UPTIME IMPROVEMENTS FOR PHOTOVOLTAIC POWER INVERTERS

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Abstract: For optimum performance, the expansion of solar energy installations requires a robust and reliable infrastructure of panels, inverters and system control. Because of the geographically distributed and sometimes remote deployment of these solar power installations, reliability and performance is paramount to wider-scale adoption of these systems. Thus, it is very important to monitor the performance and identify any degradation of the critical system components early so mitigating actions can be taken. The most critical component in a solar energy system is the power inverter. The power inverter converts the DC output voltage of the panels to AC, which supports connections to the utility power grid, or to individual household power needs, depending on the size of the installation. This paper presents an innovative reliability-prediction system for photovoltaic (PV) solar power inverters. The significance of the innovation is that by supporting overall power system health management strategies and reducing maintenance costs for deployed systems by an estimated 20%, this system can save at least $26 billion a year in losses from power interruptions due to power grid failures. With savings of this magnitude, manufacturers and power providers can reduce their costs of products and services, therefore reducing the cost per kW to the consumer. Consumers in remote and isolated communities will also benefit from affordable and reliable off-grid power systems. The approach described in this paper includes hardware and software components that are easily integrated into existing inverter platforms, and provide state of health (SoH) and accurate remaining useful life (RUL) estimates. One of the best features of the approach is its modularity and easy applicability to various inverter configurations. We also will describe a real installation and remote data gathering system installed at a local solar facility.

Key words: photovoltaic power inverters, inverters, photovoltaic, renewable energy, solar energy

Introduction: For optimum performance, the expansion of solar energy installations requires a robust and reliable infrastructure of panels, inverters and system control. Because of the geographically distributed and sometimes remote deployment of these solar power installations, reliability and performance is paramount to wider-scale adoption of these systems. Thus, it is very important to monitor the performance and identify any degradation of the critical system components early so mitigating actions can be taken.

There is general agreement that the most critical component within solar energy systems is the power inverter, as shown in Figure 1 [1]. The power inverter converts the DC output voltage of the panels to AC, which supports connections to the utility power grid, or to individual household power needs, depending on the size of the installation. These inverters consist of semiconductor power switch components, such as power MOSFETs or IGBTs, and complex control circuitry. The ability to monitor the state-of-health of the inverter, along with the ability to gain early warning of impending failures through prognostic methods, can provide a major contribution in reducing the life-cycle cost of these systems.

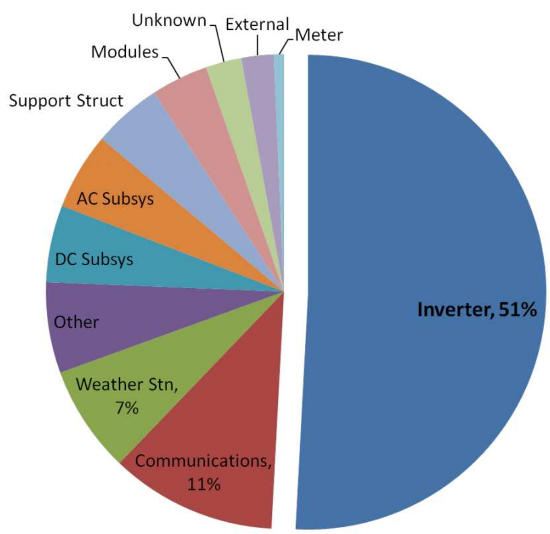

Figure 1: Maintenance ticket breakdown per subsystem.

Ridgetop Group has developed an innovative reliability-prediction system for photovoltaic (PV) solar power inverters. The significance of the innovation is that by supporting overall power system health management strategies and reducing maintenance costs for deployed systems by an estimated 20%, this system can save at least $26 billion a year in losses from power interruptions due to power grid failures. With savings of this magnitude, manufacturers and power providers can reduce their costs of products and services, therefore reducing the cost per kW to the consumer. Consumers in remote and isolated communities will also benefit from affordable and reliable off-grid power systems.

PV inverter demand is directly driven by the installation of solar plants. The technical benefit provided by this reliability-prediction system is reflected in the improvement of reliability and availability of solar systems. Through the use of Ridgetop prognostic tools, detection and corrective actions can be performed before a failure occurs in order to preserve system integrity. With these prognostic tools, inverters' maintenance costs will be drastically reduced while system availability and reliability are simultaneously increased.

The economic impact offered by the Ridgetop tool is the overall reduction in cost of ownership. This will be highly attractive to solar farm owners, whose main concern is to have a return on investment in a short period of time. Also, reducing the cost of production will lead to higher margins, which will be more attractive for newcomers into the solar farm industry, increasing the annual number of solar installations. This tool will support overall PHM strategies and reduce the maintenance costs for deployed and new system installations. With increased reliability in off-grid systems and with PHM approaches monitoring these assets, backup power will always be available.

