NSRP | National Shipbuilding Research Program

Distributed Temperature Sensing for Inspection of Electrical Panels on Navy Ships

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Presentation Outline

- Background
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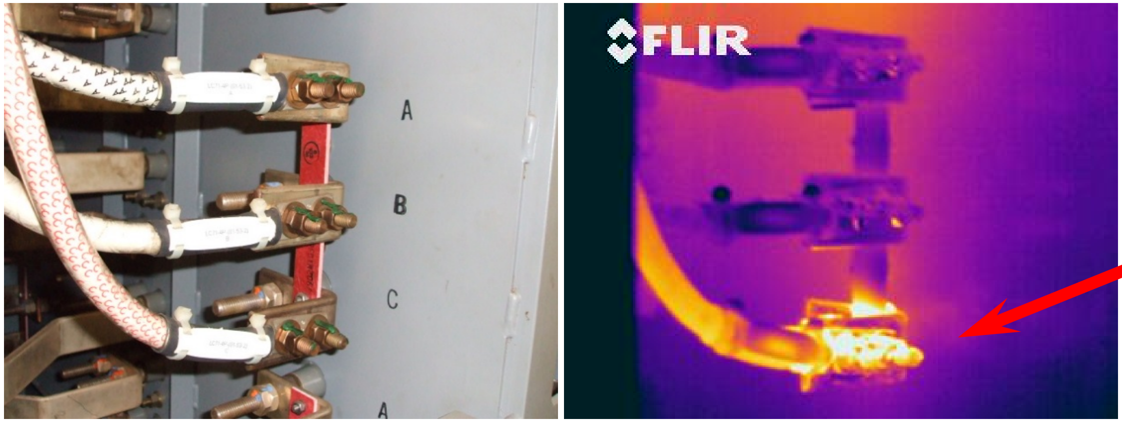
- Trade Study Technical Details
- Conclusions

Background

- Even under best practices, shipboard switchboards can develop loose connections that lead to arc faults and other electrical issues
    - Average of 8 arc faults per year throughout the navy fleet - all occurred in Switchboards and Load Centers - cost Navy millions of dollars in downtime and repairs [NAVSEA, SUPSHIP Gulf Coast]
- Newer ships have electrical systems considered medium to high voltage
    - LHD, LHA, DDG-51(FLTIII), DDG-1000 = Medium, 4160 volt systems (CVN = High, 13,800 volts)
- Switchboard Inspections are done during construction, builder's trial, during sea trials, and again at regular maintenance intervals
    - Current inspection methods: typically utilize Thermal IR imagers to investigate cabinets and comparatively identify 'hotspots'; other investigation modes require close proximity interrogation



Temperature difference between phases

Load Center

Photos from NSWC Philadelphia

Background - Issues

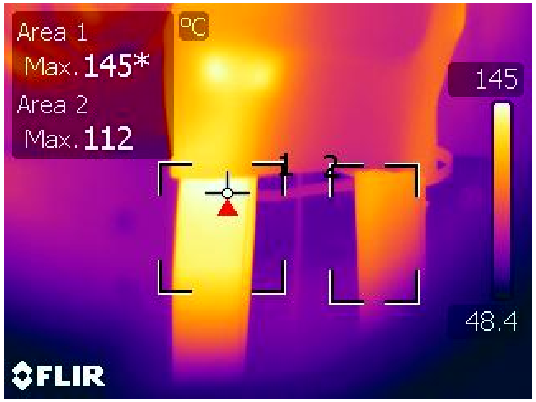
- Connections in electrical panels on Navy Ships are presently inspected using infrared thermography through open panel while under load. A bad connection shows up as much hotter than connections on adjacent phases.
- Medium to high voltage panels require OSHA waivers or preclude open panel inspection at all.
- Recently concluded NSRP panel project investigated use of IR transparent windows in panel covers to permit thermography without opening the panel.

Background – Issues (cont.)

- Results showed that use of IR windows was a viable method for IR inspections. Mil standards are being revised to include IR windows in these cabinets, partly from lessons learned in the project. However, some limitations were uncovered during the project:
  - Components and devices within the cabinets can be obstructions to viewing from the windows. Providing line of sight is a significant design challenge for the panel manufacturers - 100 % coverage of all connections might not be possible.
  - Medium and high voltage cabinets require an insulating dust boot covering all connections, to reduce the chance of arcing from electrical creep or tracking. The boot materials tested are not transparent to IR wavelengths and the temperature of the connection can only be inferred from hotspots on the outside of the boot or the cable exiting the boot.

