Signal Detection and Analysis

Arc Fault Detection

- Optical methods:

- Uses photodiodes to sense light from arc
- Used in switch gear
- Complicated optics and circuitry
- Not suitable for the large-area wiring of PV systems



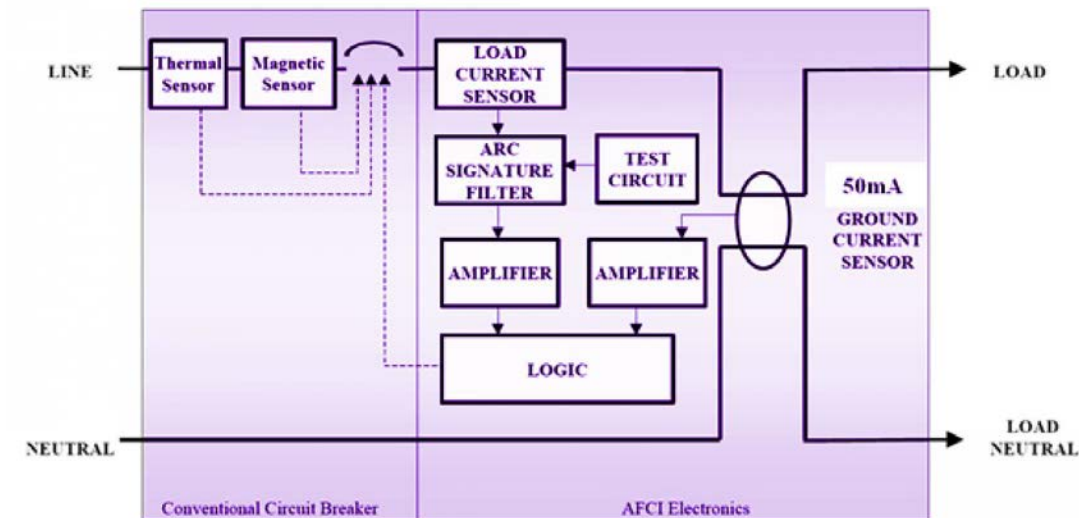
- Acoustical methods:

- Transducers pickup the sound of the shockwave
- Time delay between start of arc and propagation of shock wave to sensor
- Complicated circuitry, electrical isolation issues
- Not suitable for the large-area wiring of PV systems

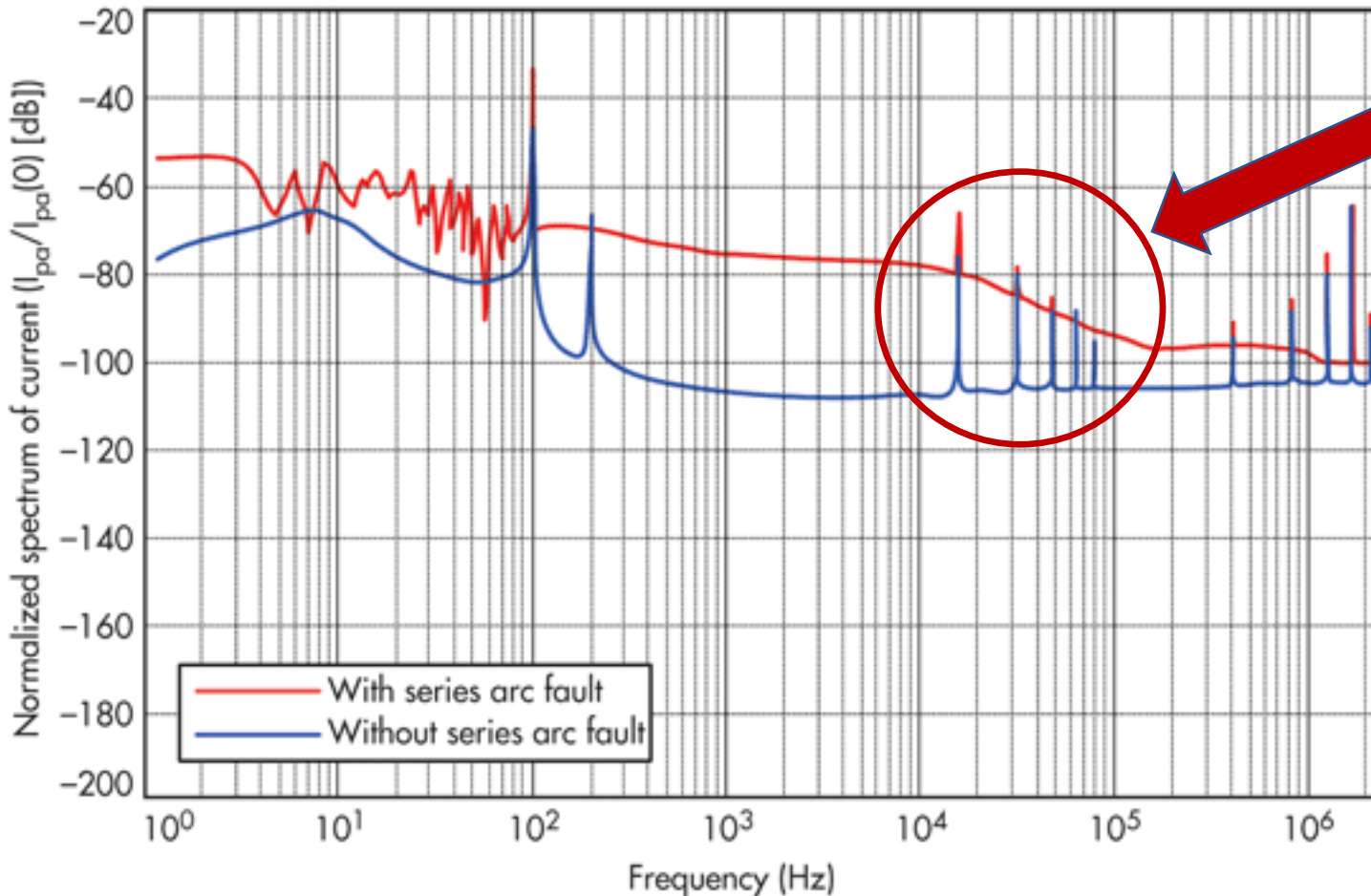
Arc Fault Detection

- Amplitude method:
 - If the amplitude exceeds a window, assume it is due to an arc
 - [Maximum power point tracking](#) (MPPT) can adjust the current to normal while the arc fault still exists
 - Not robust
- Frequency methods:
 1. Arc signature filter passes frequency components of arcing waveforms while rejecting other frequencies
 2. Perform an FFT and apply a power spectral density limit line (like EMI testing)

AC versions of ACFI – Arc Fault Current Interrupter, combined overcurrent and arc detection.



FFT Method

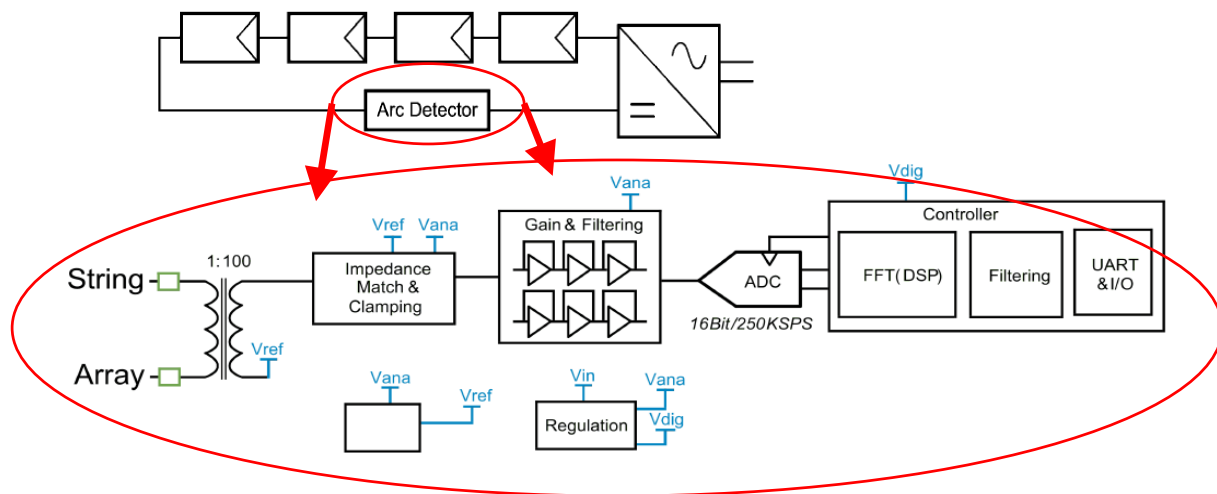


- Arcs have broadband energy.
- Inverters often also have conducted and emitted radiation in this spectrum (50 kHz to 100 kHz)
- Other man-made and natural phenomena such as lightning,
- Signal processing is needed to differentiate an arc occurring in the system from some external event that is unrelated.

FFT Method

Fourier Analysis

- Measures string current i.e., series arc fault
- Fast Fourier Transform (FFT)
- Spectral analysis of signal
- Looks for patterns of frequencies
- Only works for periodic signals
- Short-duration signals are not easily detected if within sampling window



Disadvantages

- Arc faults in power systems are not usually periodic → random noise
- Duration of arc event compared to the FFT sample window determines the detectability of the arc event
- Fourier transform gives only frequency information. Does not provide time-localization. IE, precisely when did the event occur?
- Current sensors are more expensive than voltage sensors, may not measure parallel arcs

Existed Products

(SolarMagic SM73201) / (Texas Instruments RD-195)

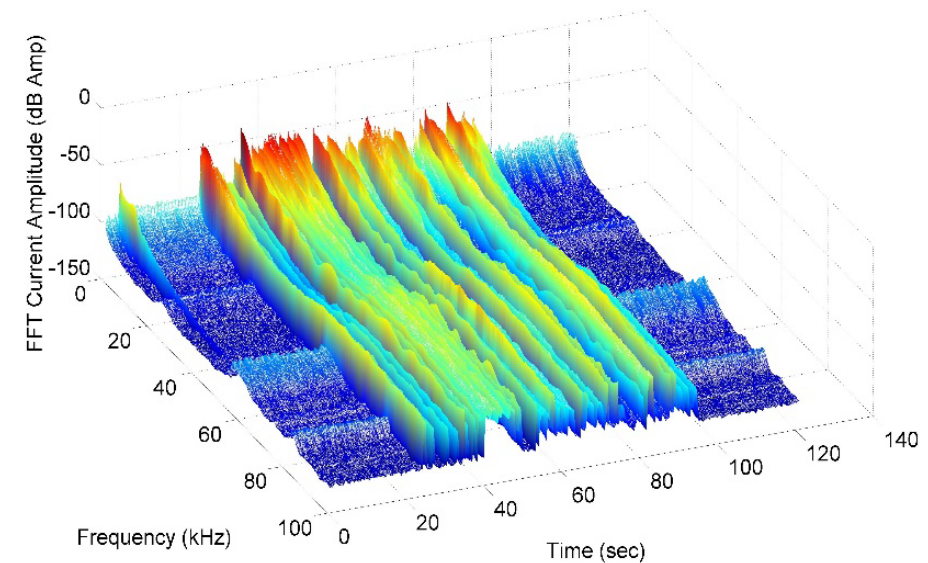
Short-Time Fourier Transform (STFT)

- STFT is a Fourier-related transform applied to short intervals “windows” of a signal
- Fundamental drawback: fixed window size → Fixed temporal and spectral resolution.
- The window length is a tradeoff between frequency resolution and time resolution:
 - A large number of samples is required to obtain high frequency resolution, which in turn causes low time resolution.
 - A shorter window provides better time resolution but inferior frequency resolution.
- STFT suitable for time-frequency analysis of harmonic disturbance, but it is not ideal for abrupt disturbances or short transient signals.

- The expression for discrete time STFT is given by:

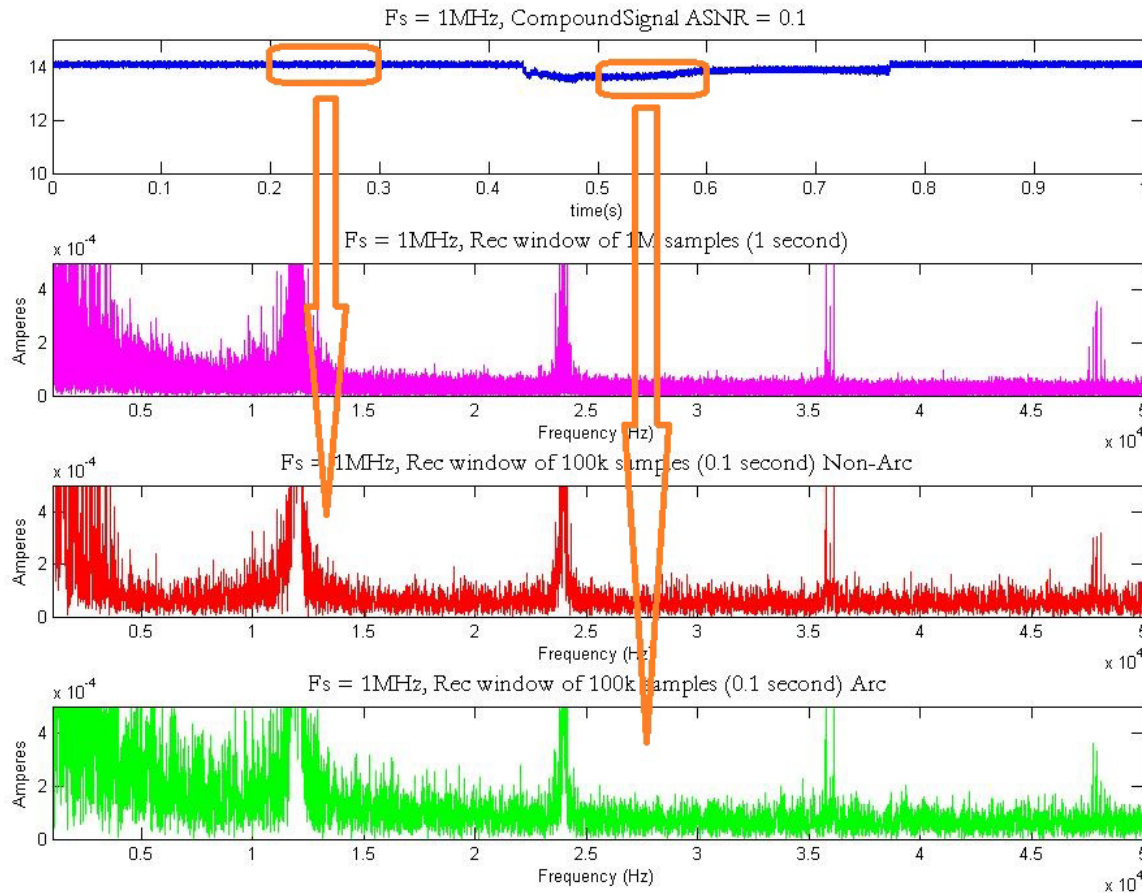
$$X(w, m) = \sum_{n=-\infty}^{\infty} x(n) \cdot w(n - m)$$

- $w(n)$ is referred to as an analysis window or analysis filter.
- The sequence $x(n)w(n-m) = f_m(n)$ is called a short time section of $x(n)$ at time m .

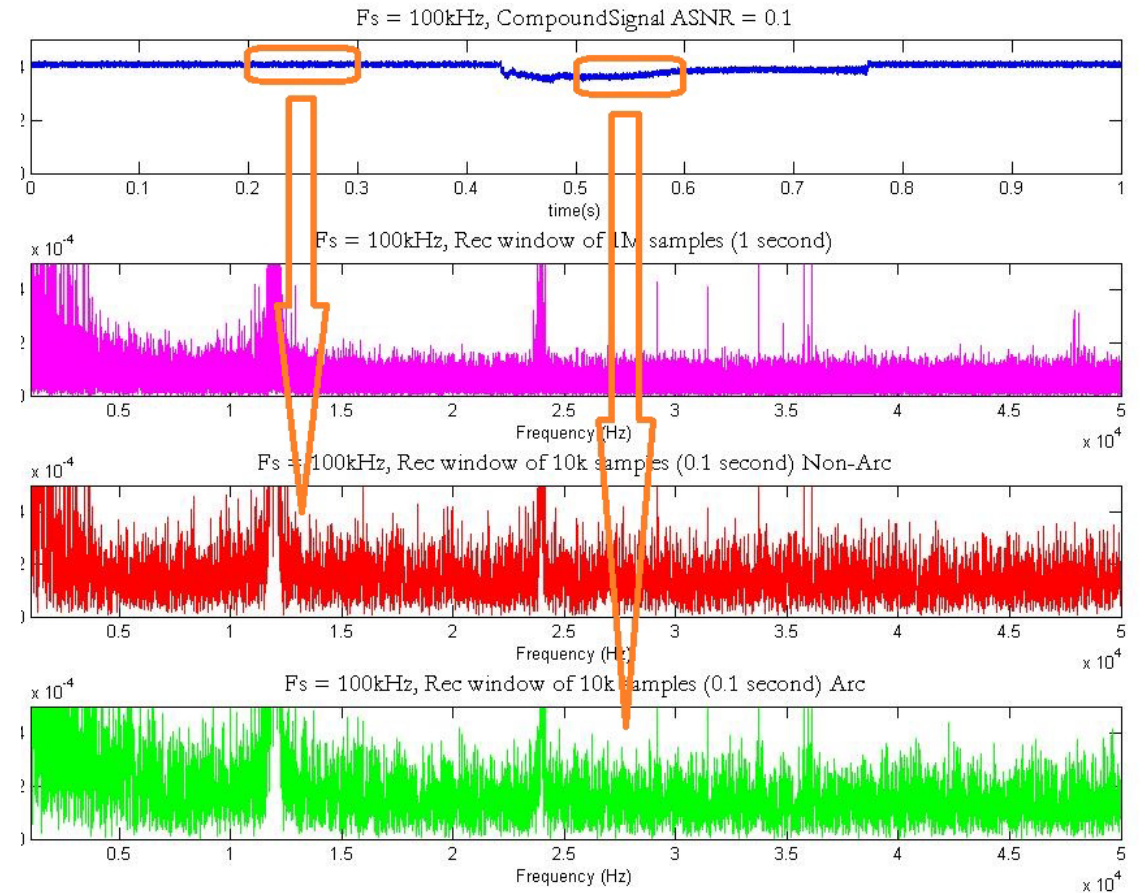


FFT Needs High Sampling Frequency

F_{sampling}=1MHz



F_{sampling}=100kHz

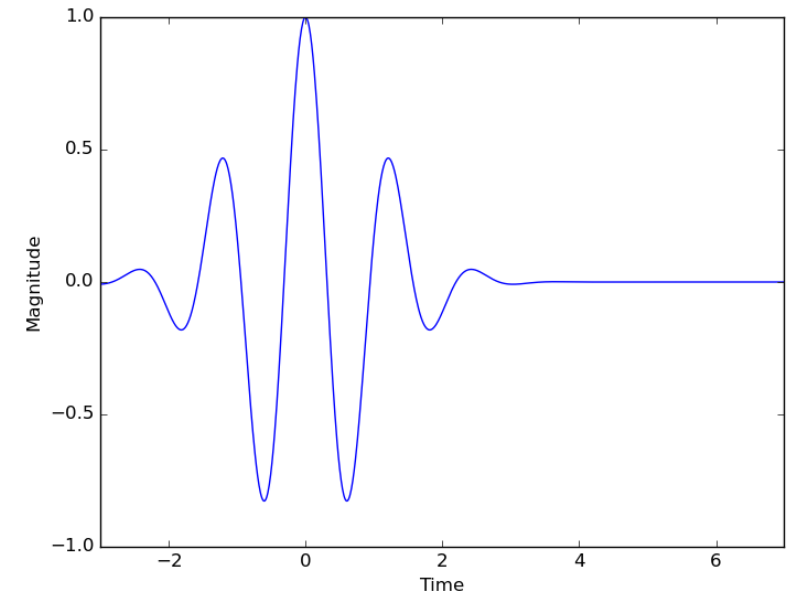


FFT requires high sampling frequency to achieve good signal-to-noise ratio and resolution

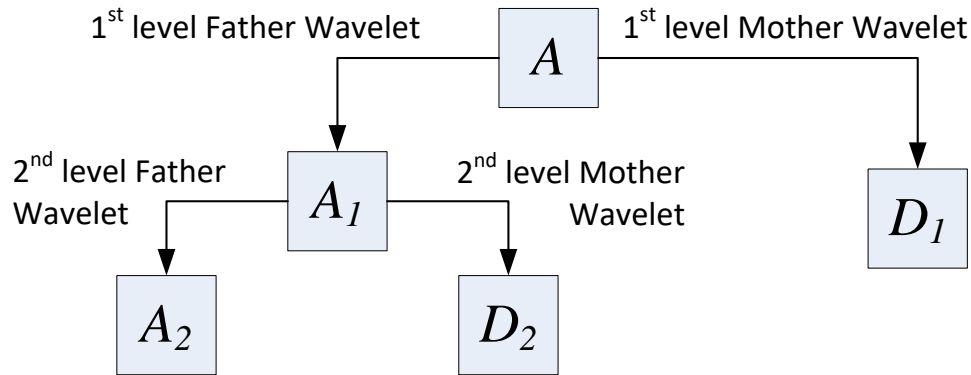
Arc Signal Analysis Using Wavelet Transform

Why Wavelets?