The impact of the Ridgetop tool goes beyond solar farms; it also represents a great benefit to end customers. The reduction of costs of solar energy generation will translate in a reduction in costs per kW for end customers. Also, the increase of PV solar system integrity will bring an environmental benefit through safe generation of energy and the reduction in CO_2 emissions by a factor of 2 tons per each 100-Watt module [2]. Furthermore, the implementation of the Ridgetop tool will position the solar industry closer to achieve the $1/Watt goal [3] shown in Figure 2.

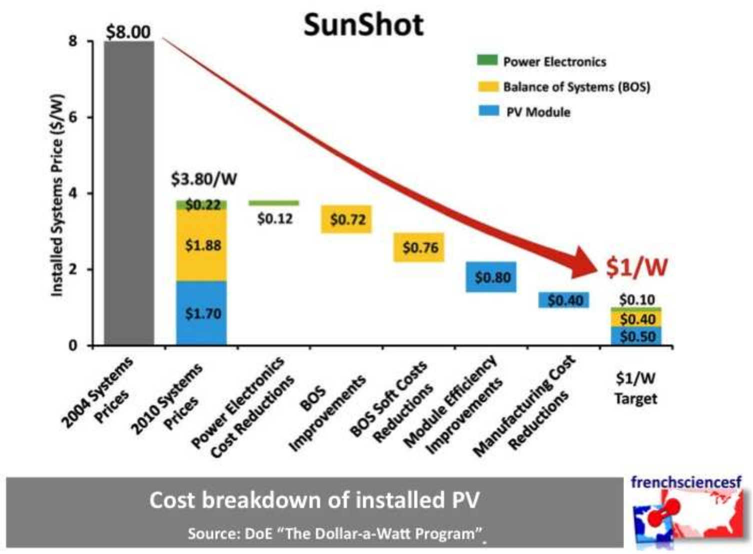

Figure 2: Cost breakdown of PV systems – graph from SunShot Initiative

For solar panel manufacturers, distributors and users, the successful implementation of prognostics and health management (PHM) enables the capability of forecasting inverter maintenance requirements. Early warning of impending failures can be used to schedule and dispatch the required maintenance activity before experiencing downtime.

Other commercial applications that would benefit from this technology include wind power inverters, automotive power inverters, small portable power systems, and space power systems.

Ridgetop's solution consists of a modular low-cost prognostics and health monitoring (PHM) subsystem, installed with the power inverter, which significantly improves system availability. By supporting condition-based maintenance (CBM) strategies, system maintenance can be scheduled to off-hours to minimize revenue loss. CBM has been proven to reduce support costs of complex electronic systems by 33% [4]. Ridgetop's design approach includes hardware and software components that are easily integrated into existing inverter platforms, and provide state of health (SoH) and accurate remaining useful life (RUL) estimates.

Technical Approach: Based on our extensive experience with power system prognostics used in high efficiency power converters and electromechanical actuators, Ridgetop has developed a practical and effective prognostic health monitoring (PHM) subsystem, which can be installed with the power inverter. This solution relies on non-intrusively extracting the eigenvalues from the power converter, and monitoring degradation-induced changes over time. The proposed solution alleviates the foregoing problems in the following ways:

- Through accurate prediction of appropriate service intervals (e.g., condition-based maintenance), system downtimes will be minimized, which will improve revenue generation. Ordinarily, untimely equipment failures cause loss of energy production during these periods. Reliability is defined as "the probability that a system will perform its designed-for functions without failure in specified environments for desired periods at a given confidence level" [5]. Thus, system reliability will be drastically improved without improvements in component failure rates, since the impending failure will be detected and repaired before it has any effect on system performance.

- Maintenance costs will be minimized with an accurate PHM subsystem. During the operational life the prognostic subsystem will be under the same exact thermal, mechanical and electrical stress conditions as the actual inverter module, thus it will provide a very accurate estimate for remaining life. Since the integrated PHM system continuously analyzes the condition of the inverter, the remaining useful life (RUL) estimate is continually updated. This allows for cost-optimized maintenance visit scheduling, i.e., any maintenance might not be required during the first four years of operation. Moreover, with the existing Ridgetop diagnostic tools the detection of impending failures can be performed remotely, via web-based networks. This capability reduces maintenance costs even further.

- Repair times are reduced significantly with the accurate diagnostic and prognostic monitoring that PHM provides. In a typical service scenario, a loss of operation is detected, but the fault isolation is not immediately clear. A technician is dispatched to the site, where diagnostic procedures are applied to determine the cause of service interruption. With continual monitoring of the inverter, the degradation can be detected and the source of the interruption is known before the technician leaves on his/her service call. Thus, any system downtimes that are caused by the repair wait periods after a failure are also totally eliminated, since the prognostic monitor allows a scheduled repair before any failures occur.

Consequently, revenue loss only occurs during the very short downtime when the failed component is replaced. No revenues are lost if the repair can be scheduled after sunset.