Visible image through window. Red dust boot covering connections

Thermal image of dust boot and cables with simulated fault



Approach

- Investigate the viability of Distributed Temperature Sensing (DTS) over optical fiber for monitoring of switchgear connections. Benefits will include:
  - Sensor is the fiber itself or is inside the fiber. Can sense anywhere fiber can be run.
  - Likely 100% coverage of all connections, beneath the dust boots and independent of window placement, for safer inspection.
  - Programmable temperature monitoring, available on demand, or optionally permanently installed for continuous monitoring. Less interpretation of results.
  - If continuous, can alert to problems as they develop, not when approaching failure. Enabler to predictive maintenance.

Project Goals

- Determine feasibility of using DTS in shipboard cabinets and whether 100% coverage is practical
- Provide demonstration of proof of concept in a relevant environment (representative electrical cabinet)
- Establish trade space for different DTS technologies with respect to use in Navy Ships

Active Project Participants

Lead Investigators		
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Technical Approach (from SOW)

- Review challenges to IR inspection and refine requirements
- Perform trade study of three DTS technologies with respect to application on Navy ships (4160V panels)
- Arrange benchtop demonstrations of three technologies geared toward this application.
- Downselect to technology most suited for this application based on results of trade study and demos
- Arrange a final demonstration in a relevant environment
- Develop a path for technology transfer.

Schedule

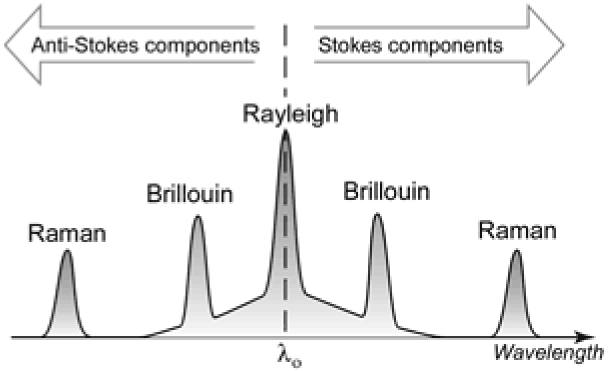
- Period of performance – 1/16/17 through 12/31/17
- Exact schedule will be dependent on availability of vendors for arranging demonstrations and venues.
- Schedule targets are
  - Refine requirements – Mar
  - Perform trade study – Apr
  - Benchtop demonstrations – May
  - Downselect to single technology – July
  - Plan and perform final demonstration – Aug-Sept
  - Submit Final Report – Oct-Nov

Trade Study Details

- Study will evaluate technical feasibility, reliability, implementation and maintenance requirements, and costs wrt implementation on Navy ships (focus on 4160 V systems)
- Identified three DTS technologies to compare:
  - Raman Shift
  - Rayleigh Scattering
  - Fiber Bragg Gratings
- Maintain sensitivity to proprietary and competition-sensitive information from vendors.

Raman Shift

- Makes use of collisions of photons with atoms or molecules along the optical fiber. The reflected light is shifted in wavelength.
- If photon loses energy to the fiber wall, the scattered wavelength is longer (known as the Stokes Component). If it gains energy, the wavelength is shorter (Anti-Stokes).
- Anti-Stokes is sensitive to temperature. Ratio of two signals corresponds to temperature change in fiber.
- Optical Frequency Domain Reflectometry (OFDR) determines the timing of the return signal which locates it along the fiber.



Raman Shift - Pros and Cons

- Pro
  - Equipment exists – can bench demo as is
  - Can calibrate for any temperature range
  - Senses anywhere along the fiber
  - Can program gating to sense specific areas along fiber
  - Up to 16 channels per controller (interrogator)
  - Distance aboard ship no problem (good to many km)
  - Uses standard shipboard fiber, attached by adhesive or clamp
  - Programming for alarms can be very specific to application
  - Continuous monitoring not a problem – can average measurements, alert on differences, offload data to DAQ

Raman Shift - Pros and Cons

- Con
  - Spatial resolution only 50 cm (possibly can be improved with programming) – may need loops between adjacent measuring points
  - Requires fusion splices rather than connectors (complicates installation and maintenance)
  - May need different fiber for high temperature extremes
  - Requires loop of fiber at measurement point to get sufficient signal over noise
  - Possible susceptibility to single point failure, with multiple sensors on same fiber
  - Requires more laser power than Rayleigh Scattering.

