FaultLine

Power Signature Analysis for Fault Detection and Predictive Maintenance

ELECOMP Capstone Design Project 2019-2020

Acumentrics is continuing their support of the Program for the 4th consecutive year:
2018-2019: AcuBMS – Battery Management System for Rechargeable Lithium-Based Batteries
2017-2018: AcuPDU – Network Managed Power Distribution Unit for Military Application
2016-2017: AESA – Acumentrics Easy Simple Network Management Protocol Application

Team Acumentrics won 2nd Prize at the 2018 ELECOMP Summit with Project AcuPDU, and 1st Prize at the 2017 ELECOMP Summit with Project AESA

Sponsoring Company:

Acumentrics, Inc.

10 Walpole Park South, Walpole, MA 02081
https://www.acumentrics.com

Company Overview:

Acumentrics, Inc., headquartered in Walpole, Massachusetts, has been a trusted market leader in RUPS™ (rugged AC and DC uninterruptible power supplies) for harsh and combat environments as well as autonomous power and heavy-duty industrial applications, since 1994. Acumentrics products provide clean power conditioning and battery backup when reliability is mission critical. Acumentrics is a preferred supplier of US-made power electronics to many of the world's largest prime defense contractors.

The modern military relies on computers and other sophisticated electronic equipment and relies on Acumentrics' products to keep that equipment online in harsh environments. Electrical variance, surges, spikes, sags, and interruptions can cause communication breakdown and data loss, especially during the rigors of active duty. With new autonomous power systems, these products can range from rack-mounted units to carry-on luggage, backpacks, and even handheld devices.

Acumentrics technology is based on over 25 years of experience in delivering trusted, reliable and rugged backup power solutions to military specifications.

Technical Director:

Brenden Smerbeck (URI College of Engineering Class of 2017)
ELECOMP Capstone Graduate 2017
Software Engineer
bsmerbeck@acumentrics.com
https://brendensmerbeck.com

Brenden Smerbeck has lead Team Acumentrics for two consecutive years, with the team placing second at the 2018 ELECOMP Capstone Summit

Project Motivation:

Predictive maintenance is a growing field of interest across all industries. The goal of predictive maintenance (PdM) is to reduce the likelihood of catastrophic failure by detecting variances when compared to equipment's normal operation. Successful implementations of these solutions operate by analyzing data collected by an array of sensors attached to the device. However, these require modification to the product and are neither easily deployable nor maintainable.

All electronic devices require energy to operate – which can be derived to a voltage and current value. In these electronics, power consumption changes over time; consuming a varying amount of power depending on the intended action. By analyzing the consumption of power, a system can not only uniquely identify a specific device amongst others, but also learn how that device operates. Through learning this "power signature", a system could identify when a device is behaving abnormally and notify a user before such abnormalities become catastrophic.

Acumentrics' products have a commonality – clean, reliable, and rugged power. Regardless of condition, our products operate at the highest level. These systems are, however, not immune to failure. And in mission-critical operations, these failures are not tolerable. Additionally, our systems are deployed in secure environments which do not permit data collection for analysis. Therefore, most cases of failure analysis occur when a system is returned to the company; after a fault has occurred.

Similar to earthquake prediction - accomplished by analyzing characteristics at notable fault lines - the goal of the project is to be proactive instead of reactive. By leveraging modeling through machine learning, we hope to be able to identify electromechanical failures before they occur.

Anticipated Best Outcome:

The Anticipated Best Outcome (ABO) is a functional prototype capable of modeling a single connected device and detecting abnormalities in behavior. The system must be non-intrusive and rely solely on the power signature of the connected device. Should the team accomplish the ABO for one device, the ideal outcome would be a prototype that can perform the above action for multiple devices connected on the same line; identifying each device uniquely by its signature.

Project Details:

Theory of Operation:

In order to understand the concept of "power signature" analysis with respect to predictive maintenance, it is requested that students read the following publications:

1. M. Marcu, M. Darie and C. Cernazanu-Glavan, "Component level energy accounting and fault detection on electrical devices using power signatures," (2017)
    a. Source: https://ieeexplore.ieee.org/document/7969888
2. A. Aboulian et al., "NILM Dashboard: A Power System Monitor for Electromechanical Equipment Diagnostics,"
    a. Source: https://ieeexplore.ieee.org/document/8371632

**NOTE* The following publications are for academic use only and may not be duplicated or distributed under any circumstances. Alternatively, students may use their E-Campus credentials to access the original sources for the publications through URI's "A-Z Databases" system via the library webpage (link).*

The concept for the project is to build a device capable of sensing the power signature of a connected electronic device. To accomplish this, the device must be capable of monitoring the following from the device:

- Voltage (instantaneous and root-mean square [RMS])
- Current (instantaneous and root-mean square [RMS])
- Phase Angle

From these three measurements, the power consumption of the device can be accurately modeled with respect to the "power triangle" (Fig. 1).