One of the best features of our PHM subsystem approach is its modularity and easy applicability to various inverter configurations. Existing inverter topologies can be used; therefore, no major changes are needed for a major improvement in system availability and maintainability. Moreover, when new innovations arrive on the market, such as improved IGBTs or capacitors that have better failure rates, the PHM design can be quickly adapted to the change.

The proposed prognostic PHM subsystem diagrammed in Figure 3 includes a prognostic monitor that noninvasively monitors the degradation signatures of the inverter to the inverter operation. The prognostic analysis platform includes a fault dictionary and a remaining useful life (RUL) estimator.

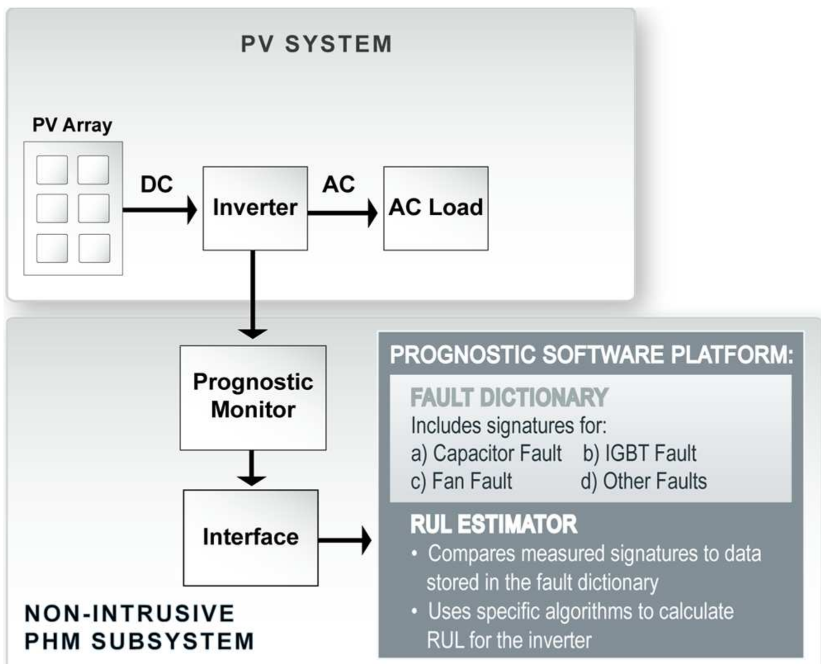

Figure 3: Diagram of the proposed prognostic PHM subsystem

As seen in Figure 2, the innovation leverages a prognostic monitor to non-intrusively extract waveform signatures from which the eigenvalues are extracted. These result from the second-order response of the switching waveforms, as shown in Figure 4.

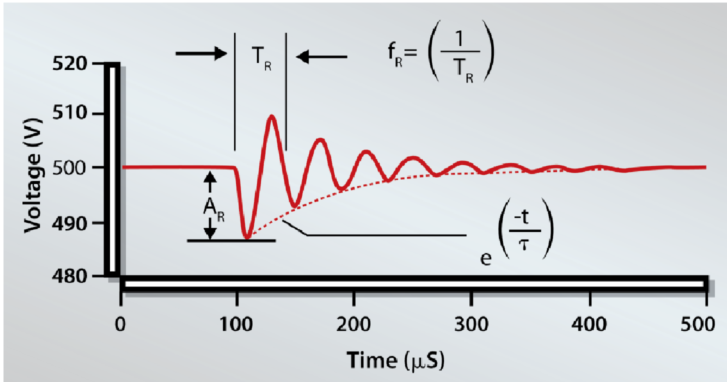

Figure 4: Damped sinusoidal response of a switched power waveform; key intrinsic variables are the amplitude, frequency and time decay constant

The prognostic sensor has two functions:

- Populate a fault dictionary with detectable prognostic fault signatures that will be used to compare new signatures against the baseline signatures
- Provide fault signatures for calibrated health assessment

In the first function, nominal, off-nominal, and catastrophic fault conditions are presented to the system while prognostic sensors acquire and digitize critical system signals. Off-nominal conditions can provide useful information on the "health" of the system. For example, Figure 5 shows actual power system measurements that Ridgetop has examined at NASA/Ames using this approach. While both power systems are still regulating voltage, the degraded system will show a much different response waveform.