Rayleigh Backscattering

- Reflection of light from structures (impurities) in an optical fiber are unique to that fiber
- OFDR sweeps a broad spectrum of light down the fiber. Strain or temperature alters the reflection
- Comparing the reflection to a reference shows the temperature difference
- An FFT on the returned signal converts it to the time domain to determine the distance down the fiber

Rayleigh Backscatter – Pros & Cons

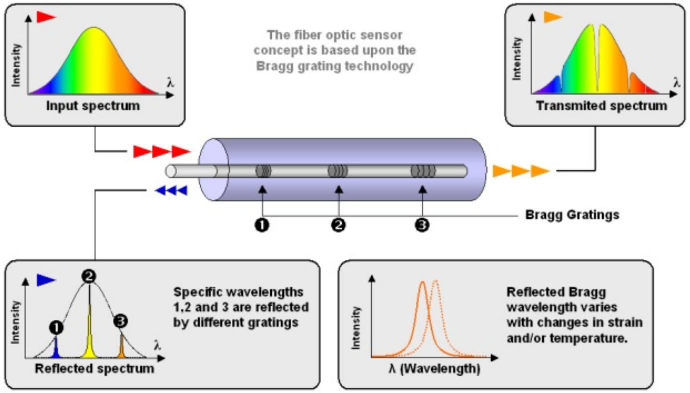
- Pro
  - Equipment exists – can bench demo as is
  - Senses anywhere along the fiber
  - Very good spatial resolution (5 mm), so no looping of fiber
  - Standard sensors of 5 m or 10 m length can yield hundreds of readings.
  - Can translate data to a map type display locating measurements in a physical space
  - Programming can be set up for averaging, continuous monitoring, various alarms. Can offload to a DAQ
  - Interrogator is single channel, but 8:1 and 36:1 optical switches can be used for multiplexing
  - Can use connectors
  - Software can identify the individual sensor fibers, so wiring errors are minimized
  - Can use adhesive or clamps
  - Software SDK is available for custom programming

Rayleigh Backscatter – Pros & Cons

- Con
  - Only short range – Interrogator has to be within 50 m of sensor fibers
  - Each machinery room would require its own interrogator, unless rooms were adjacent
  - Cost may be a factor due to number of interrogators required. Multiplexers are added cost.
  - Possible susceptibility to single point failure with multiple sensing points on a single fiber.

Fiber Bragg Gratings (FBG)

- An interferometer is etched directly onto the fiber.
- Each interferometer reacts to a very narrow spectrum.
- A wideband signal is sent down the fiber to excite. Each grating reflects at its own wavelength
- A spectrometer looks at the return signal. The amount of wavelength shift indicates the temperature rise.
- The particular wavelength that shifted indicates which sensor was affected by the temperature difference.



FBG – Pros and Cons

- Pro
  - Identification of sensor by bandwidth is very precise
  - Many measurements on same fiber are possible, since the bandwidth of individual sensors is very narrow
  - Total length of cable not a problem for ship installation
  - Can multiplex many sensors into the same interrogator
  - Very good spatial resolution (< 1 cm)
  - Identification of individual sensors allows for series or branch configuration – more flexible installation
  - Branches done by splicing (optical splitters)
  - Branches are less susceptible to single point failure

FBG – Pros and Cons

- Con
  - Equipment ban be borrowed for demos, but will likely need to have sensor fibers made up for tests
  - Multiple fiber junction boxes might be difficult to fit inside switchgear cabinets
  - Position of gratings must be carefully mapped out before production and later changes would require replacement of sensors, rather than reprogramming
  - Cost may be a factor. Interrogator cost is dwarfed by the fiber manufacturing and installation costs

First order cost comparison

- Raman Shift
  - Interrogator is cost driver. Demo unit is $50K, but production unit could be less, as unneeded features from demo unit could be removed
  - Fiber costs are low – standard fiber. High temperature fiber won't add much
- Rayleigh Backscatter
  - Interrogator is cost driver at $49.5K. 8 channel switch ($10K) or 36 channel switch ($20K) are adders.
  - Sensors are $300 each, but handle multiple sense points
- Fiber Bragg Grating
  - Fiber sensors and junction boxes/installation are cost drivers. Interrogator ~ $20K. Gratings alone are few hundred $ each
  - Fabricating fibers with gratings and the splices will dominate costs
- Much of cost will depend on number of sense points on board a ship and how they are physically distributed
- Costs will depend on whether continuous monitoring is required. If only spot checking is needed, a single interrogator could be taken between various points on board the ship to take down the readings, rather than have a permanently installed interrogator at each location

Conclusions

- DTS represents a potential long term full coverage solution to inspection for loose connections in electrical panels
- The technology can go beyond the present inspection needs if continuous monitoring is implemented.
  - Alarms can be programmed to alert when situations start to develop, rather than detecting them when they are close to crisis.
  - Data can be collected for reliability and preventive maintenance purposes
  - Electrical current usage downstream of the switchgear can be monitored for trends and predictive maintenance purposes
- Implementation of the three technologies differ enough that costs and utility will be specific to the application