- Waveforms are decomposed into wavelets identified by time scale (frequency bands) and temporal ordering.
- Fourier transform uses a fixed, uniform window for the entire range of frequencies.
- Wavelet transform uses short windows at high frequencies and long windows at low frequencies.
- Detailed frequency characteristics and signal analysis within frequency bands.
- Sensitive to irregularities, insensitive to regular-like signal behavior.



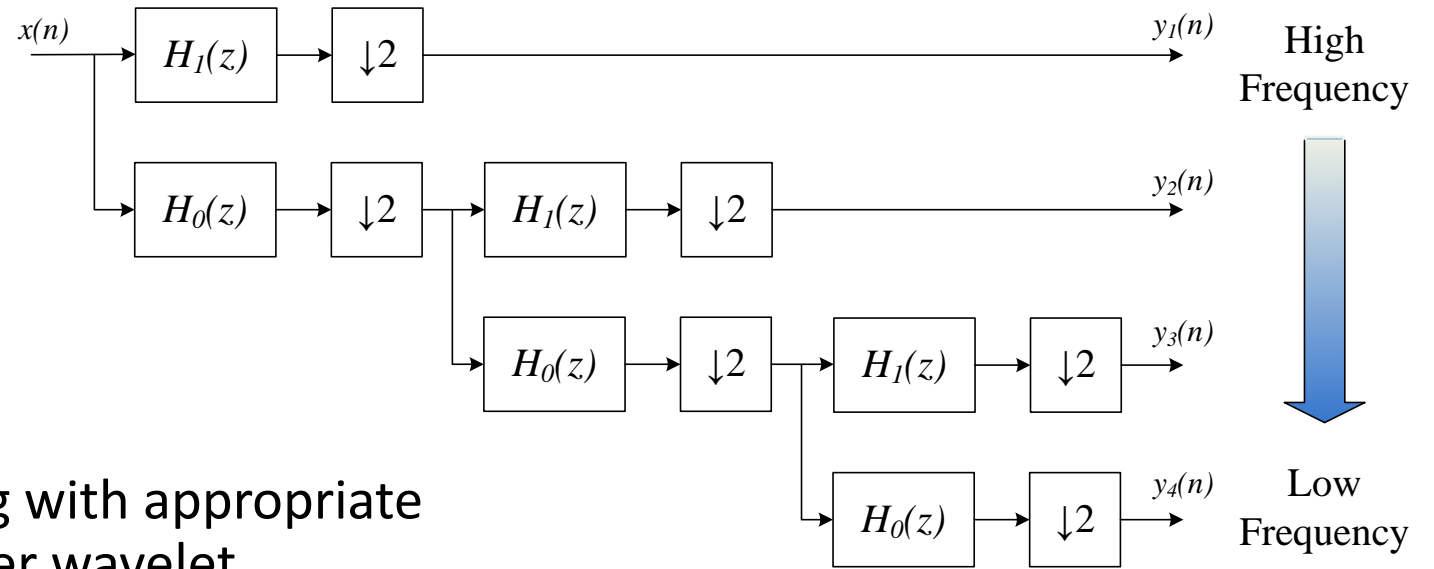
Signal Decomposition Process



$$\begin{aligned} A &= D_1 \oplus A_1 \\ &= D_1 \oplus D_2 \oplus A_2 \\ &\vdots \\ &= D_1 \oplus D_2 \oplus \dots \oplus D_n \oplus A_n \end{aligned}$$

- Equivalent to successive down sampling with appropriate “windowing filter” selected by the father wavelet.
- A is the result of the down-sample and D is the information lost from the down-sample process.
- Subsequent transforms reveal lower frequency bands.
- High frequency information only requires 1 transformation.
- D can further be decomposed into “wavelet packets” if additional resolution is desired.
- High frequency band is first, followed by lower frequency bands → requires less decomposition operations.

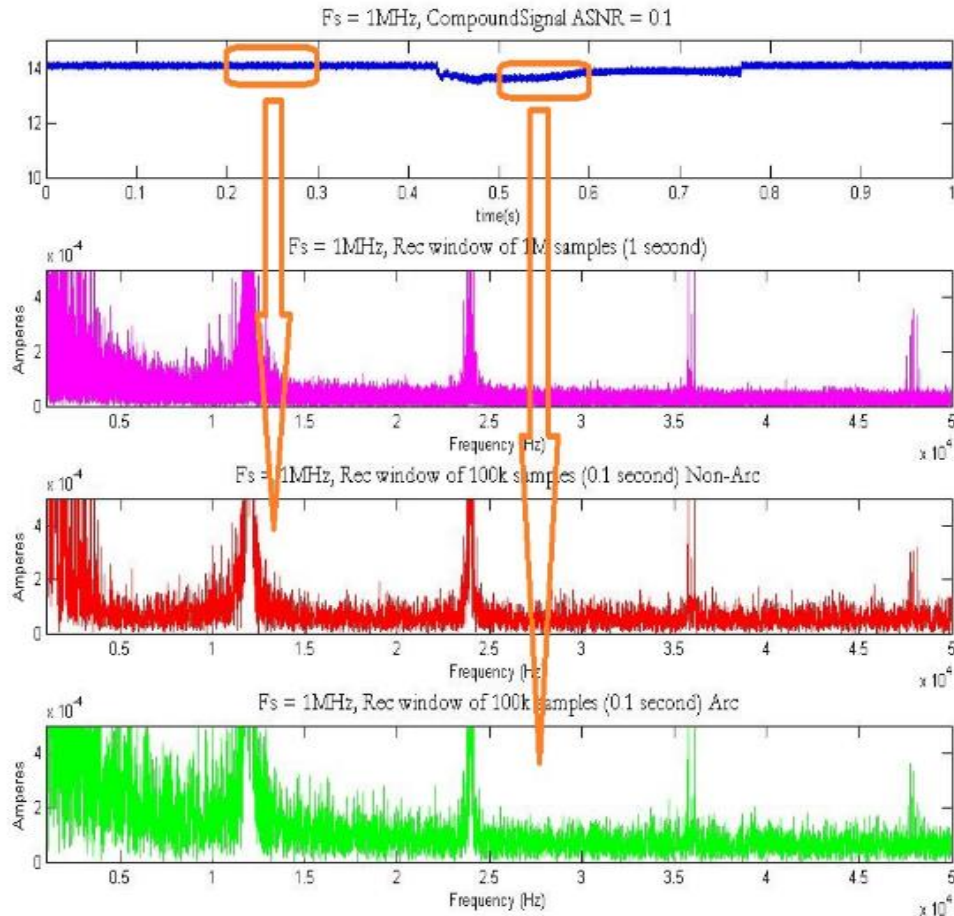
Wavelet and Filter Banks



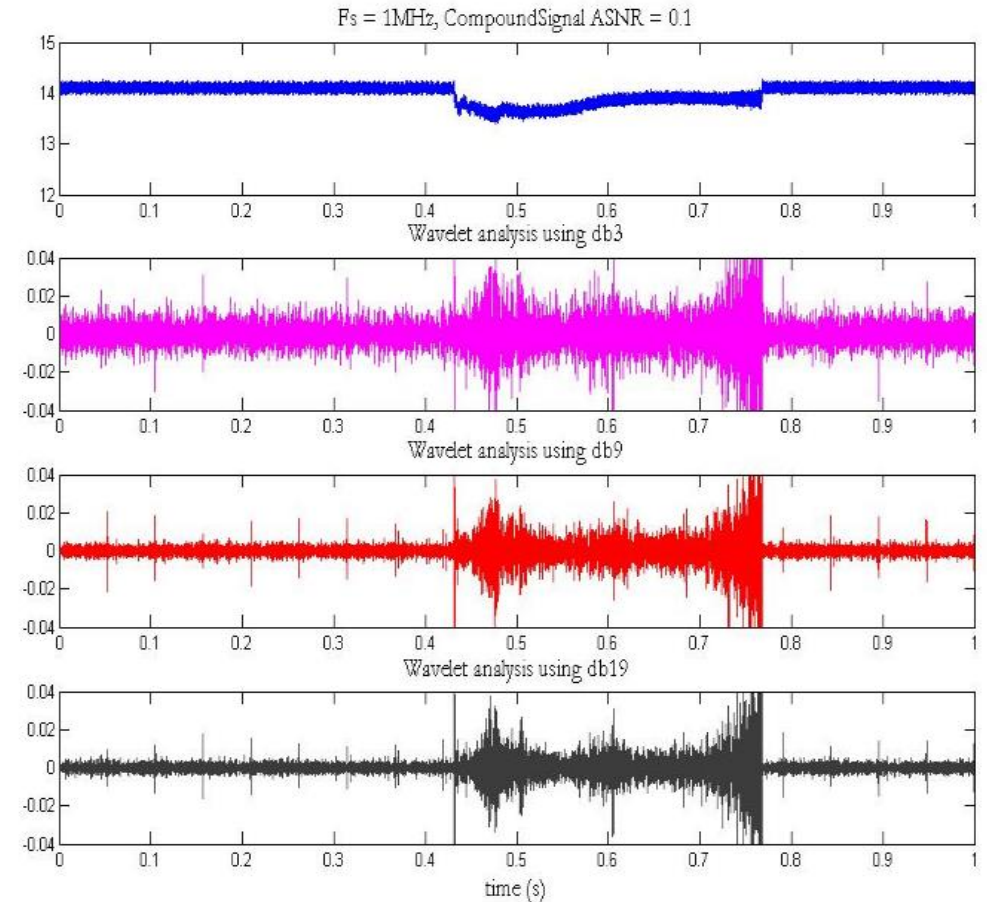
- Equivalent to successive down sampling with appropriate “windowing filter” selected by the father wavelet.
- Subsequent transforms reveal lower frequency bands.
- Highest frequencies requires least transformation steps.
- Higher frequency components can be further decomposed into “wavelet packets” if additional resolution is desired.

Comparison of FFT vs. Wavelet

FFT: No detectable difference in the spectrum – hard to detect arc

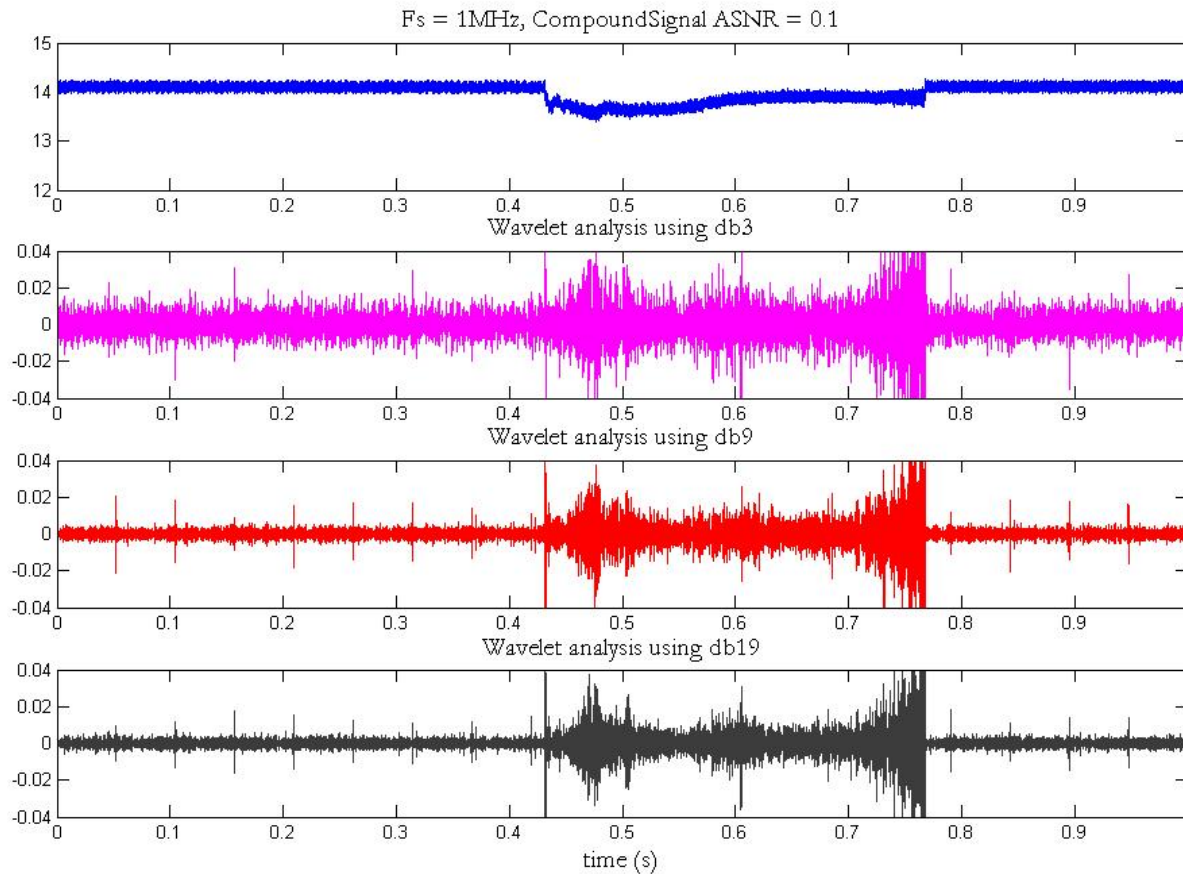


Wavelet: easily detectable difference in the signal, arc is easily detected

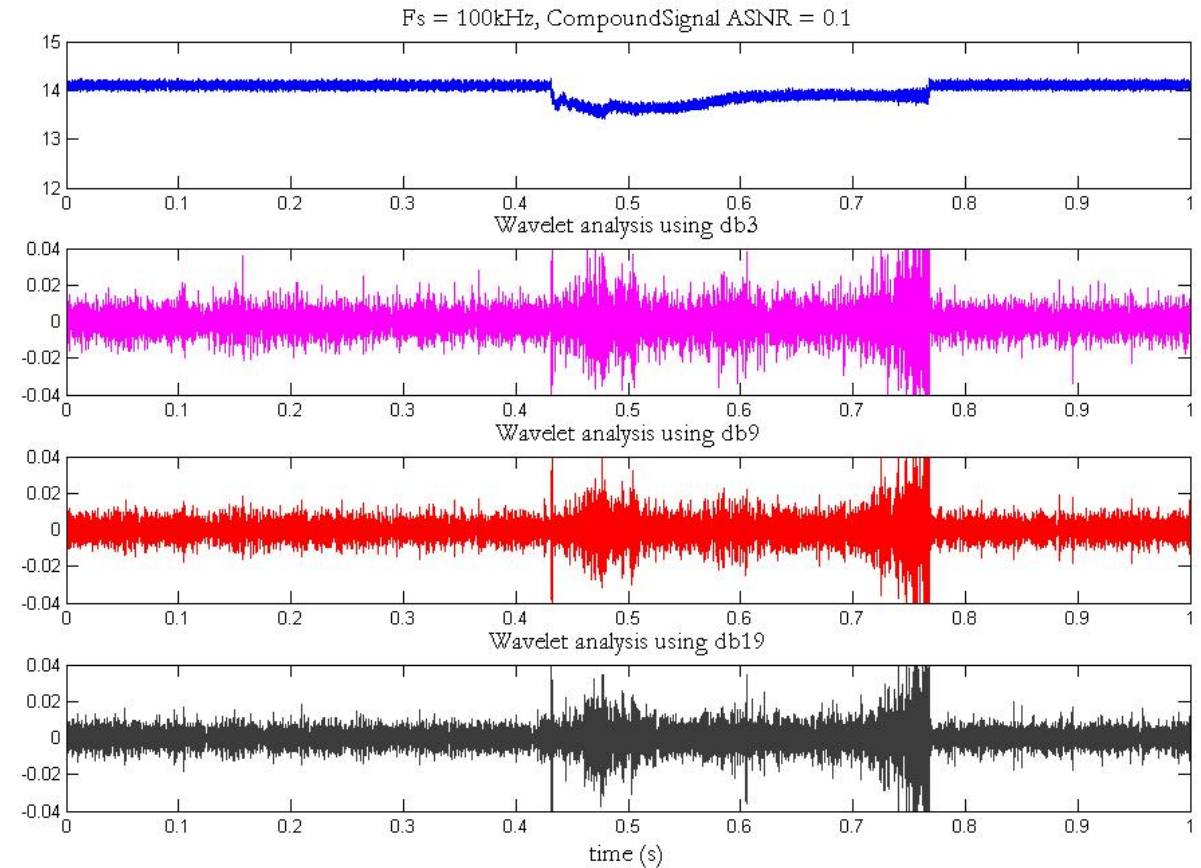


Wavelet Analysis, Easier Detection

Fsampling=1MHz

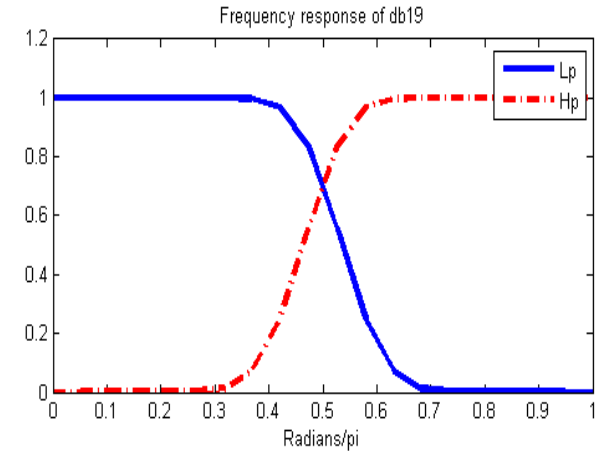
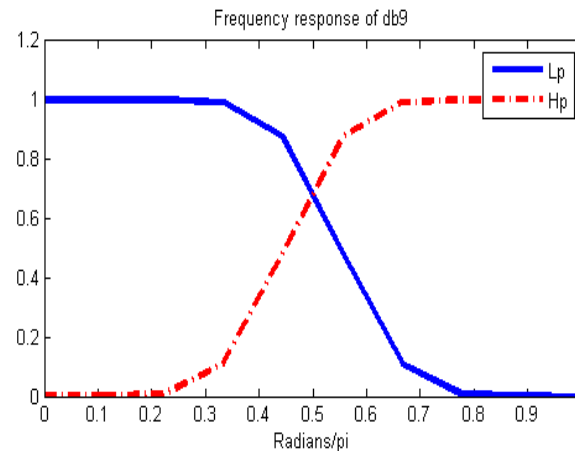
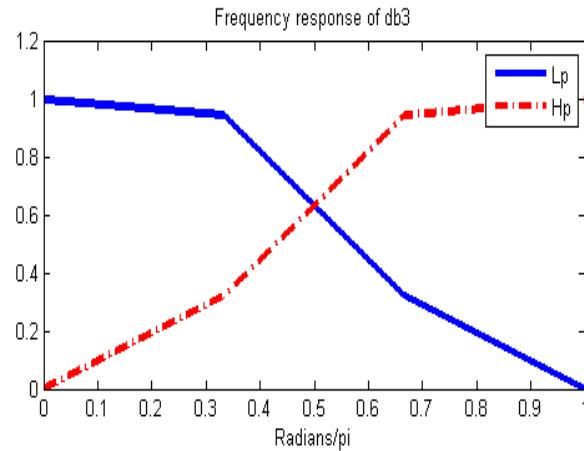