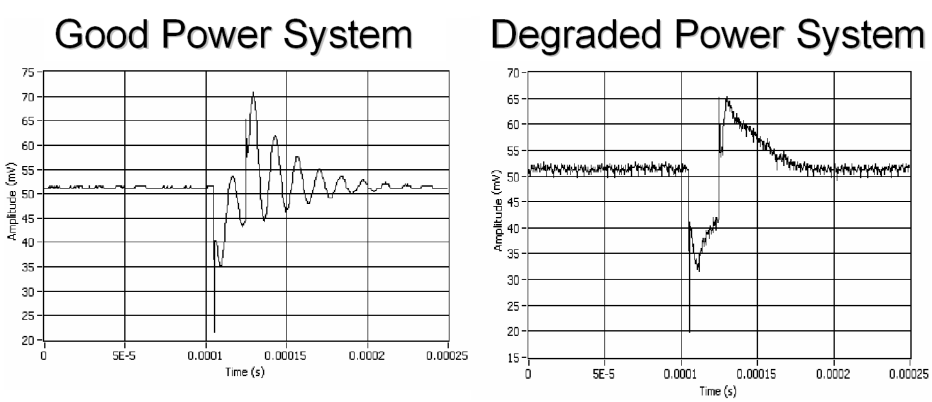

Figure 5: Actual power system measurements

In the second function, the sensor provides scheduled fault signature acquisitions for real-time state-of-health (SoH) assessment. The acquired data is delivered to a software analysis module where it is transformed into an equivalent representation suitable for programmatic discrimination of fault type and level. Combined with sophisticated case-based reasoning and pattern recognition techniques, this comprehensive fault dictionary is used for condition-based maintenance (CBM) of the inverter power system.

Integrated PHM Sensor: PHM algorithms, being robust and intensive by nature, require a large throughput of multivariate data. In order to access this volume of data collected in an inverter system, a prognostic sensor must exist onboard the inverter and consume the same data that is available to the hardware controller. These common inputs for inverter controllers are important monitoring nodes for diagnostic and prognostic analysis. They include but are not limited to the measurands and nodes shown in **Table 1**.

Table 1: Common Inputs for Inverter Controllers

Node	Controller Use	Prognostic Use
PV voltage and current input	Maximum power point tracking	Calculate efficiency
		Detect anomalies in PV array
Internal DC-DC converter voltage	Regulates DC-DC step-up transformation	Monitor DC-DC health
		Monitor DC-bus capacitor health
Grid voltage and output current	Calculates power output	Detect power transistor degradation
	Enables grid-tie mechanism	
	Prevents islanding	Detect grid anomalies

Enabling an inverter platform to share the controller's common operating inputs to a prognostic sensor, allow for an integrated PHM approach. This methodology adds no extra sensors, or complexity to the electrical design. Hybrid controller-PHM architecture is illustrated in Figure 6.

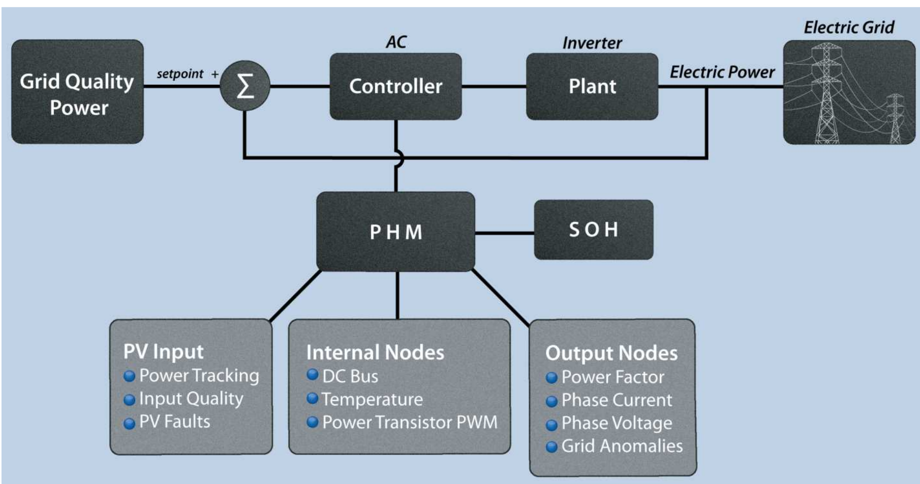

Figure 6: Integrated PHM solution architecture

State-of-the-Art Inverter Topology: For this research we selected a common use, general purpose DC-AC 1 kW inverter from ST Microelectronics. The ISV001v1 is an evaluation kit that provides an open schematic, PCB layout/Gerber files, bill of materials, microcontroller source code, application notes and a technical brief. This platform allowed access to a mature design as well as all relative design documentation needed for our experimentation.

The converter (on the left in Figure 7) is fed by a low DC input voltage varying from 20 V to 28 V and is capable of supplying up to 1 kW output power on a single-phase AC load. These features are possible thanks to a dual stage conversion topology including an efficient step-up push-pull DC-DC converter, to produce a regulated high-voltage DC bus and a sinusoidal H-Bridge PWM inverter to generate a 50 Hz, 230 Vrms output sine wave. Other relevant features of the proposed system are high power density, high switching frequency, galvanic isolation and efficiency greater than 90% over a wide output load range [6]. The inverter is a complex combination of subsystems which operate serially to produce a 50 Hz 230 Vrms output waveform. Figure 7 illustrates the different subsystems and their interaction to produce power.