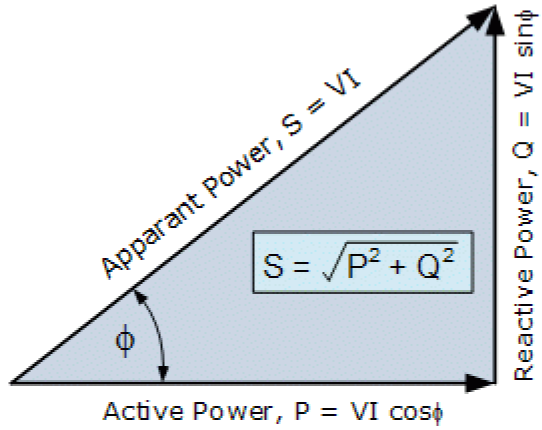

Fig 1. power triangle showing the relation between real, apparent, and reactive power.

Understanding the characteristics of the load is critical to modeling the power signature. Active power is the real electrical power consumption of a circuit, whereas reactive power is the imaginary inductive and capacitive power consumption of a circuit. Apparent power is therefore the power supplied to the circuit in order to support both the active and reactive power requirements. Any circuit that is not purely resistive has a reactive power requirement, and it is in these variances that the device can be identified. In the case that devices cannot be uniquely identified, variances can be found in higher harmonics. This is accomplished using Fourier transforms of current waveforms at high frequencies (>8kHz) (Fig 2).

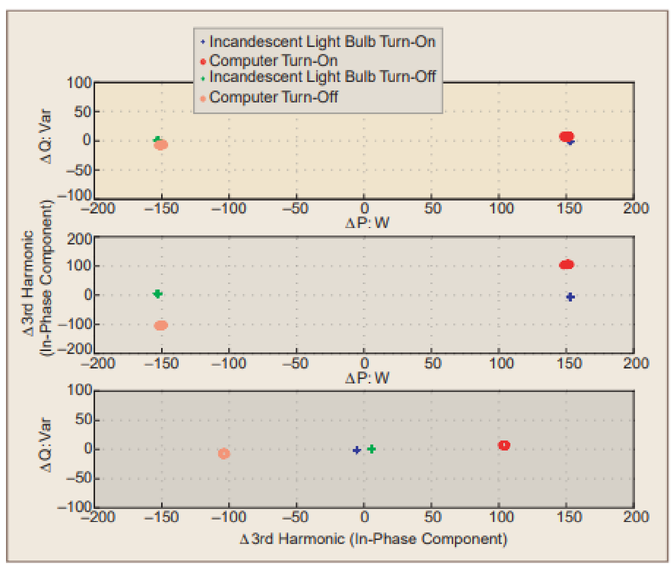

figure 3. Three cross-sections of the ΔP, Δ third harmonic, ΔQ coordinate system, illustrating the separation of clusters.

Fig 2. Source: C. Laughman et al, "Power Signature Analysis" (2003)

Power Signatures:

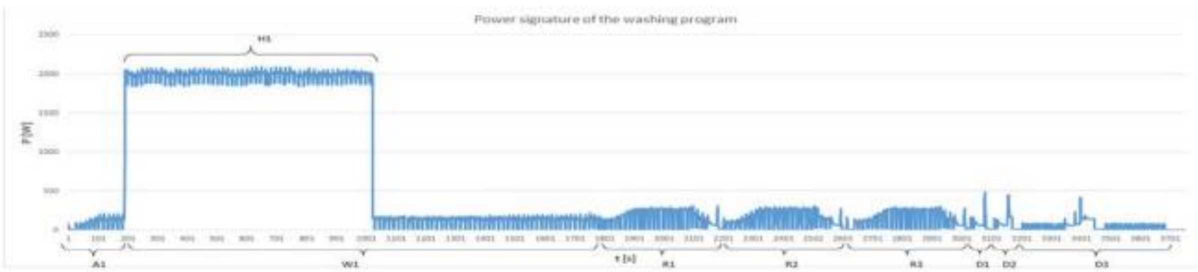

Fig. 3. Power signature of the washing program

Fig. 3. Source: "Component level energy accounting and fault detection…," (2017)

The above Figure (Fig. 3) shows the power signature of a typical washing machine. The phases of water admission, heating, washing, rinsing, and draining are represented by the amount of power consumed. Researchers at the University of Romania used this device as a reference due to its easily identifiable phases and varying amounts of power consumption. Once the signature of a functional device is collected, a model is formed. A model can be defined as *a mathematical representation of a real-world process* and is quintessential to predictive maintenance. The model, trained for accuracy with a set of data (in this example, instances of the washing cycles), can express the "typical" characteristics of the device. It is then used on real-world data collected from another device in order to gauge the similarities or differences in operation.