Fsampling=100kHz



Easier to observe the arc event, even at lower sampling frequency. Plus we know exactly when the arc occurs (temporal localization)

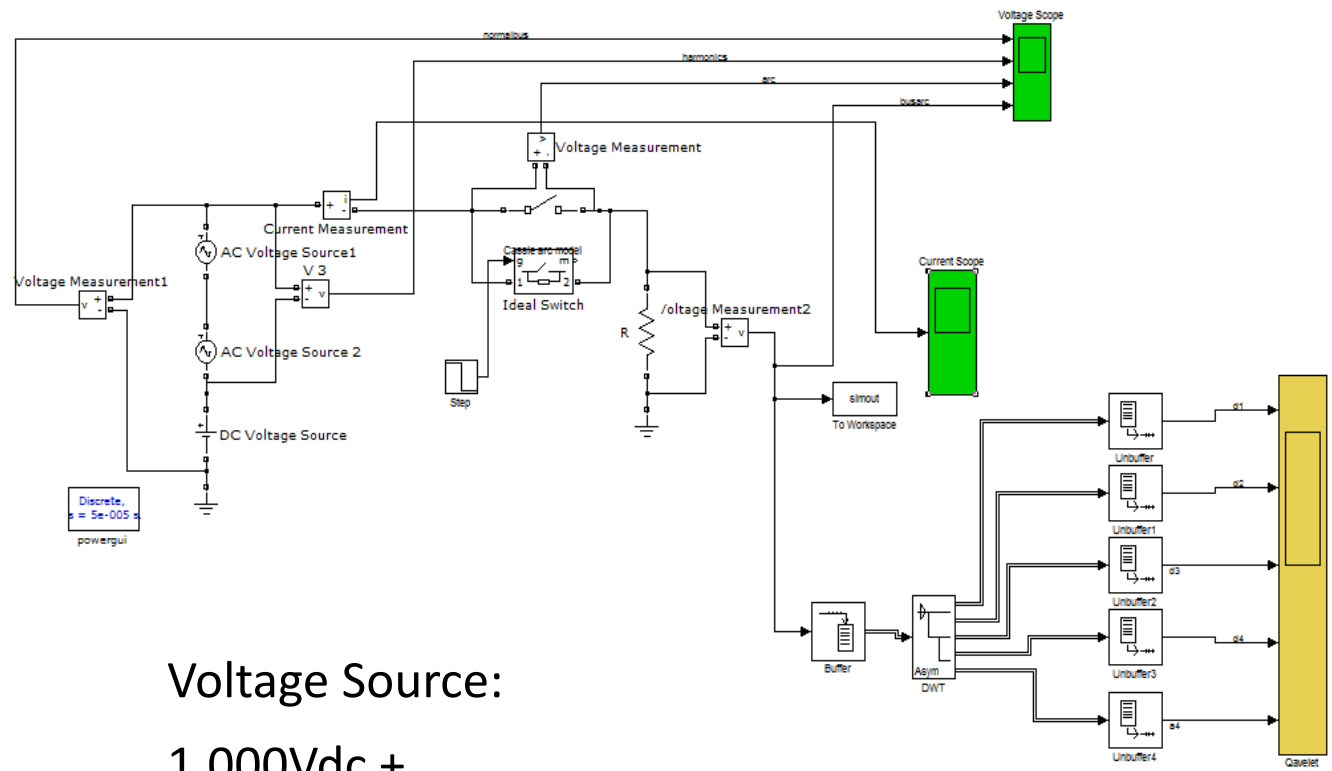
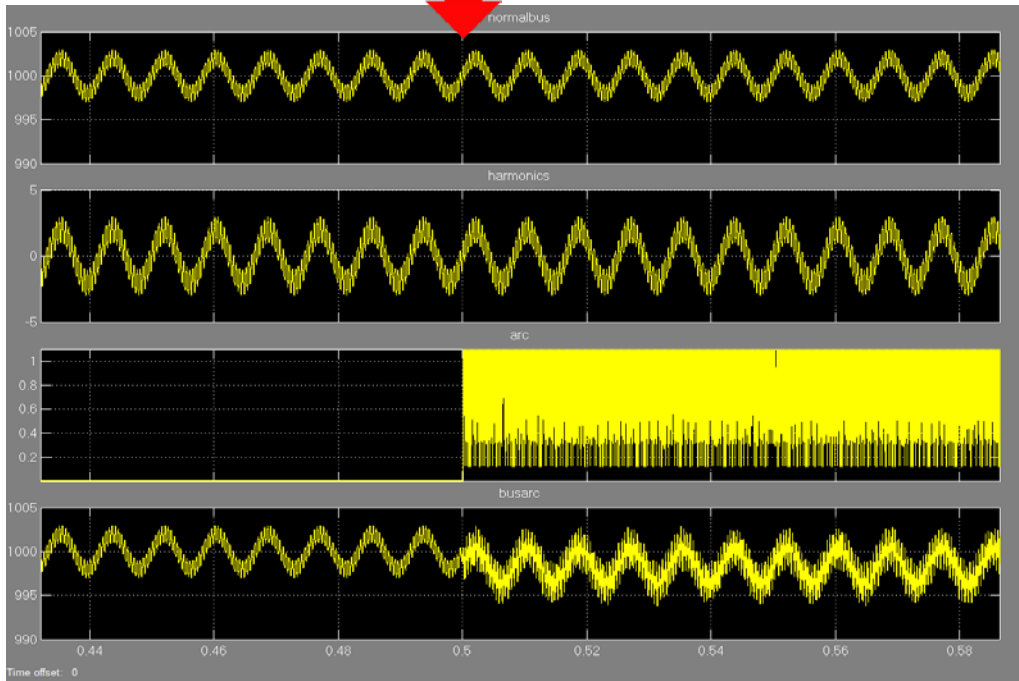
Selecting Mother Wavelet



- Higher order filters provide better frequency response, but require more mathematical operations to implement.
- Frequency response of filter banks of Daubechies 3 (db3), Daubechies 9 (db9), and Daubechies 19 (db19) are shown above.
- It can be seen that the frequency response of db9 filters has a significantly sharper cutoff frequency in comparison with that of db3 filters. But db19 does not provide equally significant improvement over db9.
- Considering the extra computational load brought on by filters with more coefficients, db9 seems like a good compromise.

Simulation Model

Sustained arc begins at 0.5s



Voltage Source:

1,000Vdc +

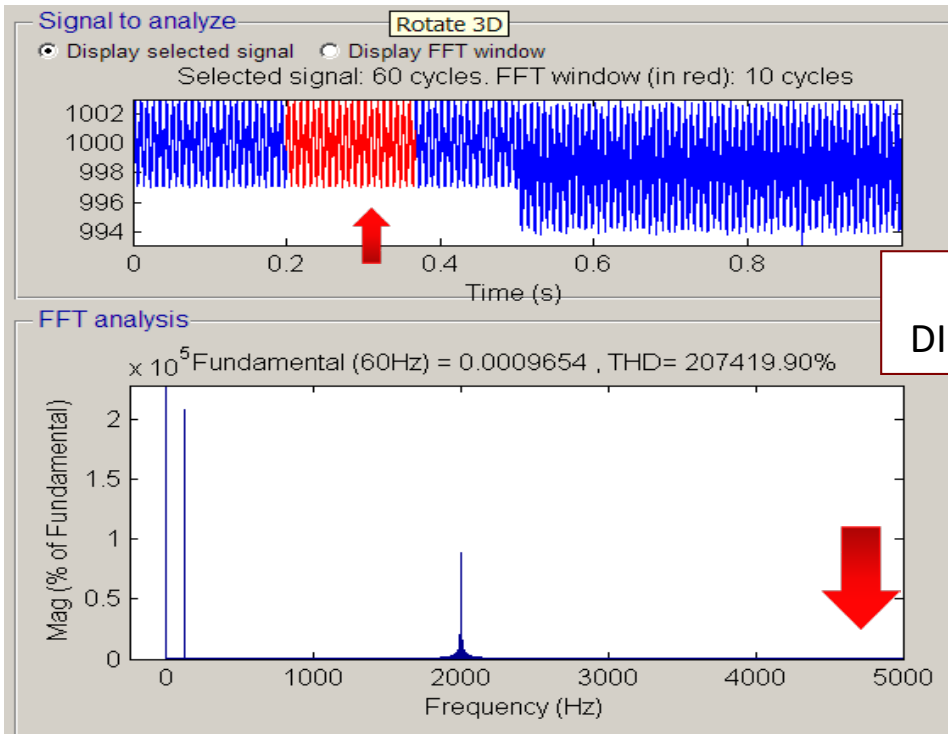
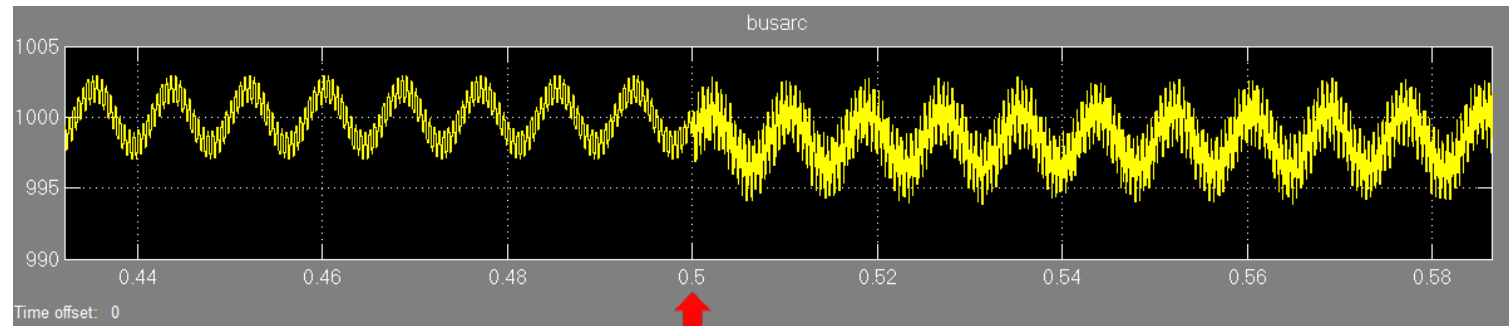
120Hz ($2V_{pk-pk}$) +

2,000Hz ($1V_{pk-pk}$) superimposed

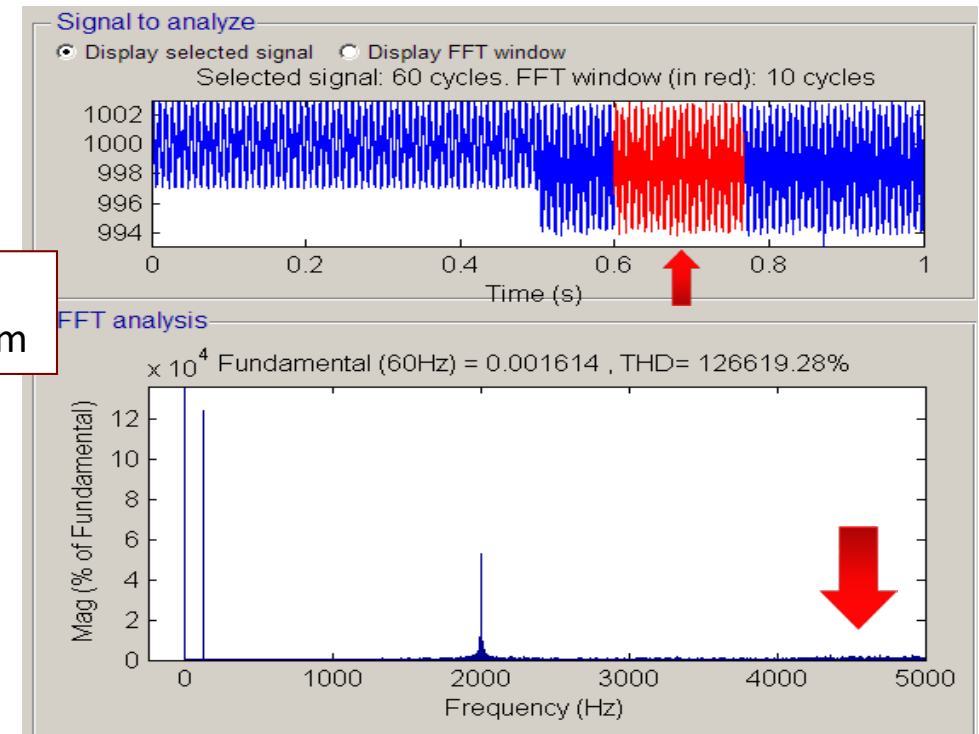
Cassie Arc model

Simulation: Spectral Analysis (FFT)

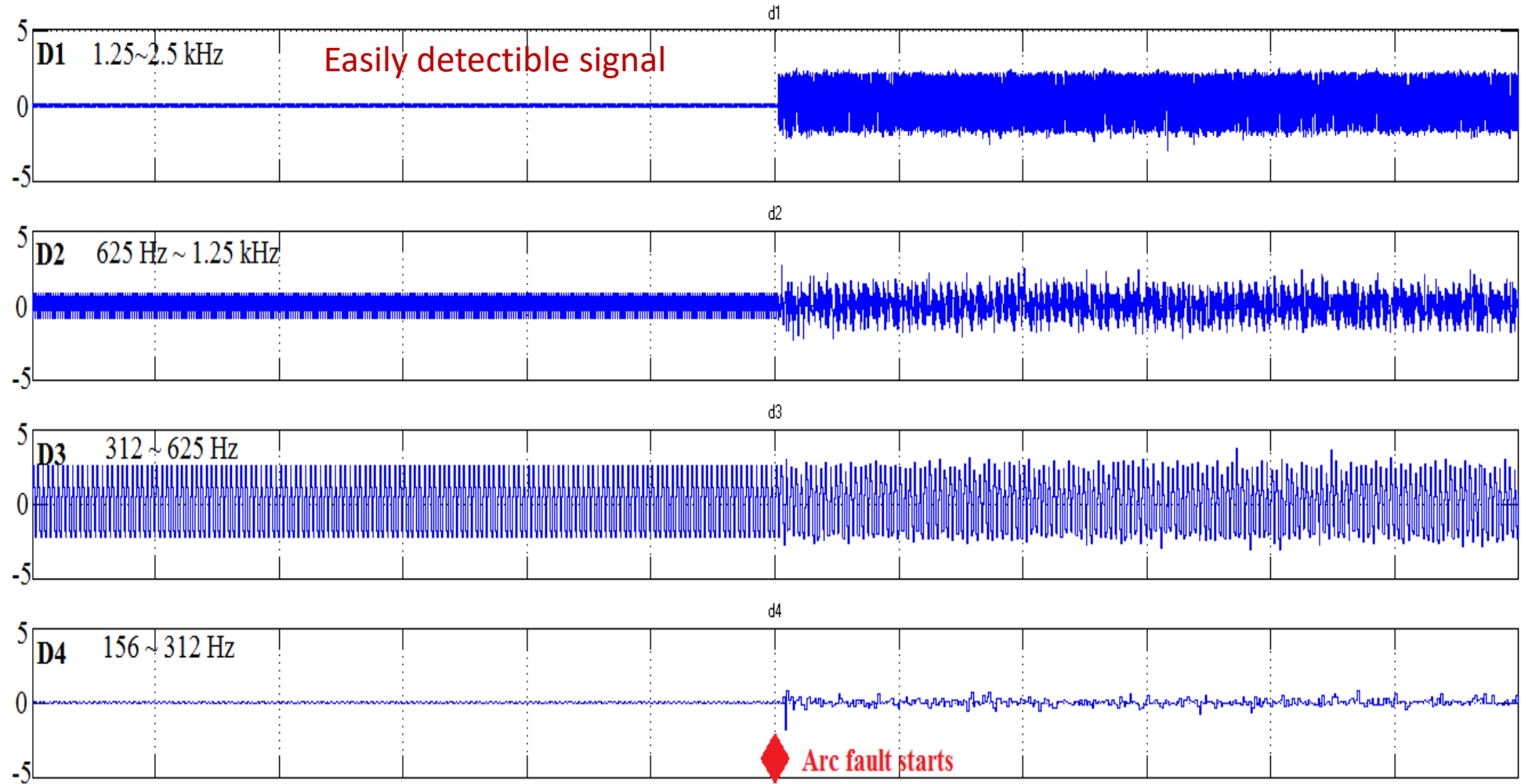
1,000Vdc with
120Hz and
2,000Hz superimposed