Figure 7: Inverter subsystems, operating serially

Each subsystem of the ISV001v1 suffers from unique failure mechanisms, enabling us to create a complex Fault Dictionary that is inclusive of all major inverter failures. The Push-Pull DC-DC Converter subsystem operates by conducting current in alternating directions through a transformer, then feeding the output of the transformer to a full bridge diode rectifier. Power MOSFETs conduct current through the transformer at a frequency of 100 kHz. A high switching frequency is essential to minimizing noise in the final output stage. Mitigations to this potential hazard are the Snubber circuit, in between the Push-Pull subsystem and the Switching IGBT subsystem, as well as magnitude of the switching frequency above the output frequency.

A power electronic simulation test bench was needed to fully simulate the STMicro PV-inverter. Being an alliance member of National Instruments, Multisim was used to provide a Spice-level simulation to the inverter. The Multisim model performed very well, and followed the characteristics of its hardware equivalent closely. This simulation test bench was good environment for creating virtual degradation and fault conditions, while monitoring which nodes provided visibility to these failure modes.

A Fault Dictionary: The inverter model was used to seed different faults in the hardware, and simulate their effects to the inverter’s internal nodes and operating performance. This methodology allowed for rapid development of fault experiments, both in variety and severity of fault. In order to validate that the model correctly mimics the hardware during failure characterization, a fault was created in the evaluation hardware by reducing the DC link capacitance. Shown in Figure 8 is the internal +370 Vdc bus during the activation of a switching IGBT. Note how ringing attributes, amplitude, and frequency vary between the two tests. Table 2 shows the RingDown analysis results.

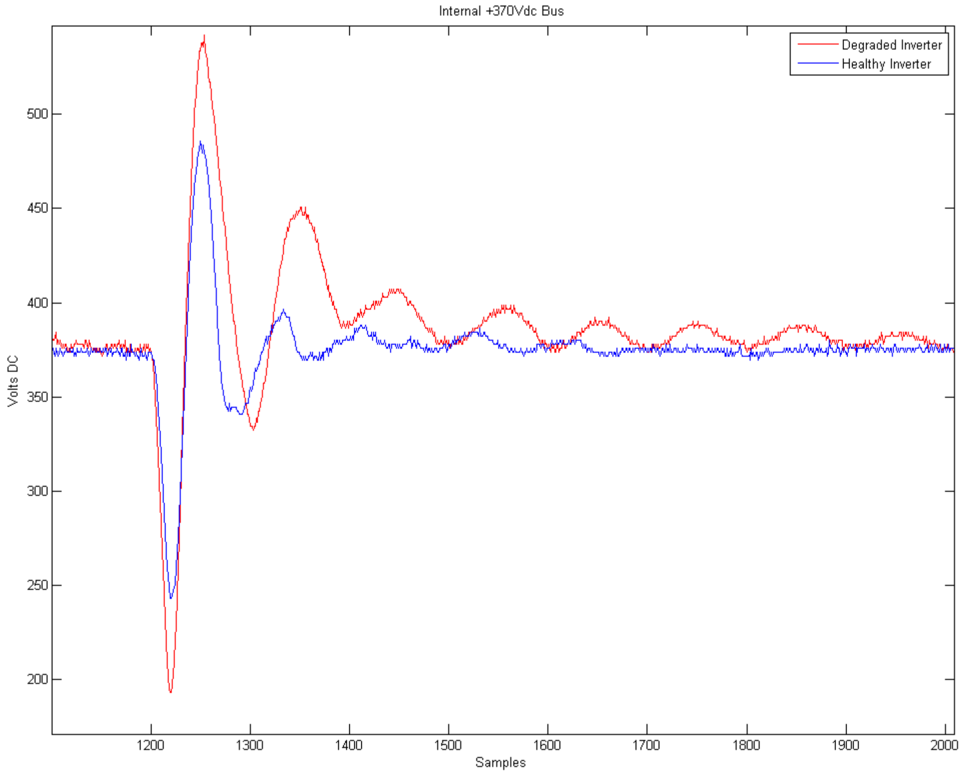

Figure 8: Fault seeded inverter characterization

Table 2: Results of RingDown Analysis of the Two Tests in Figure 8

Trial	Ring Primary Frequency	Ring Amplitude
Faulty	22.2 MHz	184.0 Vdc
Healthy	28.98 MHz	128.8 Vdc

Similar circuit components were changed in the inverter model, to validate that similar degradation characteristics were present. Shown in Figure 9 are the outputs of two model simulations. The components that were changed from the baseline design caused a similar effect as in the real inverter hardware experiment, shown in Figure 8. A decrease in capacitance causes a characteristic shift in ringing characteristics. This affects the overshoot and damping frequency, both viewable via a fast Fourier transform (FFT) of the internal +370 Vdc bus.