Should the connected device be nearing failure, it will behave differently than the model's prediction. For example: If the heating element of the washing machine is defective, the machine may consume more power than is modeled in order to bring the water to the correct temperature for washing. The system, analyzing the power signature of the washing machine, would identify the increased power consumption during the heating phase and notify the user of the abnormality. This notification could, in turn, allow the user to repair the heating element before a catastrophic failure, such as the device overheating and melting components together or damaging the interior casing of the circuit boards.

Mathematical Tasks (All Team Members):

- Complete introductory course on Machine Learning (ML)
- Identify features and labels for model definitions
- Classify data collected as needed to construct ML model
- Define algorithm for ML model
- Properly train model using chosen algorithm

Electrical Tasks:

- Gain understanding of single-phase power and its characteristic elements
- Research and select a device for power signature analysis (ELE + CPE)
- Research and determine a viable Integrated Circuit (IC) for measuring electric characteristics for a single device
- Design a schematic for the prototype device to meet specifications and meet requirements for:
  - power signature analysis
  - fault detection
  - communication to host device
- Design a printed circuit board (PCB) to match the beforementioned circuit
- Verify the PCB meets specifications and accomplishes project requirements

Computer Tasks:

- Complete Google Crash Course course on Machine Learning using TensorFlow (link)
- Select microcontroller that meets both initial project specifications and design specifications as determined by Electrical Engineers (ELE).
- Gain understanding of embedded systems (sensors, actuators, analog-to-digital converters, etc.)
- Perform basic data collection of both voltage and current data from an electronic device.
- Research and select a device for power signature analysis (ELE + CPE)
- Assist in selecting an Integrated Circuit (IC) suitable for power signature analysis
- Develop software to read sensor data at a rate sufficient for modeling a connected device
- Design machine learning (ML) model for selected device.
- Train model using test data or other training data
- Using model, correctly identify when a device is behaving abnormally and requires attention

Composition of Team:

1-2 Computer Engineers (CPE), 1-2 Electrical Engineers (ELE)

Preference will be given to students who have completed Google's Crash Course in Machine Learning (link) or have experience with Machine Learning. Also, preference will be given to students enrolled in Mike Smith's PCB Design Course.

Additionally, Electrical Engineers interested in the project should be comfortable programming/performing some CPE duties as the project has a significant CPE requirement.

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Skills Required:

As the University of Rhode Island lacks courses in the discipline of Power Engineering, it is not expected of students to have a background in the subject matter. Nonetheless, students considering the project should be confident in their computer and electrical engineering skills and be comfortable in the field of mathematics. The proposed project is non-trivial, and requires motivated students to meet its Anticipated Best Outcome

Electrical Engineering Skills Required:

- Analog and Digital Circuit Design
- Digital Signal Processing
- Linear Systems and Signals (e.g. ELE 313+314)
- Calculus, Linear Algebra (MTH 362, MTH 242 + MTH 243)

Computer Engineering Skills Required:

- Proficiency in Object Oriented Programming (OOP)
- Competency in software design architecture
- Experience in Python development
- Calculus, Linear Algebra (MTH 362, MTH 242 + MTH 243)
- Linear Systems (ELE 313)

Anticipated Best Outcome's Impact on Company's Business, and Economic Impact:

As Acumentrics' products are built to last in normally inoperable environments, integrity is an absolute requirement. As the company extends its knowledge of power systems to autonomous power, the need for data analytics and understanding only grows. To have a deeper understanding of electrical devices and their power signatures, Acumentrics can not only improve its own products but also improve the longevity of devices connected to those products.

Should the project succeed, there is a growing market for predictive maintenance across all industries – not just the military industry in which Acumentrics primarily exists. Therefore, the economic impact is too large to accurately measure. For existing customers, the project would allow Acumentrics to better understand its devices points of failure and continue to improve the ruggedness and longevity of those devices.

Broader Implications of the Best Outcome on the Company's Industry:

Power systems are a necessity often overlooked by the typical consumer. Yet power systems can be found behind every startup tech company and telecommunications firm, every first responder, every family, every military operation, and – frankly – every modern business. As technology advances, so too does the energy requirement of the world. In order to provide clean and reliable energy in every environment, companies within the industry of power systems must evolve as well. Today, machine learning and artificial intelligences have opened a gateway to medical innovations, seemingly impossible designs, and otherwise limitless opportunity. Yet these opportunities are equally matched by a demand for enhancement and improvement at every stage. It is because of this ever-growing demand that the innovations of the next generation are possible, and why projects like this are necessary.