NO DETECTIBLE
DIFFERENCE in Spectrum

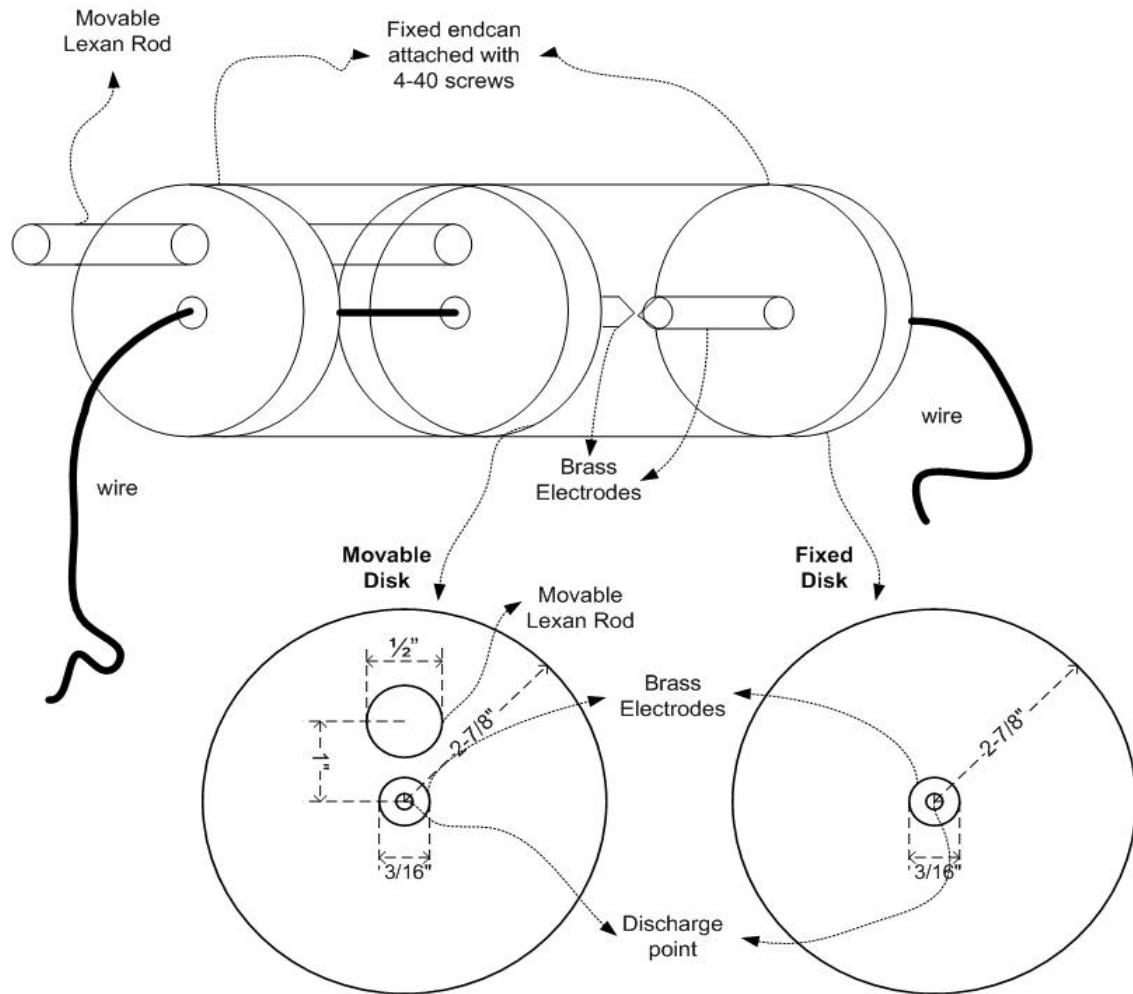


Simulation: Wavelet Decomposition



Experimental Verification

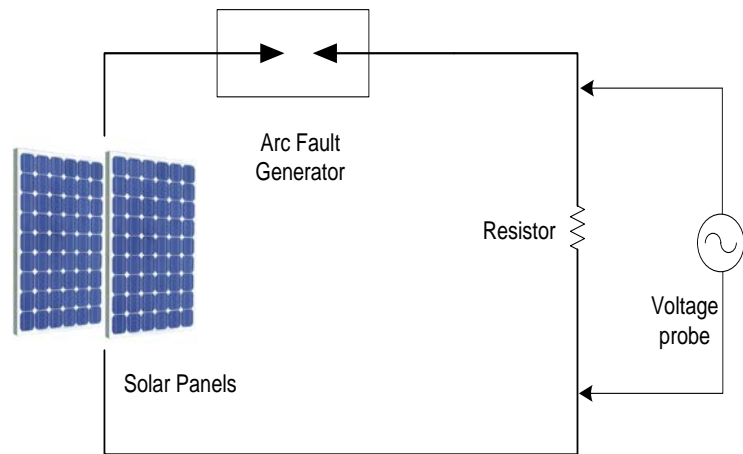
Experiment Setup – Arc Fault Generator v1



“Pull-Apart method” from Sandia National Laboratory / UL 1699B

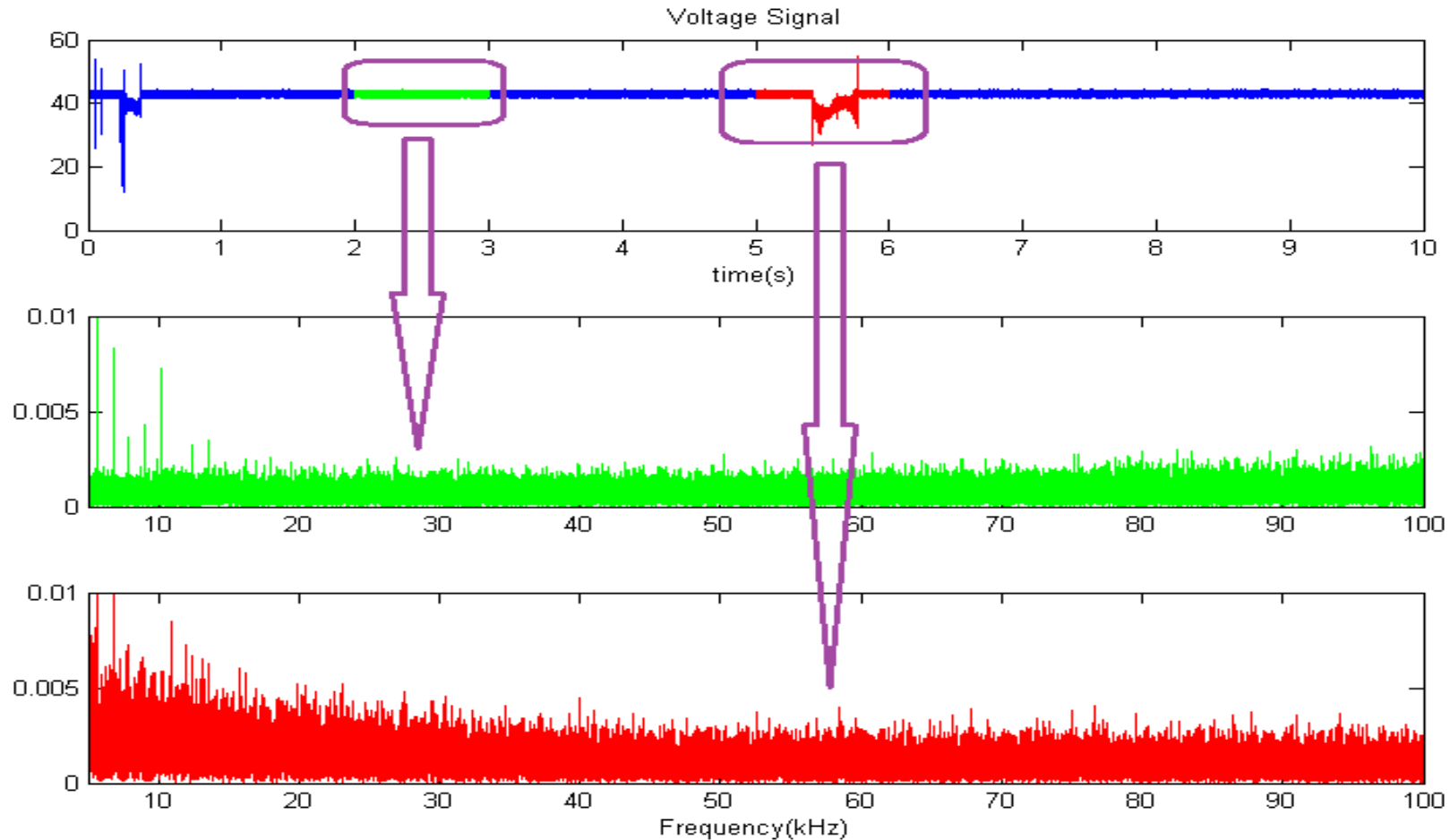
The generator is comprised of two brass electrodes (a stationary electrode and a movable electrode) contained in a polycarbonate tube for safety.

Testbed Setup



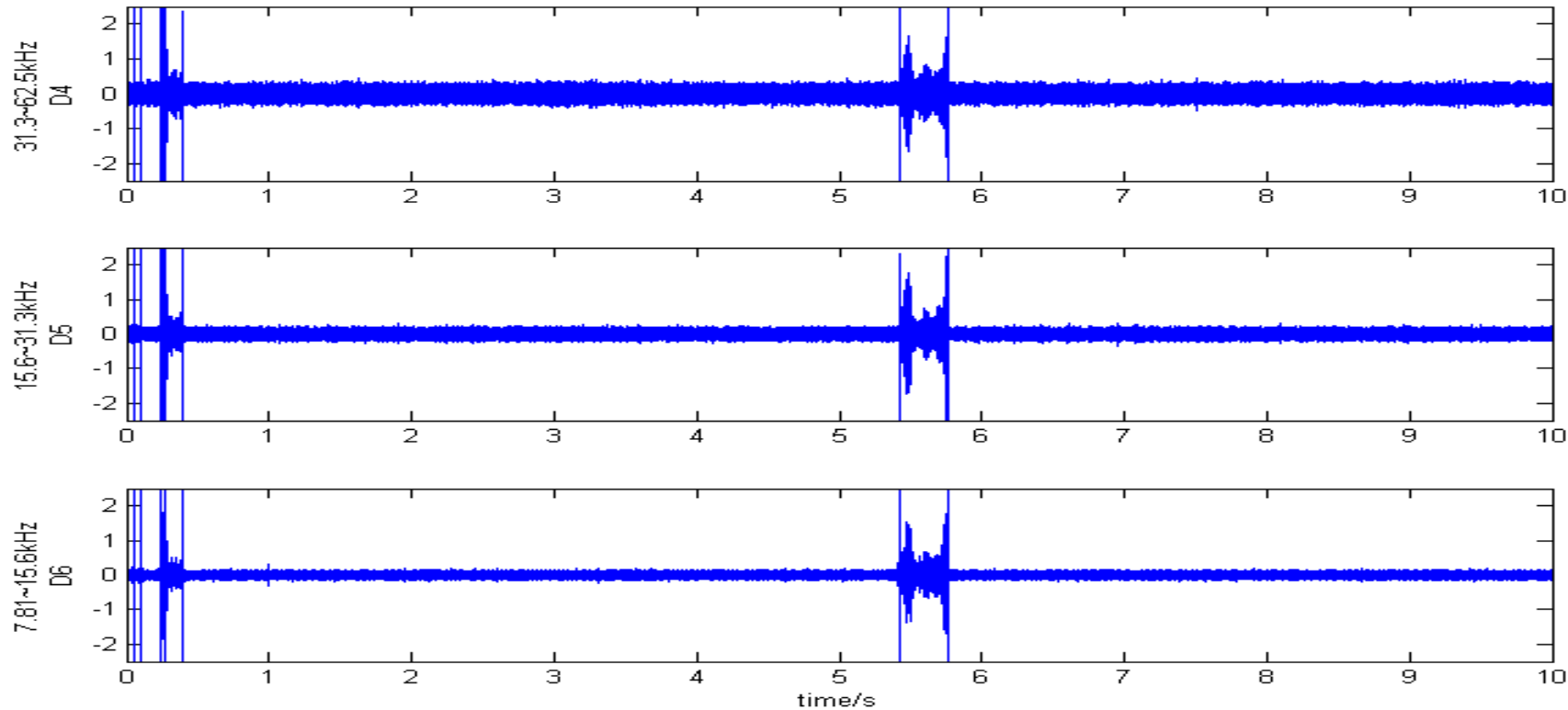
The series arcing condition is created initially placing the electrodes in contact and then gradually separating the two electrodes until a desired air gap, in this case 2mm, is achieved. This is the so called “pull-apart method” for generating a series arc.

Load Voltage Signal Processing - FFT



Some literature on arc fault signal analysis in DC systems reports the arc signal bandwidth as 5kHz – 40kHz, others suggest as high as 200kHz

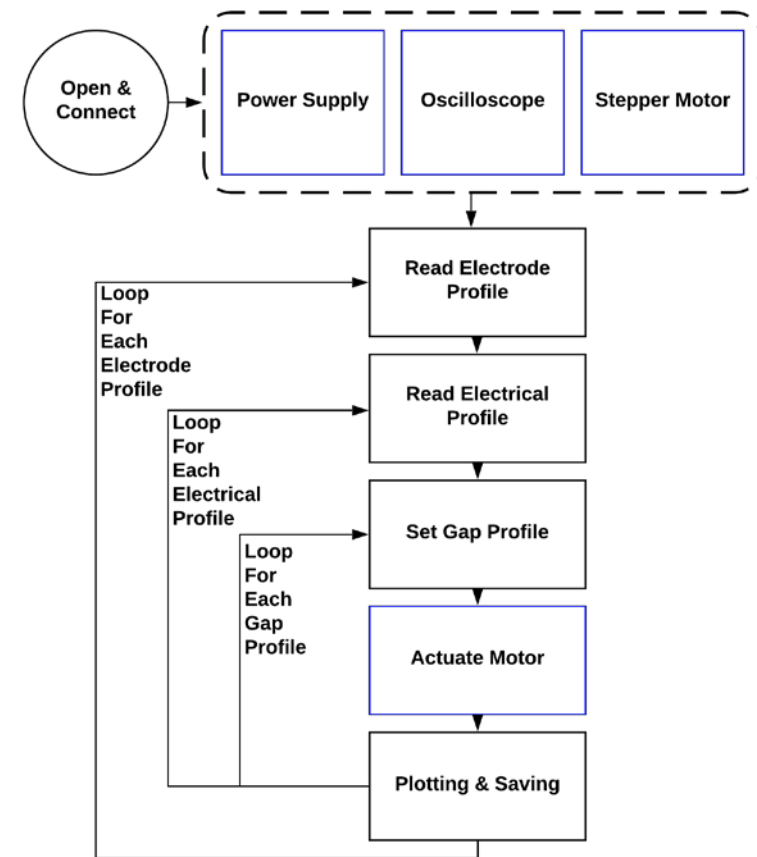
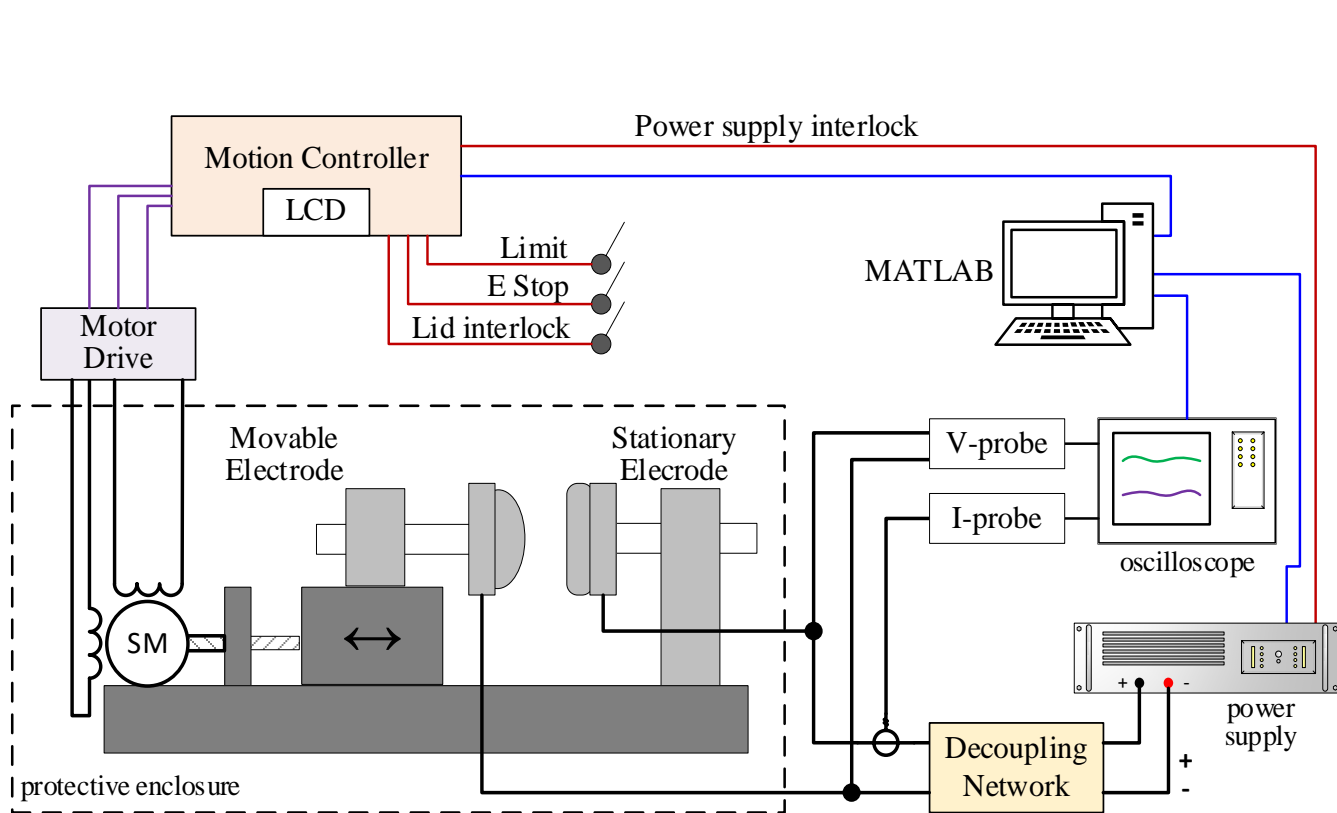
Load Voltage Signal Processing - DWT



- Given that the bandwidth for the arc signal bandwidth is reported to be 5kHz – 40kHz
- For the wavelet decomposition, the frequency band of the 4th – 6th level of wavelet decomposition was selected to be approximately 7.8 kHz – 62.5 kHz

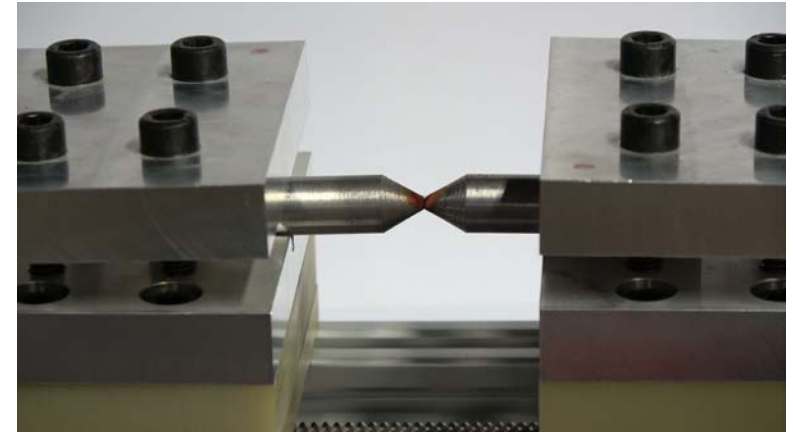
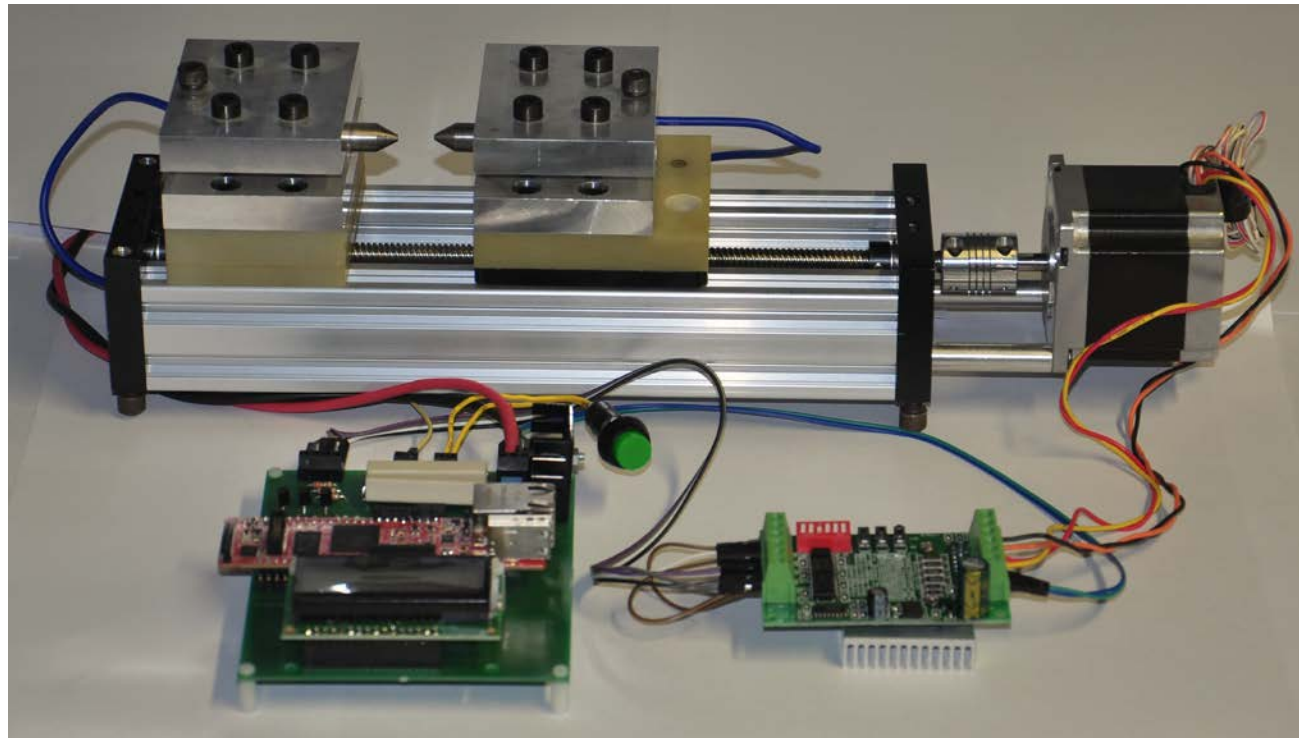
Automated Arc Generating Test Bed