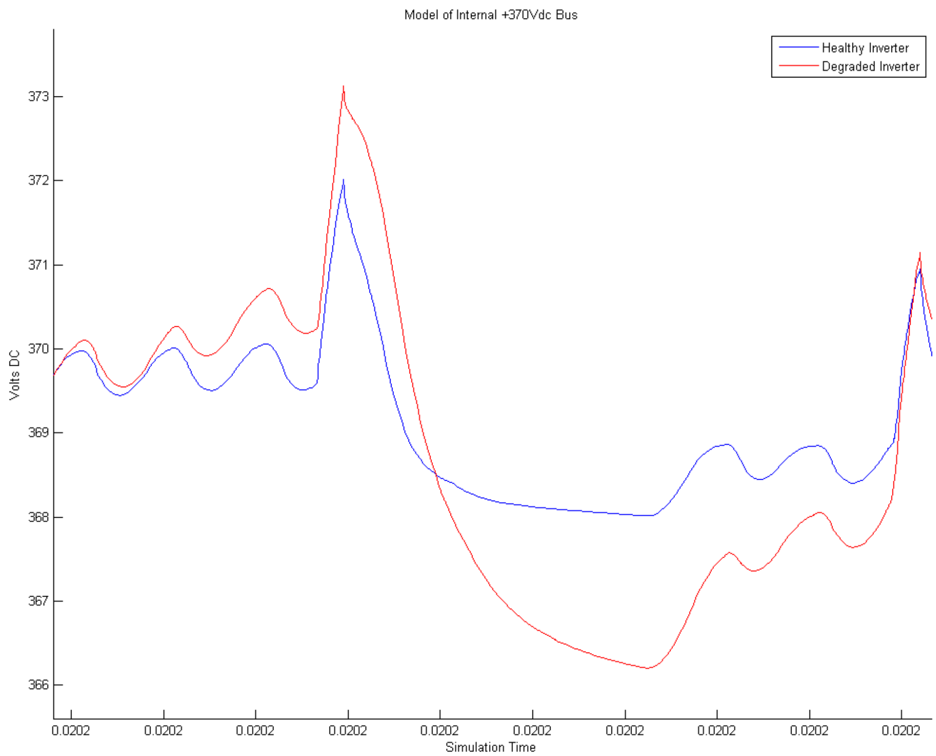

Figure 9: Model inverter simulation results; "degraded" inverter contains degraded internal capacitors

A fault dictionary is the critical component for a prognostic solution. Using Pareto ranking, the most common failure modes regarding long-term degradation were applied to the Multisim model. The fault-to-failure signature results are shown in Table 3.

Table 3: Fault Dictionary Summary

Fault Mode	Values Simulated	Health Progression	Fault-to-Failure Signature
370 V capacitor value	67 to 8 µF	100 to 0%	FFT of 372 VDC
Capacitor ESR	1 to 200 Ω	100 to 0%	FFT of 372 VDC
IGBT emitter resistance	0.001 to 50 Ω	100 to 0%	FFT of 230 Vrms
MOSFET drain resistance	0.001 to 50 Ω	100 to 0%	FFT of 372 VDC

A Remaining Useful Life (RUL) Estimator: Building a RUL estimator requires understanding of damage propagation in inverters and subsystem interaction. PV inverters contain multiple subsystems which contribute serially to convert solar energy from direct current into grid-connected alternating current. The health of each system affects the production capability for the entire system. Any decrease in the health of a subsystem affects the overall system's health. Subsystems' health is equally important in PV inverters, as shown in Figure 10.

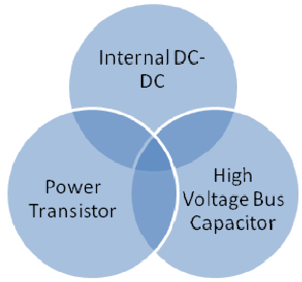

Figure 10: Subsystem health is weighted equally toward total system health

The state of health (SOH) is inherently difficult to measure in complex, multi-component systems. The algorithm developed in the first phase of work operates by consuming a sample of operating data such as output current and voltage, and computing the state of health for a particular operating period. This algorithm flow is illustrated in Figure 11.

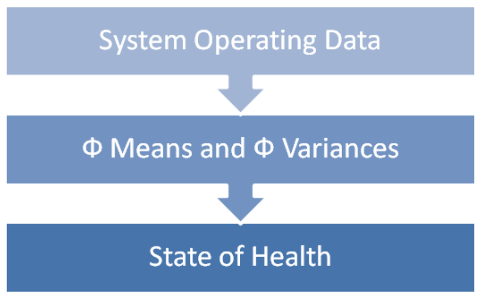

Figure 11: PV state-of-health algorithm flow

City of Tucson Solar Installation: Located in the Sonoran desert, Tucson receives more than 320 days of sunshine per year, and is considered an ideal place for solar power. Ridgetop developed a plan to retrofit a problematic inverter with monitoring capabilities, and allow the City of Tucson Solar Installation facility access to debugging and remote control capabilities. Historically problematic Xantrex 20 kW inverters were installed at a City of Tucson water reclamation plant. These inverters would often fault, causing them to turn off without warning. Because of the remote nature of the facility, weeks or even months lapsed before these inverters were restarted and began producing power again. These inverters were out of warranty, manufactured in 2007, and they provided no remote monitoring capabilities. The need for monitoring of remote systems and tools to diagnose faulty inverter systems is large; most of the City's large inverter systems are responsible for a $10,000 loss in revenue per week!