Mechatronics systems provides precise computer control and repeatability

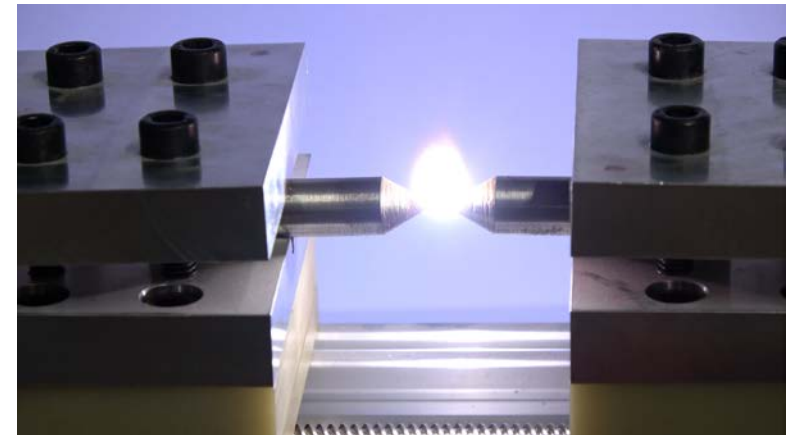


Automated Arc Generating Test Bed

Experimental arc generation. The electrode geometry is conical and the material is stainless steel. The electrical profile is 200V and 1A.



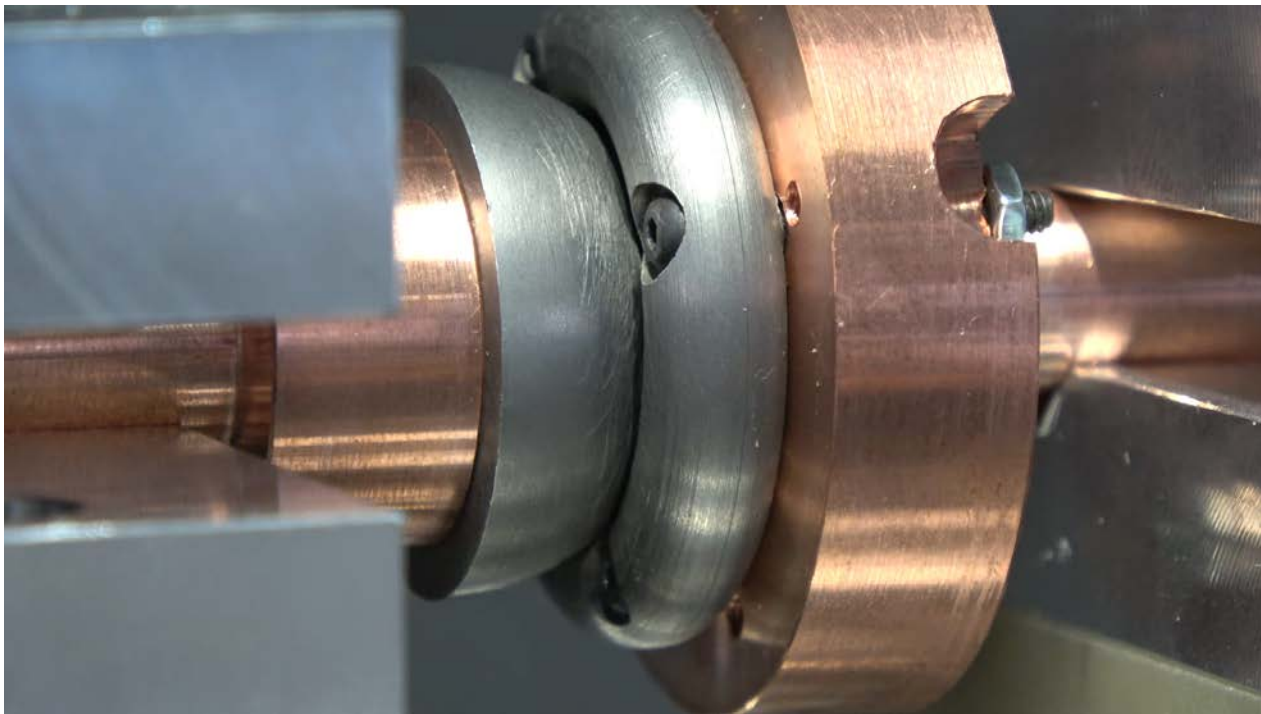
No gap - electrode touching.



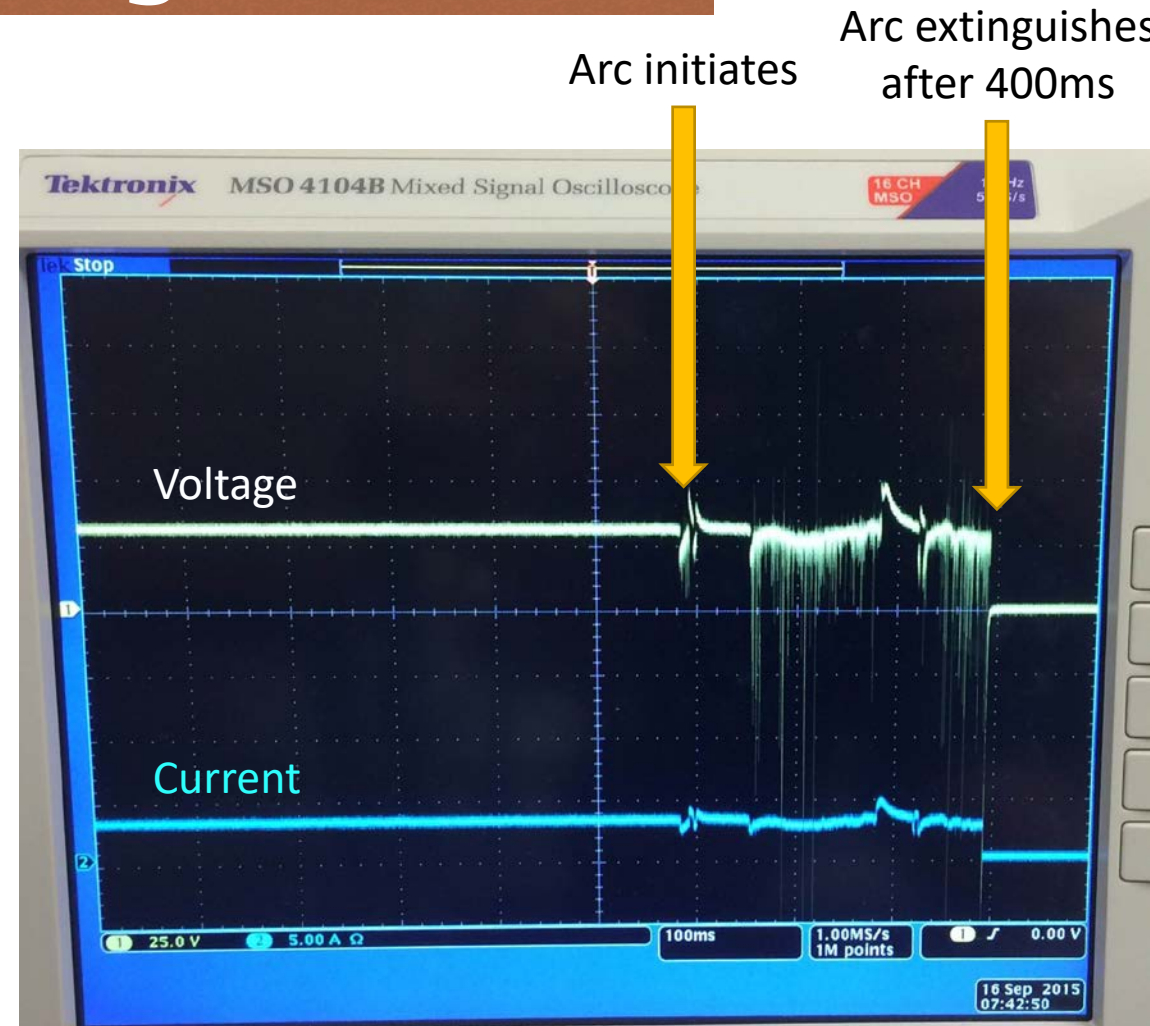
5mm gap

Automated Arc Generating Test Bed

Mechatronics systems provides precise computer control and repeatability with automatic collection of signal data



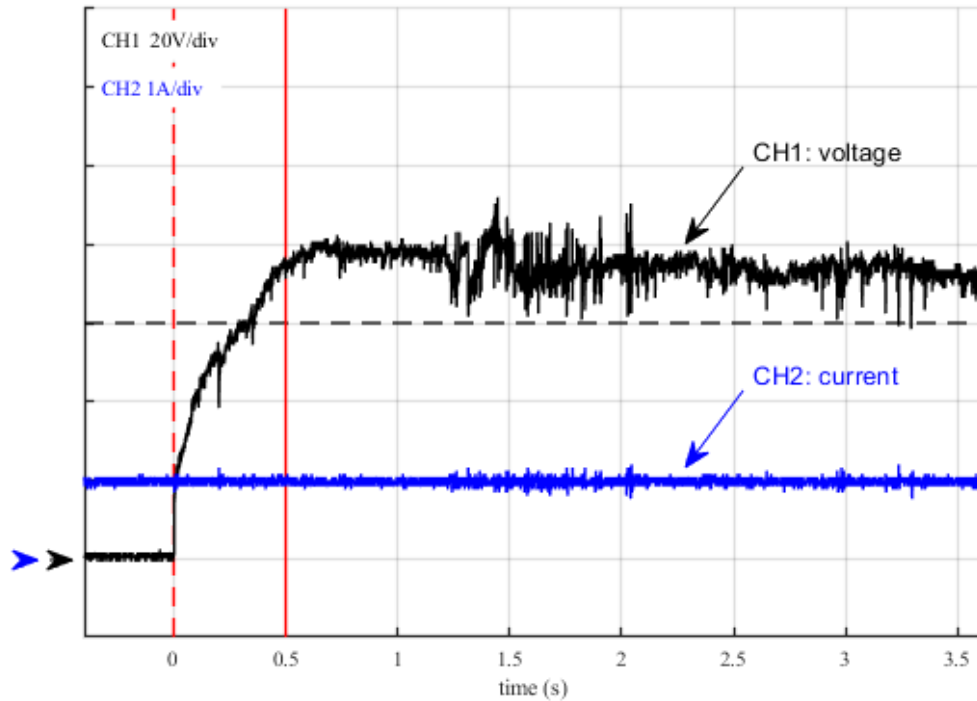
Sintered tungsten "ball and ring" electrode.



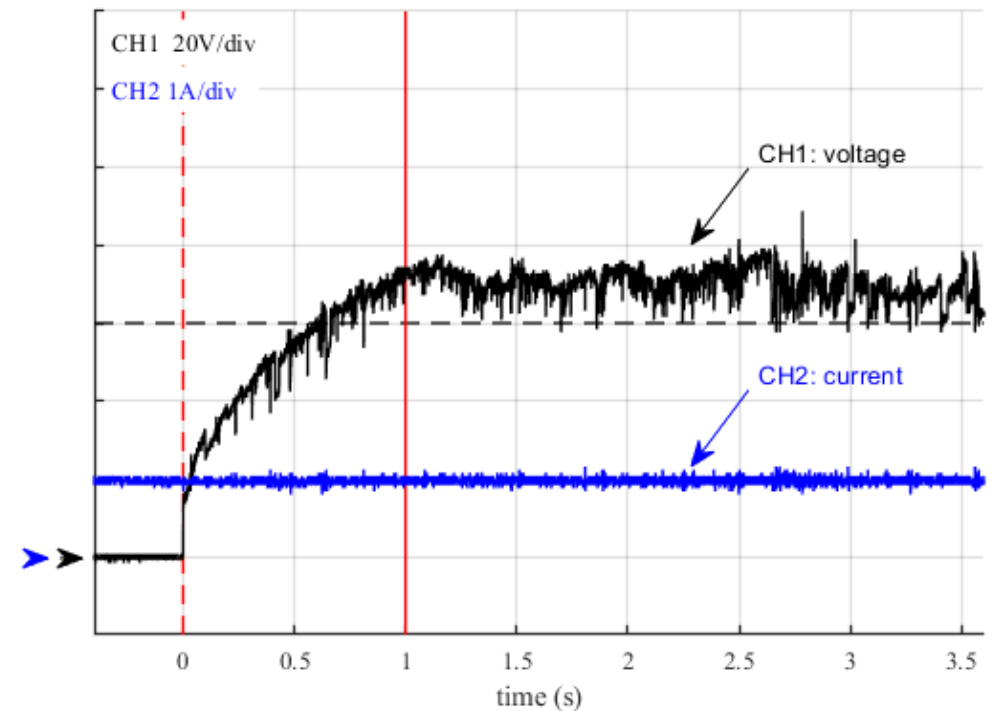
Resistive load with series arc using pull-apart

Effect of Electrode Separation Velocity

5mm separation in 0.5s



5mm separation in 1s

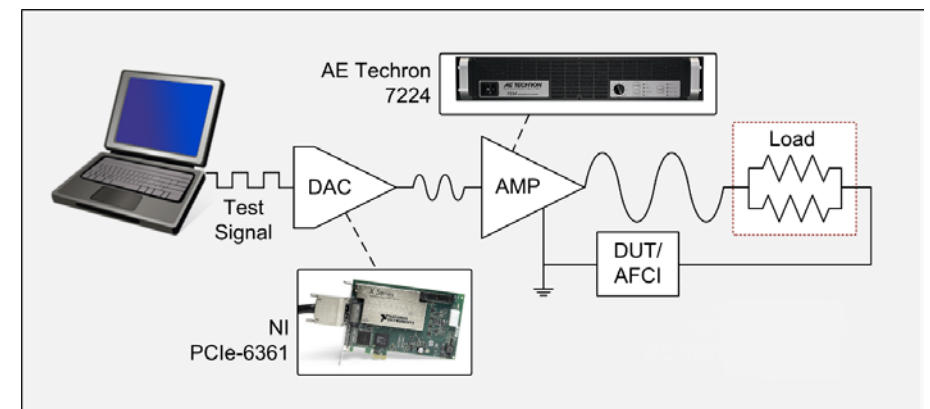


Experimental arc generation. The electrode geometry is conical and the material is stainless steel. The electrical profile is 200V and 1A.

Replay Method

“Replay Method” Arc Fault Testbed

- Waiting for an arc to naturally occur is time consuming!
- Arcs can be created using an pull-apart arc generator connected to a PV system
 - However, this method requires large experimental effort
 - The arc power is uncontrollable – based on MPPT of PV system
 - Not scientifically repeatable
- Trying to create one in the lab has too many variables and does it even represent the real work?
- An arc study testbed that can create arc signal precisely with highly repeatable operation is needed



Signal Analysis Using Composite Signal

- Designing an experiment to create **scientifically repeatable results** is difficult because of the unpredictability, and lack of control over the arc characteristics including ignition, duration, and stability.
- Sustained arc faults possess **chaotic** electrical characteristics, which makes it impossible to scientifically repeat the experiment with **consistent** test data.
- We synthesized a signal using time-domain inverter noise signal data measured from a PV array and time-domain arc signals obtained from an arc generator. We define a metric called the **arc-signal-to-noise ratio (ASNR)** which determines the proportion of power from each source in the composite signal.
- Adjusting this user-specified parameter in the synthesizing process enables the **synthesis of a family of test signals for validation, sensitivity, and efficacy studies** of the detection algorithm **based upon real-world signals and scenarios**.

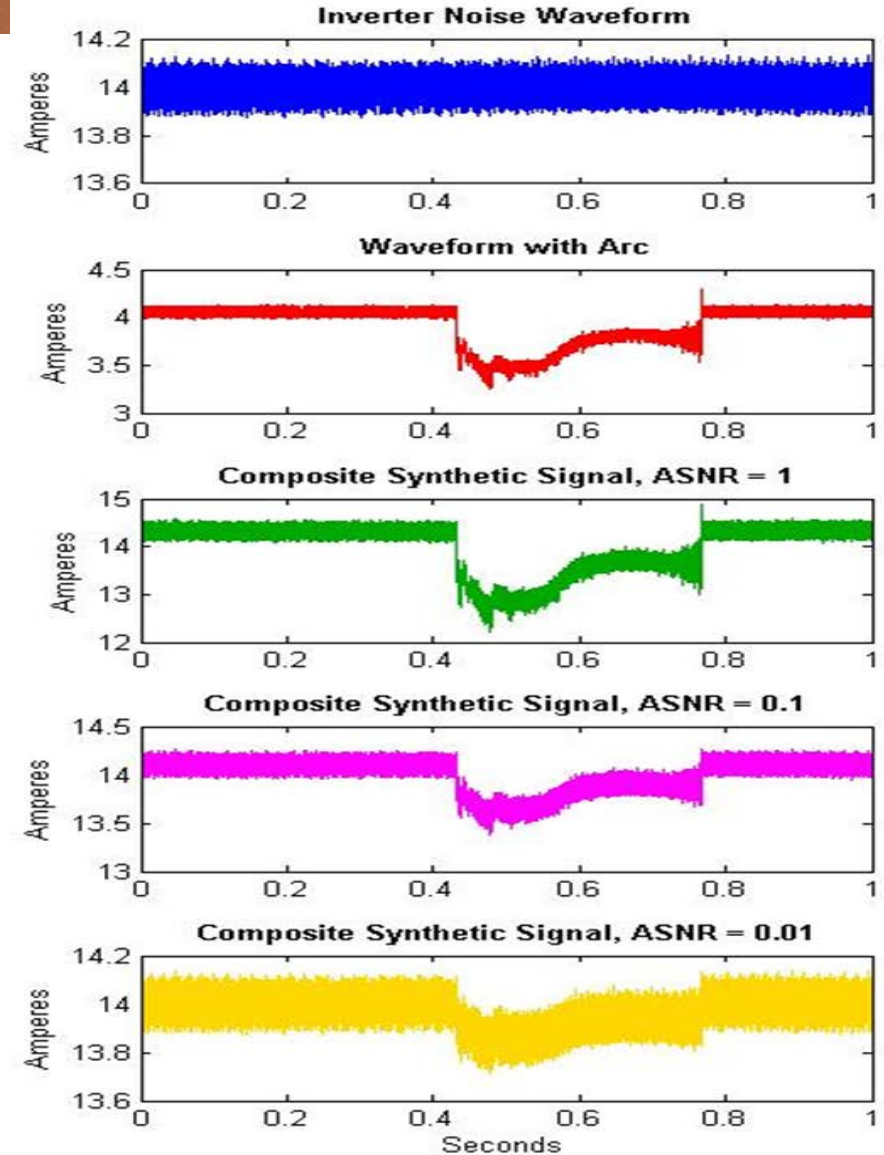
Arc Signal to Noise Ratio

- Define the **arc-signal-to-noise ratio (ASNR)** which determines the proportion of power from each source in the composite signal.
- Replicates attenuation of the arc based on location in the array.

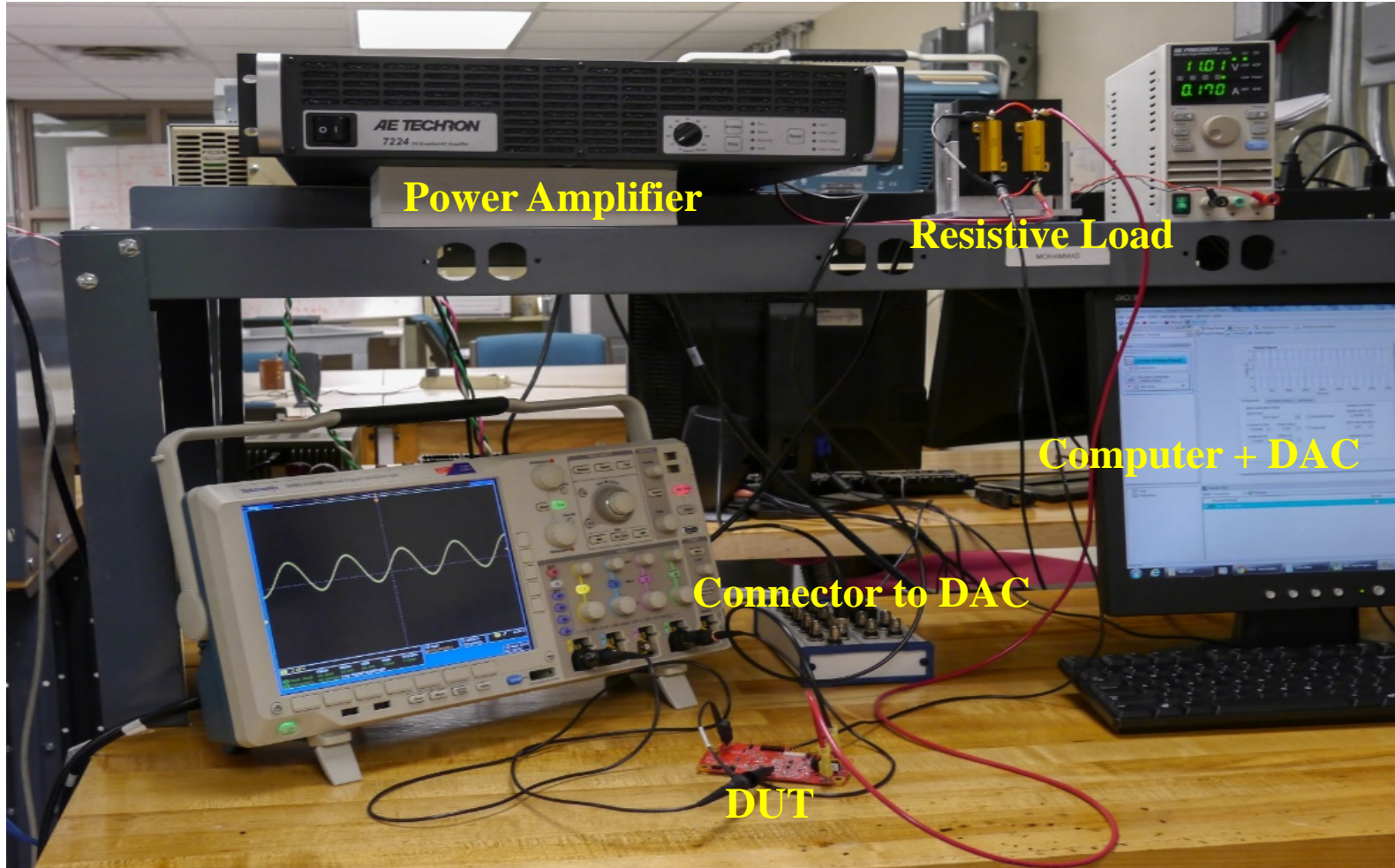
$$ASNR = \frac{P_{arc}}{P_{noise}}$$

- Synthesize a signal using time-domain inverter noise signal data measured from a PV array + time-domain arc signals measured from an arc generator:

$$Arc_{composite} = Inv + Arc \times \sqrt{\frac{ASNR_{desired}}{ASNR_{original}}}$$



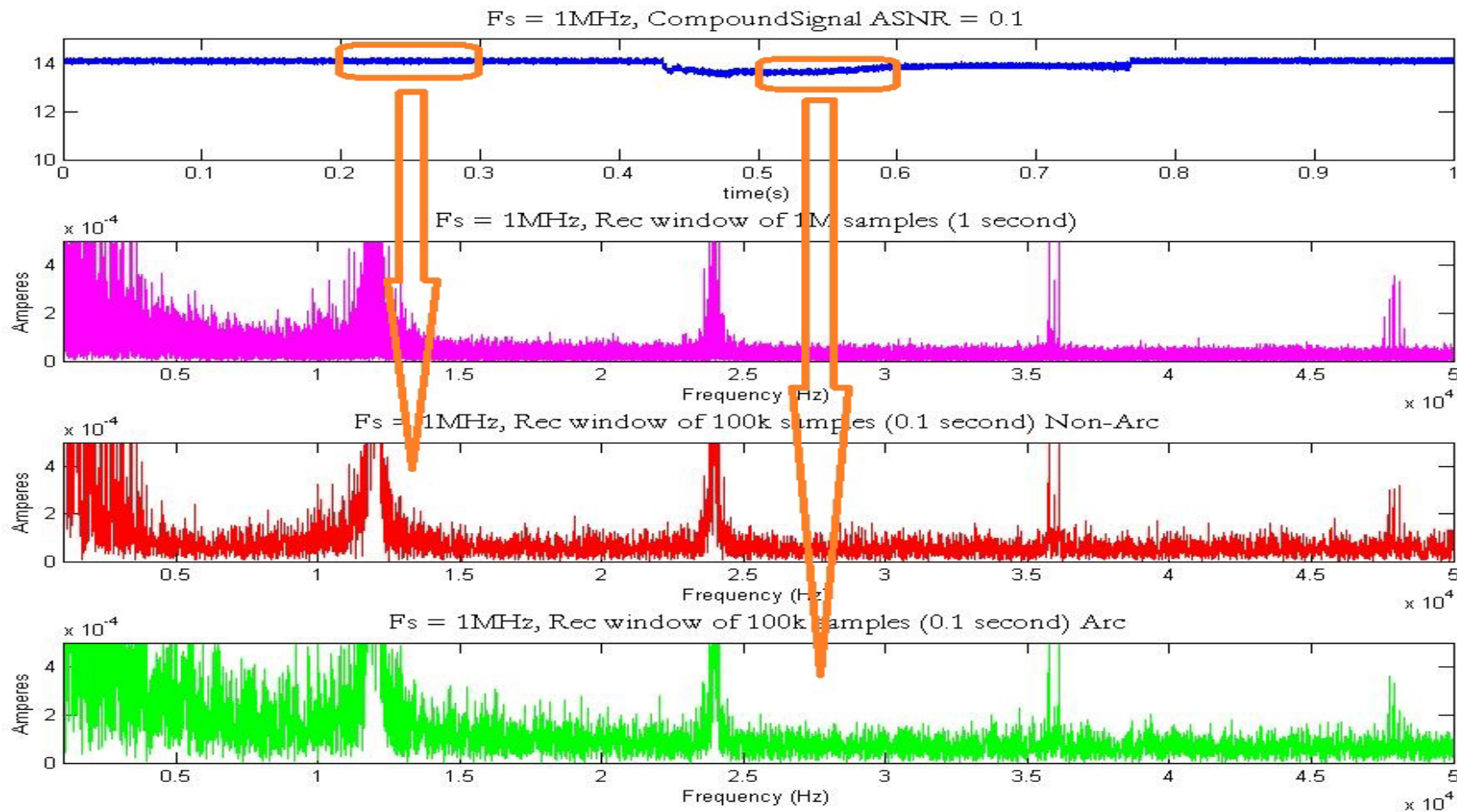
Lab Setup



- Arc signals are generated and recorded
- PV system operation is recorded including inverter noise
- “mix” the two and adjust the ratio of arc signal to system signal
- Amplify using wide bandwidth liner amplifier

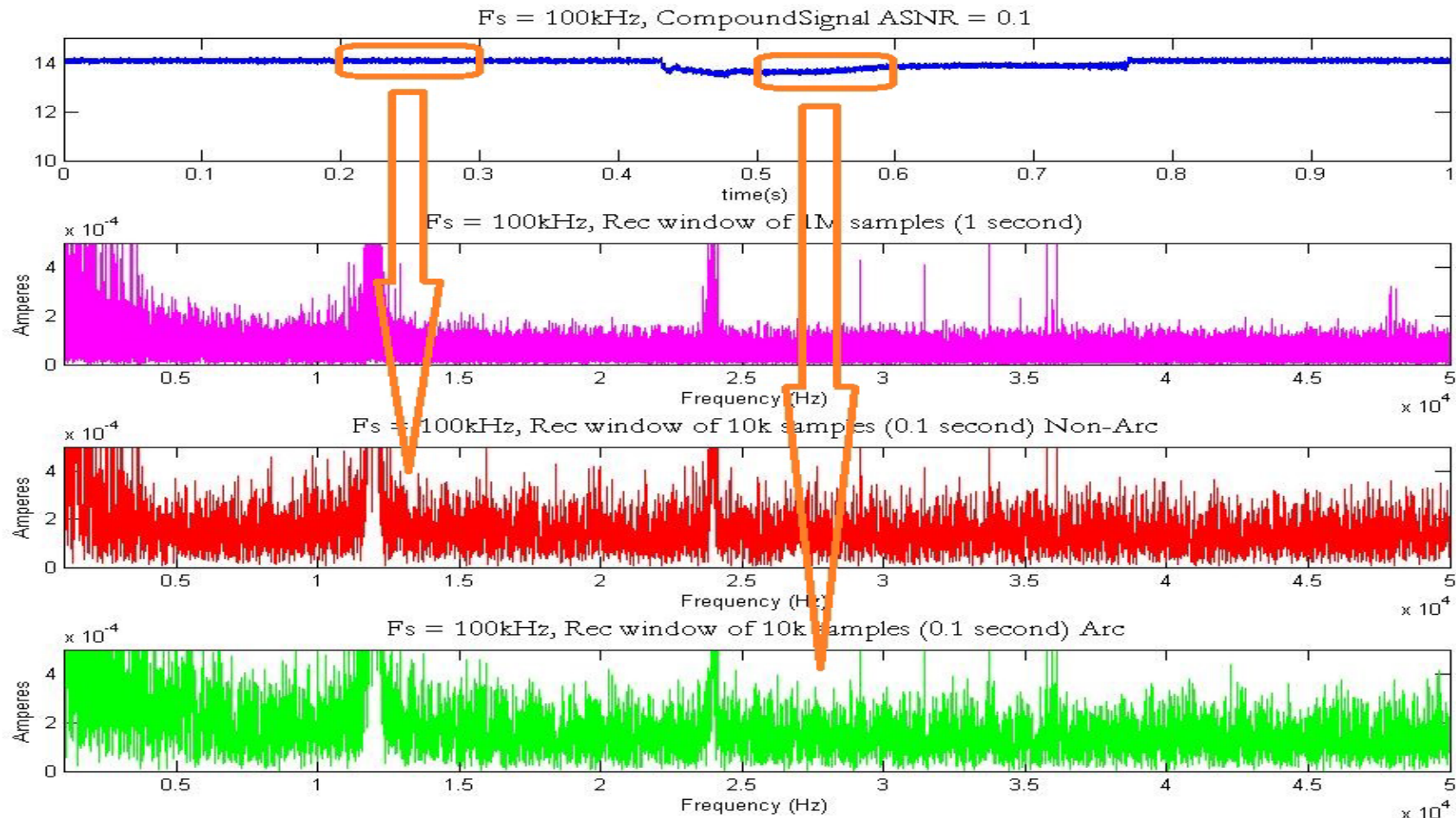
Composite Signal ($F_s=1\text{MHz}$)

FFT:



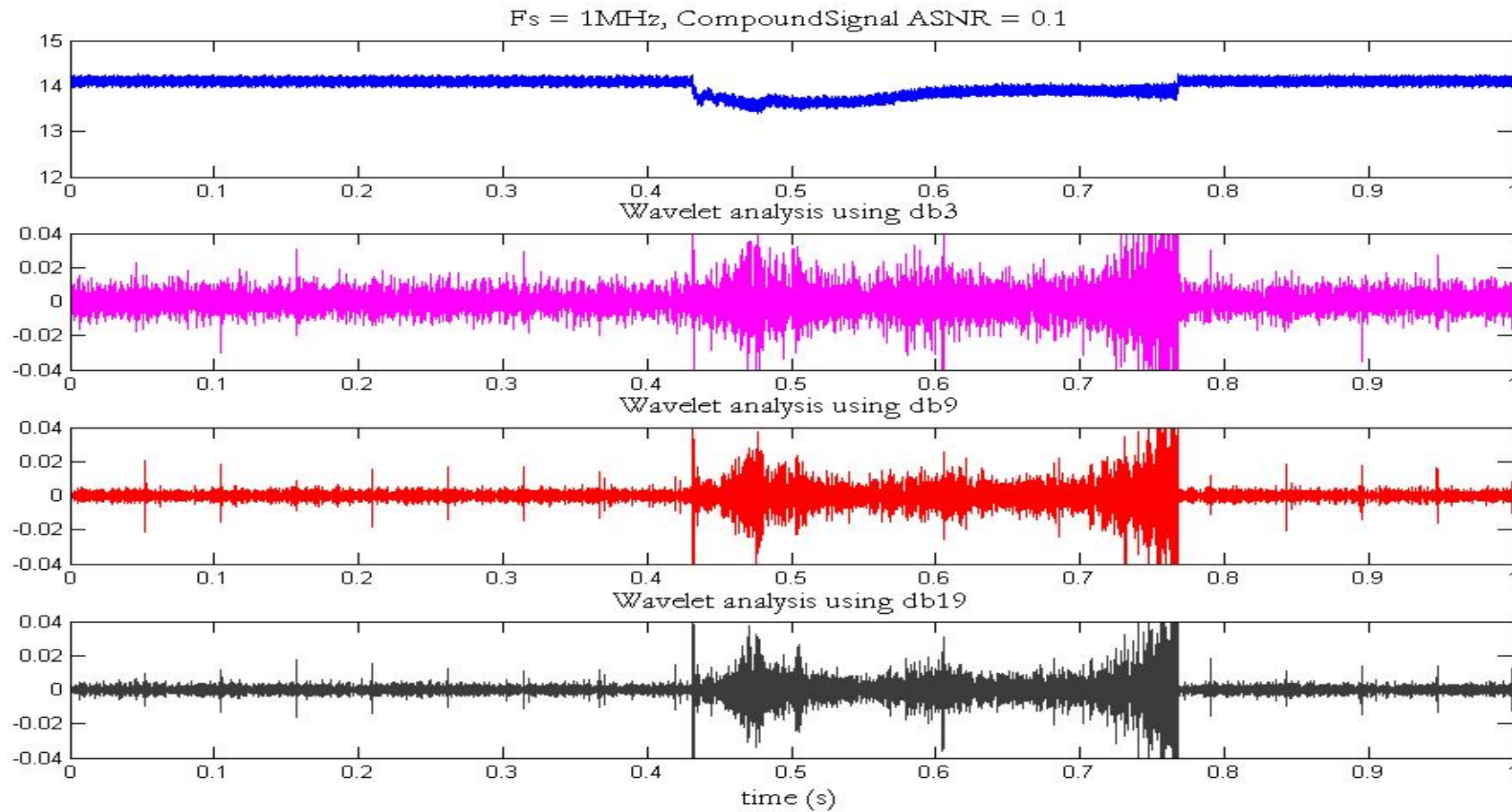
Composite Signal ($F_s=100\text{kHz}$)

FFT:



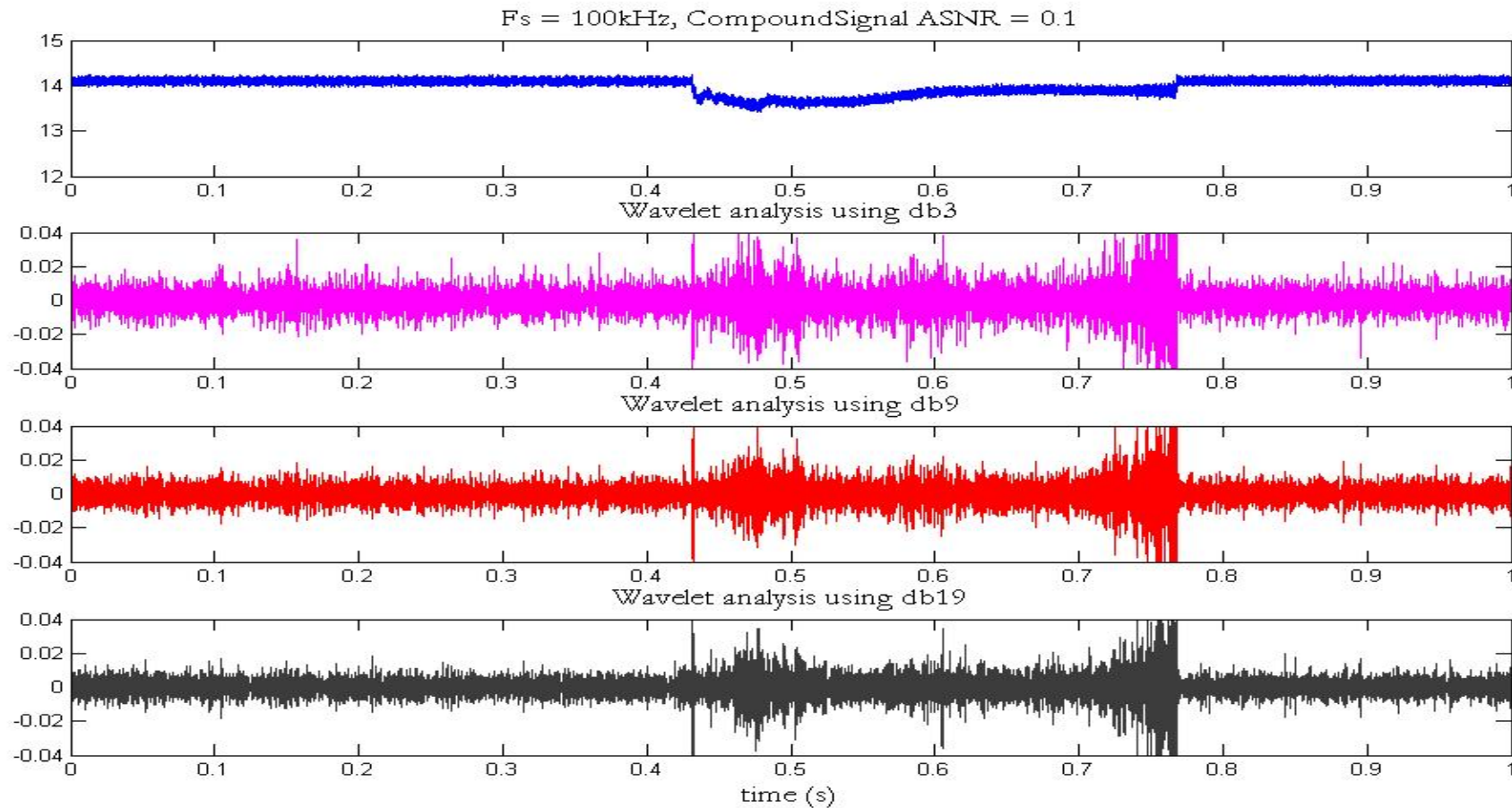
Composite Signal ($F_s=1\text{MHz}$)