As a test of the PV SOH algorithm, operating data from a test site was fed into the algorithm. The inverter under test was an older, problematic model Xantrex 20208, Operated by the City of Tucson at a water treatment facility. The algorithm's results, shown in Figure 12, were promising, showing that operating inverter's health will fluctuate during the course of a day, while still producing electricity into the grid.

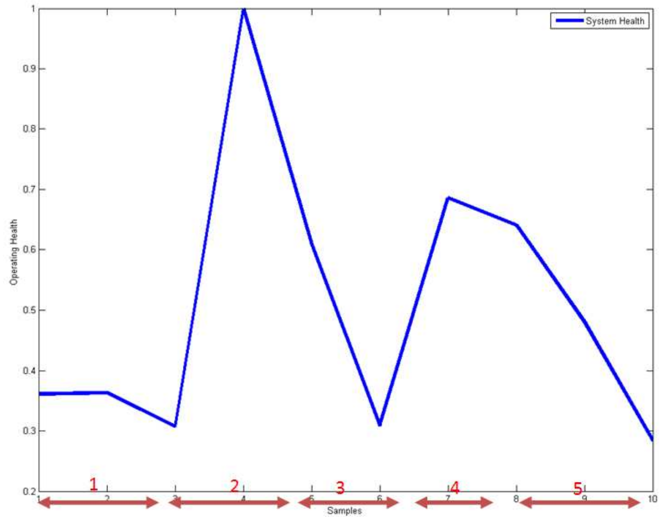

Figure 12: Operational health algorithm output; 24 hours of data is consumed to produce several measurements

In Figure 12:

- Sections 1 & 5: The inverter is offline (no sunlight) during the early morning and late evening hours. Health is low because of variations in the line voltages common in industrial power.
- Section 2: The inverter is online and operational.
- Section 3: An anomalous event occurs, affecting the balance of I/V across the three phases.
- Section 4: The inverter recovers from anomalous events.

The anomalous event which occurred was an operating fault classified as a phase voltage imbalance error. One of three phases (Vca) was detected as fluctuating above the known save range of 208 ±20.8 V, as specified by IEC industry standards. This malfunctioning system could have continued operating in this handicapped state for some time until eventual failure. But Ridgetop's monitoring methodology was able to discover a system fault before system failure, and properly manage the generation reduction to prevent long term loss. A brief analysis of savings to the City of Tucson is shown in Table 4.

Table 4: Power Generation and Loss detection Value

	Power Generated	Daily Value at Market Price $0.09/kWh	Yearly Loss
Normal Operation	141 kWh	$12.69	
Anomalous Operation	106 kWh	$9.54	
Generation Lost	35 kWh	$3.15	$ 1,121.50

A remote network of computers and access points to communicate with its sensors was deployed. These sensors consisted of an embedded computer, National Instruments Compact RIO (NI cRIO), and a wireless access point. Data collection between the NI cRIO and the Xantrex inverter was done through the diagnostic Serial RS232 port located inside the inverter enclosure. A PC running inside the control room maintained constant communication between to the NI cRIO and logged each transmission of inverter data. The network topology is shown in Figure 13.

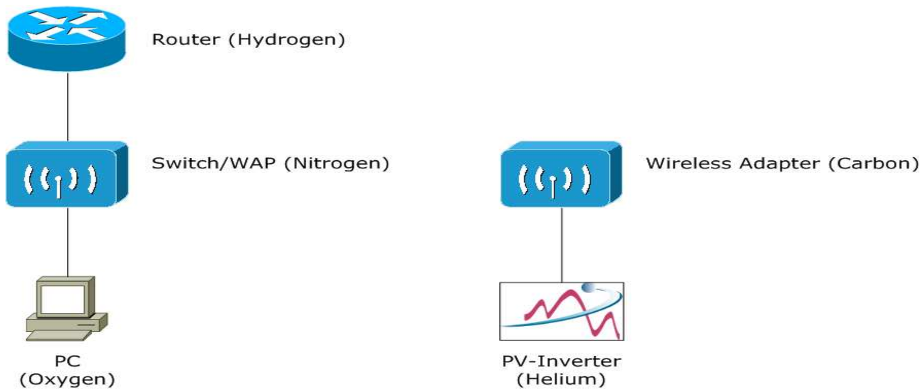

Figure 13: Site monitoring network topology

Data are currently being collected at periodic intervals (60 seconds) 24 hours a day, and results are viewable by accessing the network via virtual private network (VPN) connections. Many internal and external nodes are represented in the data, as shown in the list below:

- Machine type
- System state
- Fault code and description
- 3-phase voltage
- 3-phase current
- Output power
- Grid frequency
- PV input voltage
- DC bus voltage

The inverter is located about 50 yards from the site control room, across a roadway for heavy machinery. Wired communication is not feasible, so a wireless connection was deployed, connecting the NI cRIO to the remote network.