DWT:

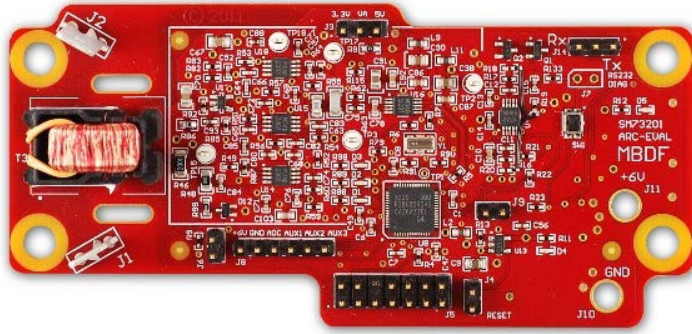


Composite Signal ($F_s=100\text{kHz}$)

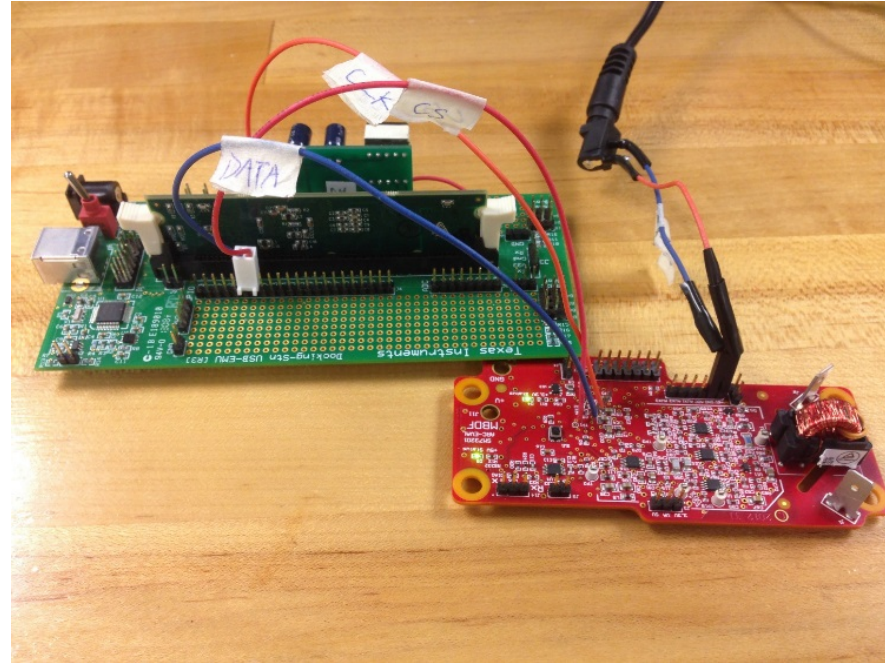
DWT:



Hardware Implementation



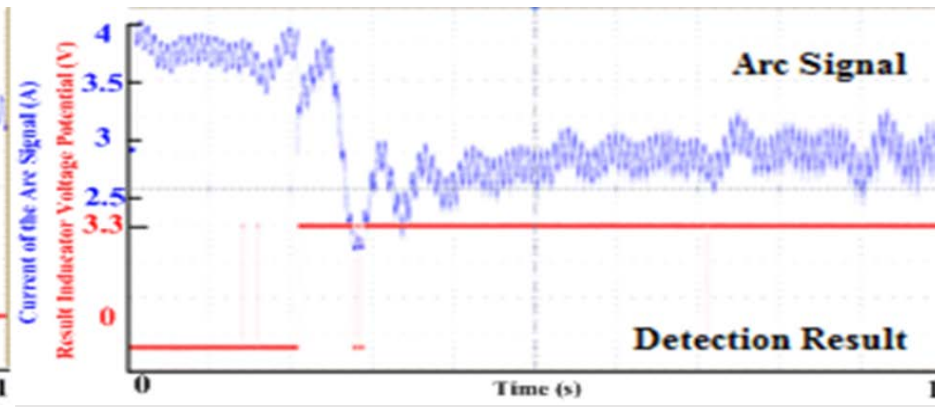
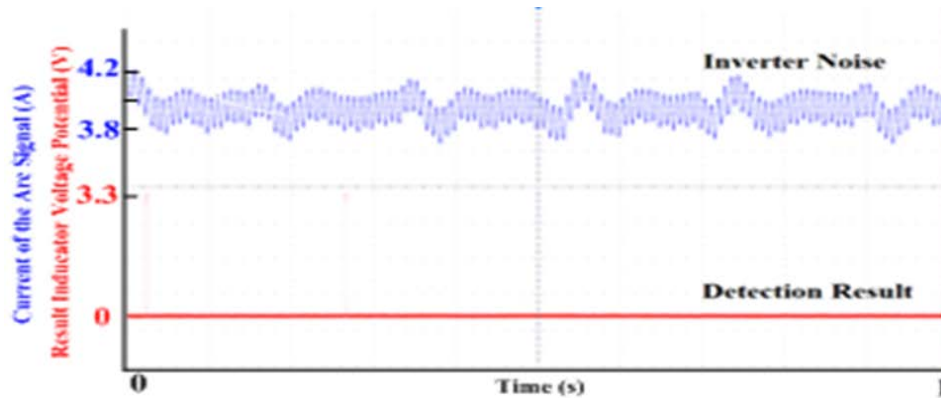
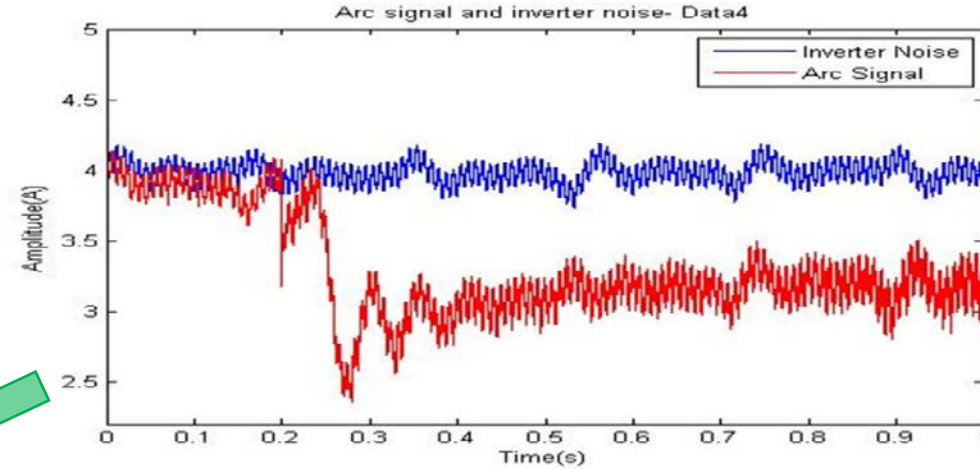
Experiments modified the TI RD-195 to add the TI F28335 processor.



Selected Wavelet	db3	db4	db5	db6	db7	db8	db9
Time Needed for DWT (us)	0.6	0.72	0.84	1.02	1.16	1.32	1.46
Bandwidth (kHz)	138.9	127.6	130.2	124.4	120.2	116.7	112.1

Real-Time Detection Using Replay System

- $R = P_{processing} / P_{reference}$
- If $R > 1.4 \rightarrow$ the frame being processed is determined to contain a potential arcing event.



Analysis and Conclusions, so far...

1. It is **difficult** to find any significantly **detectable arc fault features** by comparing the FFT results of the non-arcing part and the arcing part of the signals.
2. Wavelet analysis plots, **arc features can be easily distinguished from the non-arcing signal** and selection of a detection criteria potentially suitable for an embedded microcontroller for real-time arc fault detection.
3. Wavelet transform preserves the **time-domain localization information**, the precise time of the arc is available for cross-correlation with other events in the system and environment which may **improve the confidence** of arc fault detection rather than some other benign electrical events.
4. DWT is ideal for **real-time sample-by-sample** implementation since the computation load is similar to a simple FIR filter. FFT is not suitable for sample-by-sample analysis in real-time.
5. **Optimize wavelet selection:** Comparing 3 different Daubechies wavelets, we conclude that the decomposition results from db9 and db19 are significantly better than those from db3, which is expected according to the frequency responses of the wavelet filters being used. But db19 doesn't provide much improvement over db9.

Arc Signal Detection Using DWT and SVM

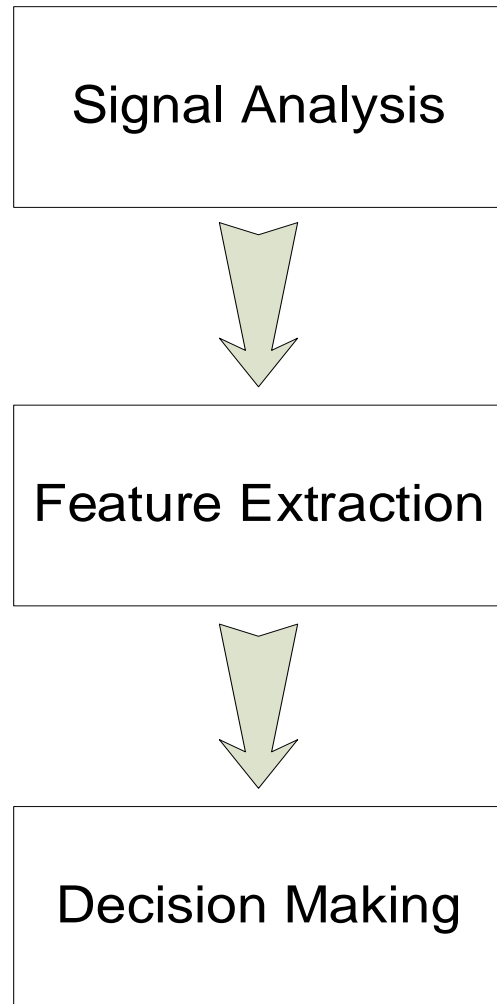
Detection Criteria

- Two arc fault detection failure modes:
 - The detection device fails to detect the arc fault.
 - The detection device falsely indicates an arc.
- The question becomes, **how to formulate detection criteria** that can be algorithmically implemented and is robust and accurate
 - Avoid no-detection.
 - Avoid false detection.

Machine Learning/ Classification Rule

- Although wavelet analysis has been demonstrated to be effective with arc fault signal analysis, practical implementation needs a way to distinguish arc/non-arc events and provide annunciation that can be included in a DSP or microcontroller.
- A more robust way is to classify the feature vectors acquired by the wavelet transform.
- The classification model, which includes both the model structure and specified values of the model parameters, is programmed into the Arc Fault Detector (AFC).

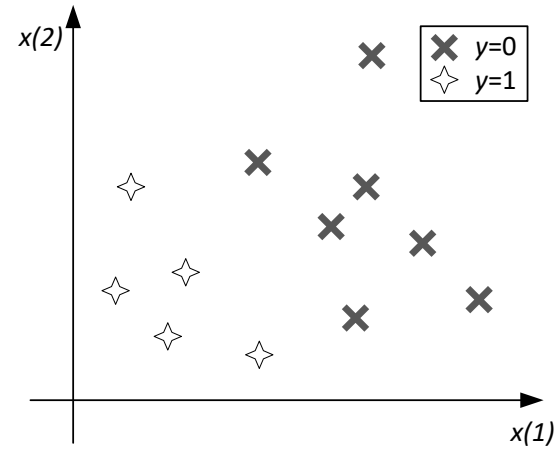
Work Flow of the Process



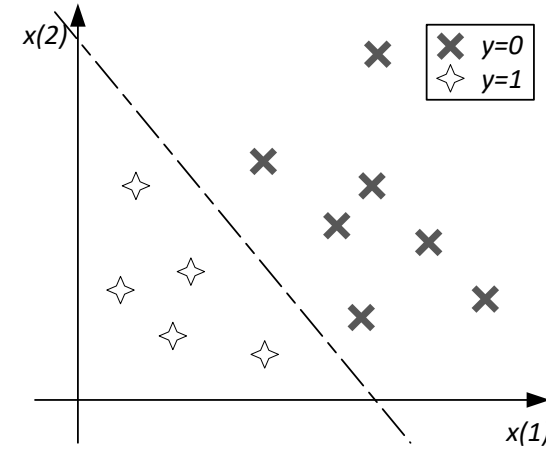
- The work flow of the detection process involves data acquisition, signal analysis, feature extraction (including data preprocessing and rescaling), and decision making (classification).
- Typical raw attributes to arc fault detection may involve ambient temperature, PV module temperature, average power, current flowing through the conductor, and other related electrical measurements.
- Current or voltage signals are used in this work as raw attributes for series or parallel arc detection.

Machine Learning

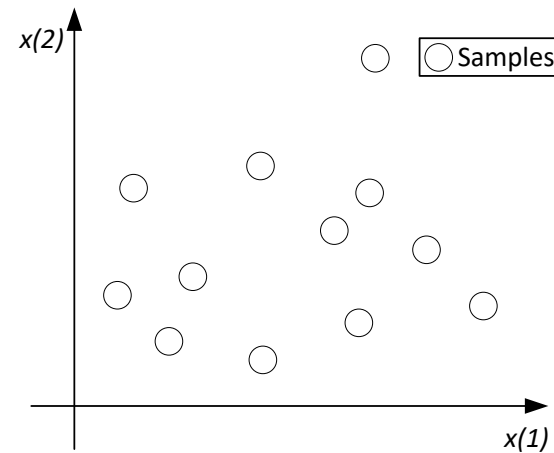
Supervised Learning



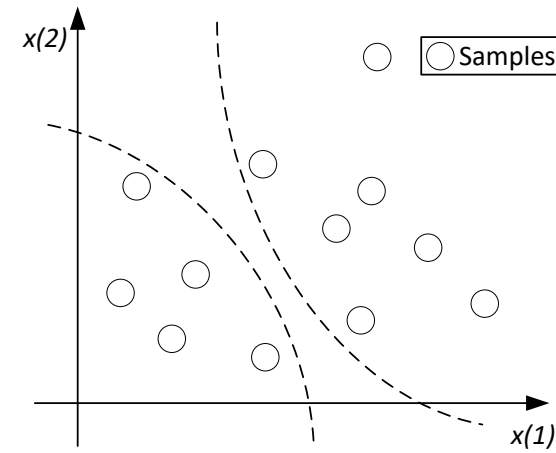
Classification



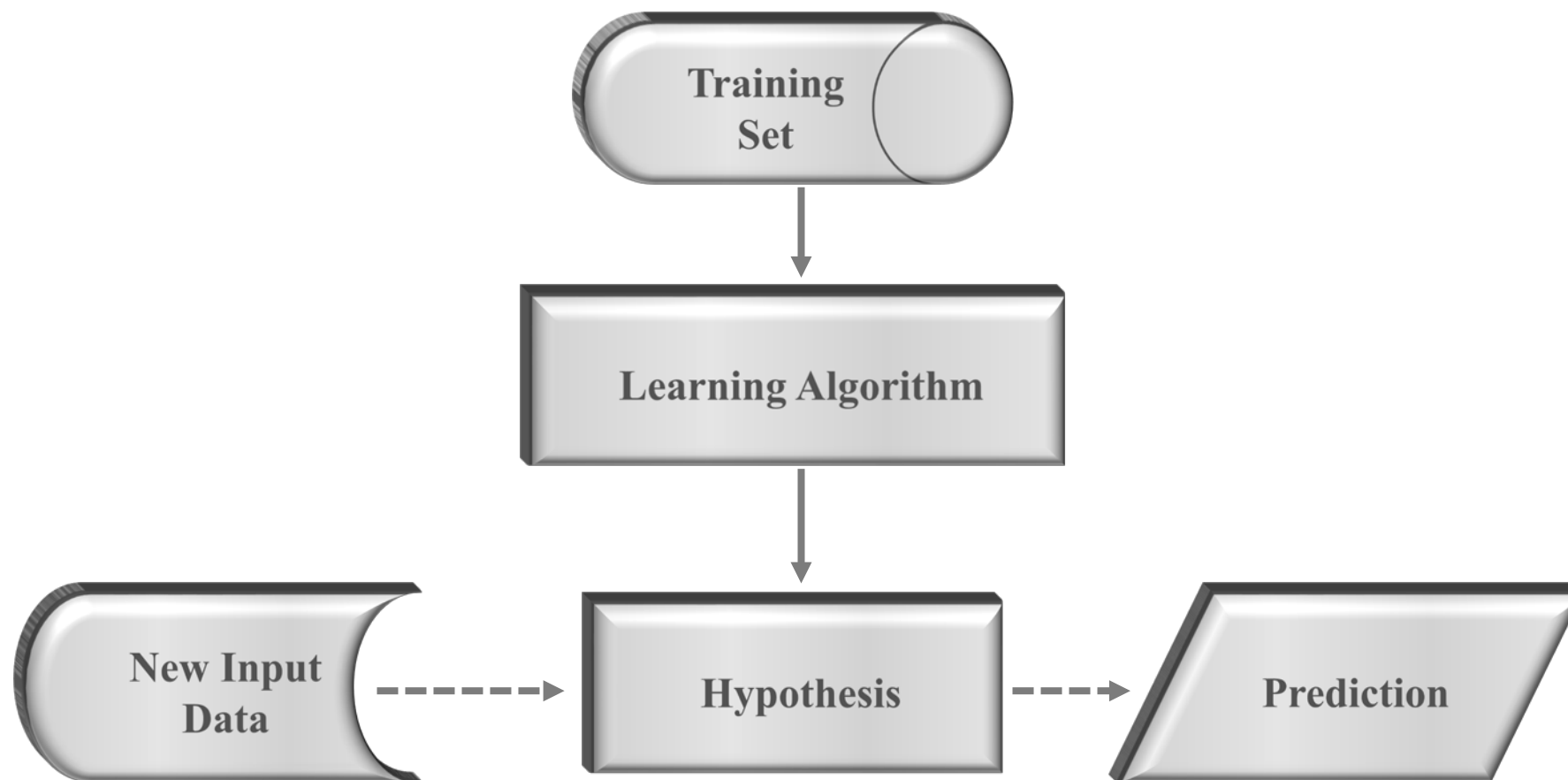
Unsupervised Learning



Clustering

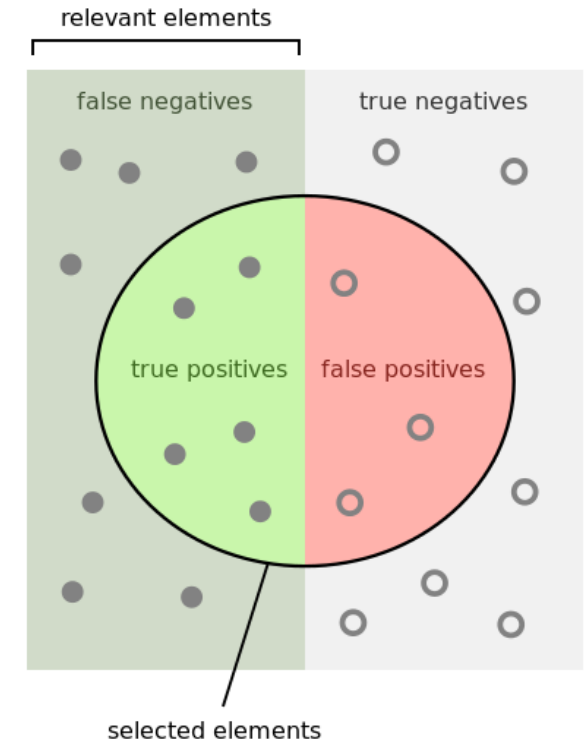


Supervised Learning



Precision vs. Recall

- In pattern recognition and information retrieval with binary classification:
 - precision (also called positive predictive value) is the fraction of retrieved instances that are relevant,
 - recall (also known as sensitivity) is the fraction of relevant instances that are retrieved.
- Precision can be seen as a measure of exactness or quality
- Recall is a measure of completeness or quantity.



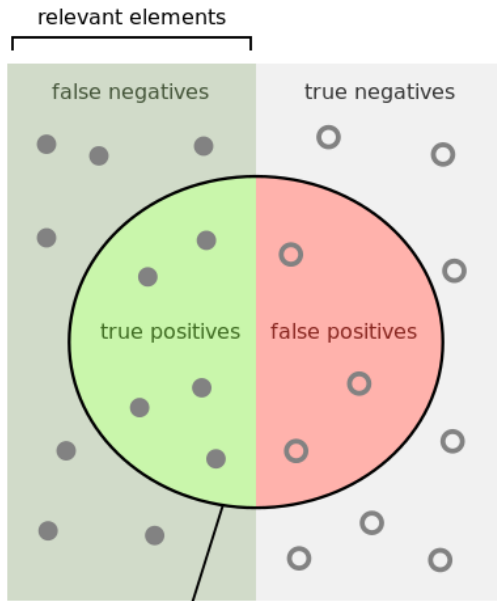
How many selected items are relevant?

$$\text{Precision} = \frac{\text{true positives}}{\text{true positives} + \text{false positives}}$$

How many relevant items are selected?

$$\text{Recall} = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}}$$

Precision and Recall in Arc Fault Detection

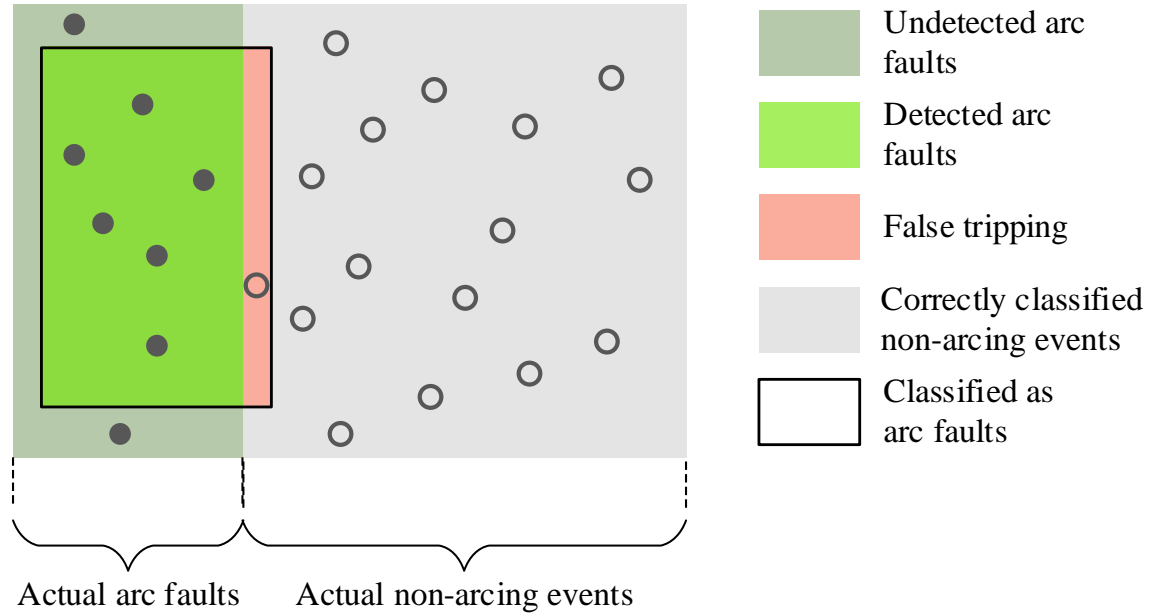


How many selected items are relevant?

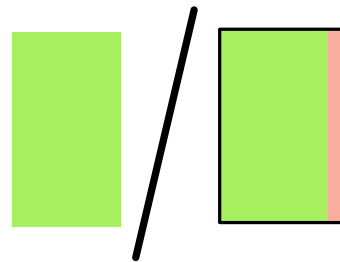
$$\text{Precision} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Positives}}$$

How many relevant items are selected?

$$\text{Recall} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Negatives}}$$

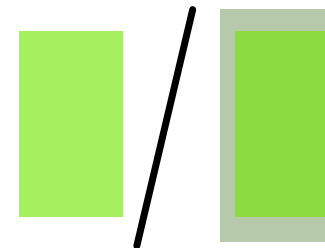


Precision =



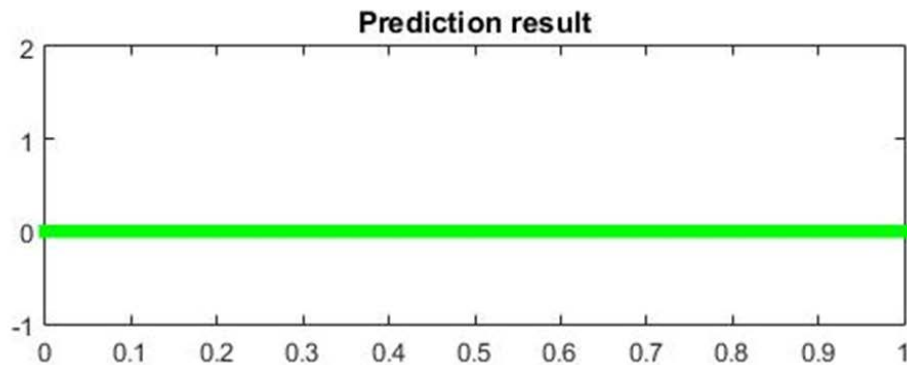
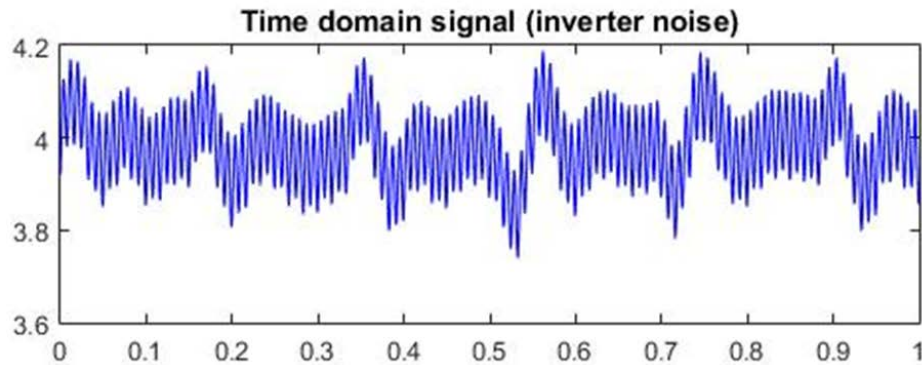
= Proportion of actual arc faults detected

Recall =

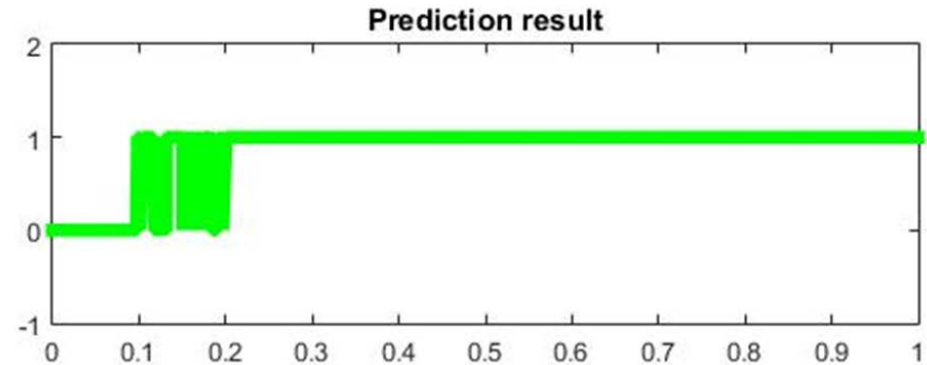
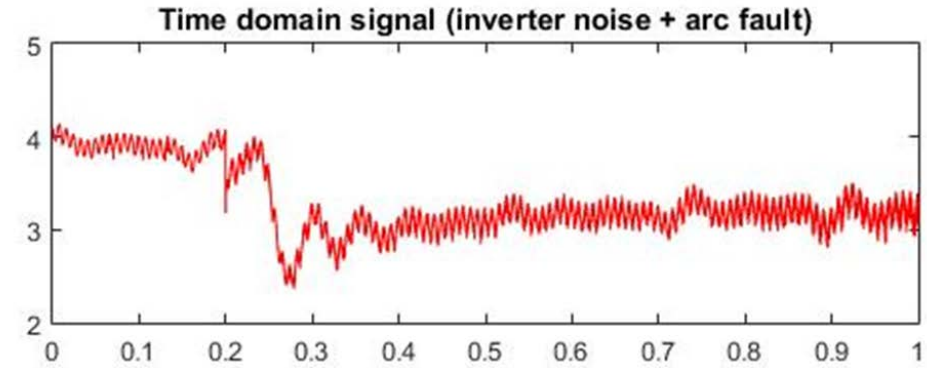


= Proportion of classified arc faults are actual arc faults

Simulated Real-Time Implementation



No false tripping

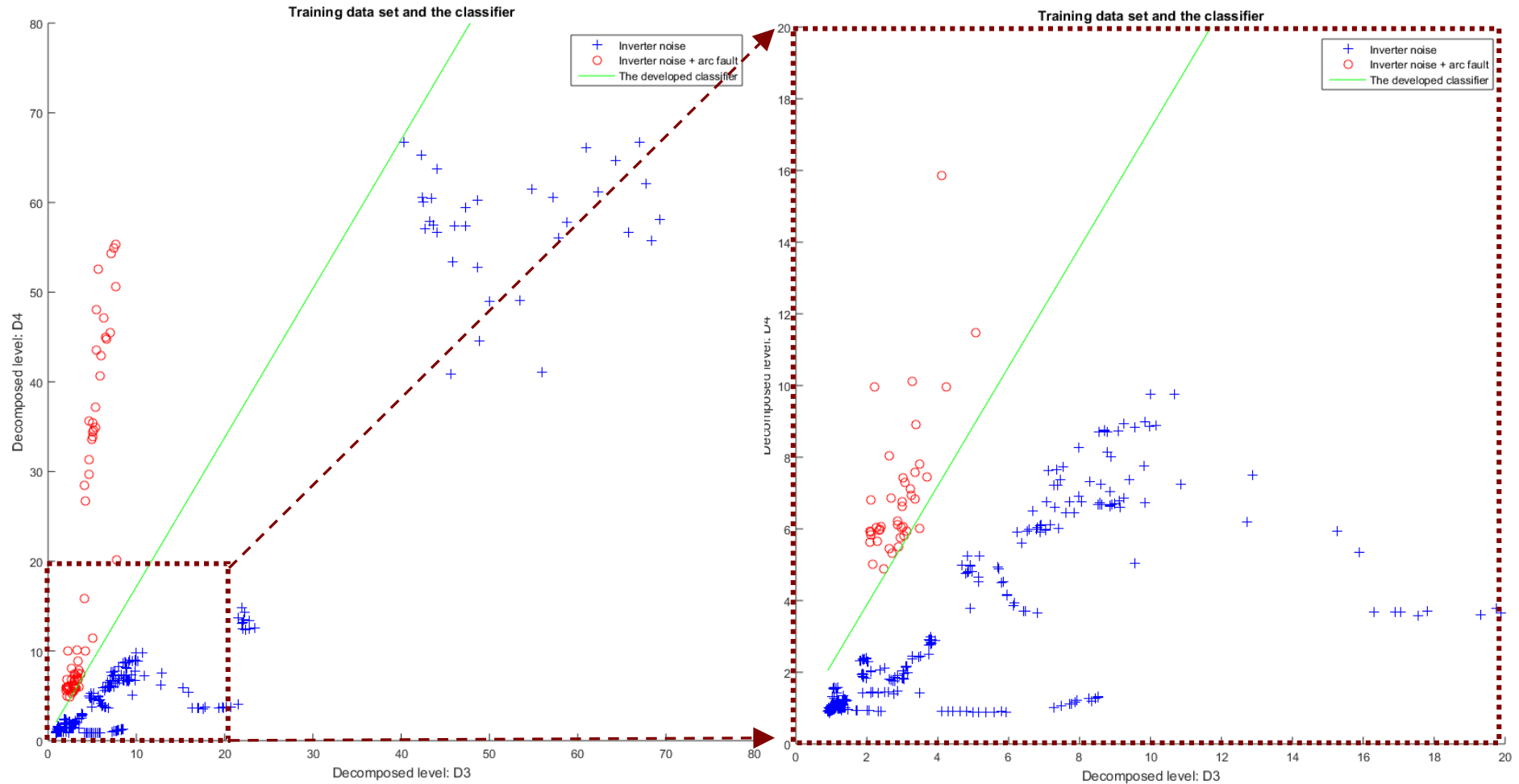


Accurate and fast response

Classification – Support Vector Machines

Linear feature set:

$$D(x) = \omega_1 x_1 + \omega_2 x_2 + b$$



Classification – Support Vector Machines

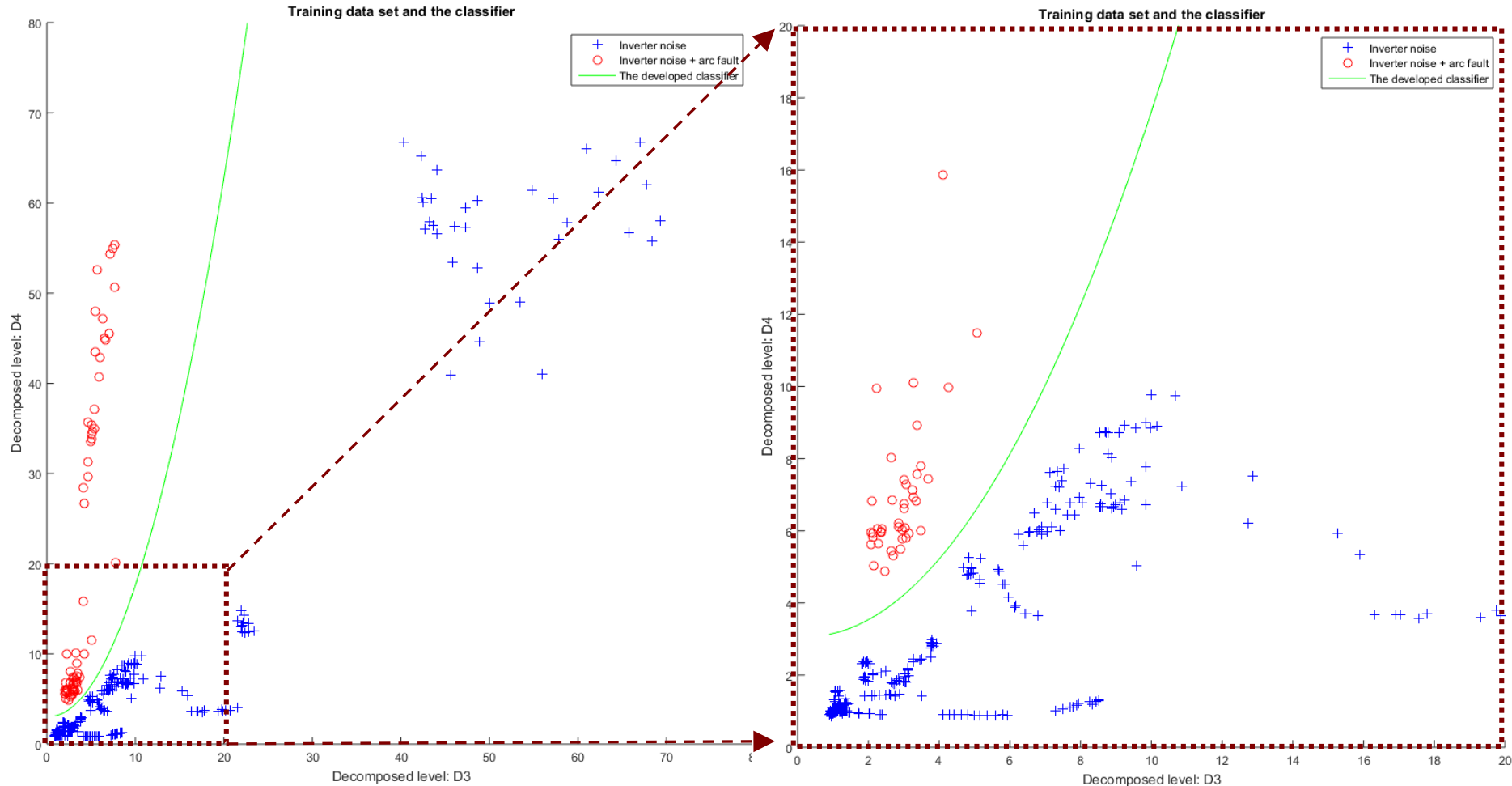
Semi-quad feature set

$$D(x) = \omega_1 x_1^2 + \omega_2 x_1 + \omega_3 x_2 + b$$



Accuracy = 100%

Precision = 1, Recall = 1



Conclusions

- Arc Faults and Arc Flashes are unavoidable hazards associated with electrical systems like PV
- Commoditization of components and wider-spread use of PV will likely increase the frequency of incidents
- Examined methods to detect and extract features of signals in the PV system
 - Wavelets seems to be ideal
- Discussed testbeds to scientifically test arc fault detectors
- Examined the need for a classifier system to process the signals detected and classify them as arcing or non-arcing.

Patents & Publications

- [1] "Systems and Methods for Determining Arc Events," application no. 16/000,694 filed 5-Jun-2018, U.S. Patent pending.
- [2] "Method to Determine Arc Faults and Arc Flashes," application no. 62/515,071 filed 05-Jun-2017.
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