HealthVIEW-PV is an application that runs on the control room computer ("Oxygen") and is capable of displaying and recording the information collected by the NI cRIO for performance tracking, maintenance calls, and fault debugging. Keeping a record of performance data and system operating conditions such as PV input, Phase Voltage, and Current is a crucial component of managing an Inverter Health Management program. Many times prior events, such as weather (rain, snow, and lightning) can be used to characterize faults. This knowledge is n important input into the debugging process, and can drastically improve system availability. A screen capture of the HealthVIEW-PV data analysis application is shown in Figure 14.

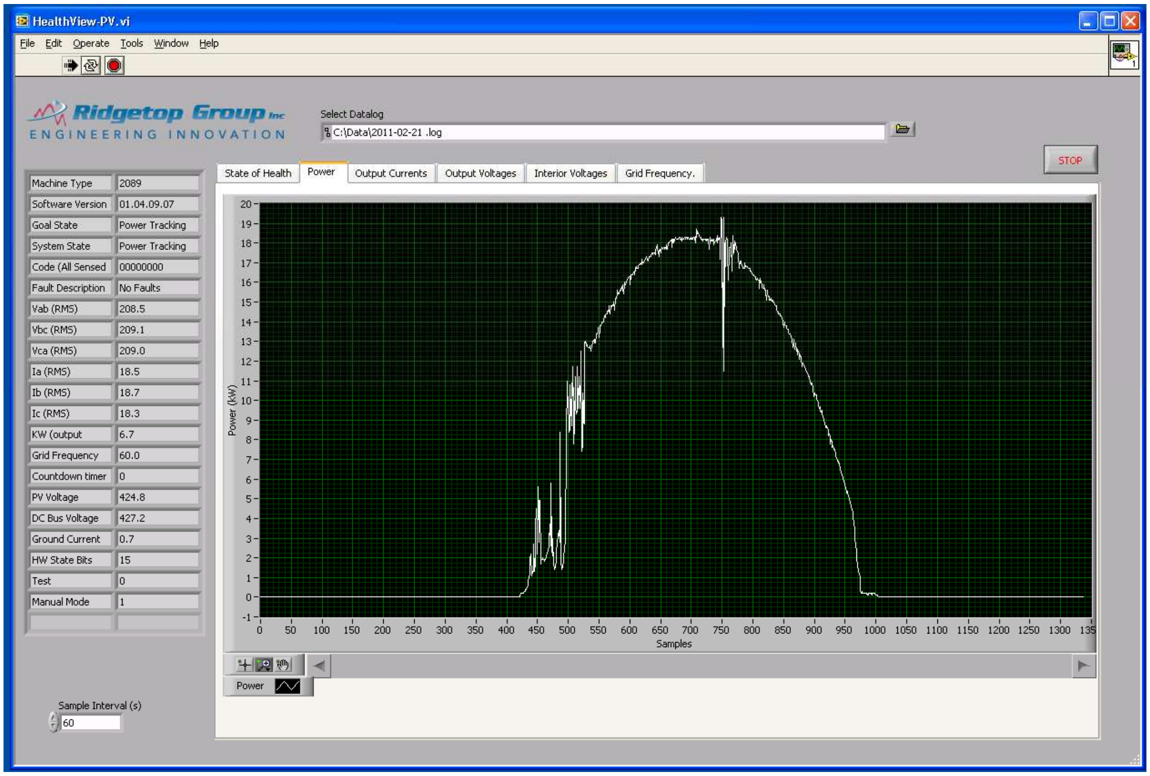

Figure 14: HealthVIEW-PV data analysis application

Conclusion and future developments: The current inverter model needs to be developed into a 20kW, three phase, grid-tie inverter such as those found in commercial use. By working in industry partners, a prognostic sensor that is natively supported by inverter firmware will be developed, creating a non-obtrusive and power real-time prognostic sensor. Diagnostic and prognostic algorithms for the PV system's SOH and RUL also need to be refined and implemented by reducing the dimension of multi-state variables, detecting the degradation of the system components in order to identify failures and loss mechanisms and minimize system downtime. By leveraging our existing network health management application for discovery, monitoring, data collection, reasoning and recovery, we can discover the PV inverters and allow for remote recovery from known failure modes.

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Acknowledgement:
We greatly appreciate the support given to us by our Department of Energy during initial Small Business Innovation Research (SBIR) contract to design and develop this technology. In addition we are grateful of the support given to us by Bruce Plenk, Solar Energy Coordinator at the City of Tucson.

Bibliography:
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