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Low-Cost Sensors to Monitor Underground Distribution Systems

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NOTE

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Product Description

This report describes the last component for Electric Power Research Institute (EPRI) Project Agreement EP-P22269/C10882, also known as Southwest Research Institute (SwRI) Project 16-12565 and referred to as *Phase 2 Backscatter Sensors*.

Results and Findings

This second phase of the program focused on the feasibility of using radio backscatter sensors to evaluate underground distribution components, in particular, medium-voltage joints and cable sections that are located inside underground concrete vaults. The first program phase (EPRI Project Agreement EP-P18896/C9332 and SwRI Project 16-11679) was similar in scope but focused on separable connectors located inside pad-mount transformer enclosures.

Challenges and Objectives

This report documents the objectives of this project phase, which are the following:

- Perform a feasibility assessment for the use and leverage of EPRI's wireless backscatter sensor technology.
- Investigate magnetic field power-harvesting circuit enhancement for the existing EPRI backscatter sensor.
- Make sensor application recommendations for underground diagnostic applications.
- Create a functional specification for wireless sensors to be used in underground diagnostic applications.
- Create a functional specification for an interrogator to wirelessly read sensors.

Applications, Value, and Use

Under separate EPRI project agreements, wireless backscatter sensors are being developed for electric power utility component diagnostics for overhead transmission line and substation applications. It may be possible to leverage and extend those developments to include temperature and current measurements of underground distribution components. Although sensing technology in general is mature and widespread, electric power utility applications require operation in relatively harsh environments with exposure to weather, electrical noise, and high electric and magnetic fields. Wireless backscatter technology offers some unique advantages for electric power applications, but this engineering investigation focuses on its applicability to the unique sensing requirements of underground distribution components.

EPRI Perspective

Because underground distribution systems have much lower currents flowing through them than overhead transmission lines, magnetic-field power-harvesting circuit enhancements to the EPRI wireless backscatter sensor were investigated in order to significantly decrease the operating threshold, which is approximately a minimum of 100 amperes (A). Voltage-multiplying circuits are used in order to significantly lower the operating threshold toward 20 A with the existing coil. Circuit changes were resolved, and performance was verified using laboratory test data. Further reduction in the operating threshold can be addressed by coil configuration changes.

Approach

Functional specifications from related EPRI backscatter sensor developments were tailored for the separable connector sensing application (investigated in Phase 1) and are now extended to include the medium-voltage joint and cable section applications inside underground vaults. EPRI training materials and a report documenting the Manhole Cover Event Evaluation Facility (located at the EPRI office in Lenox, Massachusetts) have been reviewed for application insight into cable joints, underground vaults, and manhole openings. Subject matter experts at EPRI and power utilities have been engaged to identify practical and viable sensing applications that would maximize the return on investment. The initial feasibility of the concept is based on wireless communication measurements made at the EPRI Lenox facility.

Keywords

Backscatter sensor
Distribution system centers
Power-harvesting circuit
Radio backscatter sensor
Wireless backscatter sensor

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Contents

Contents

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List of Figures

List of Table

1 FEASIBILITY TESTS

1.1 Feasibility for the Use and Leverage of EPRI's Wireless Backscatter Sensor Technology

Tests were conducted at the Electric Power Research Institute (EPRI) Lenox, Massachusetts, facility to determine the potential for wirelessly communicating with a backscatter sensor located in an underground concrete vault from ground level above the manhole with the manhole cover installed. The following two types of tests were conducted:

1. Reading a prototype sensor
2. Measuring the radio frequency (RF) signal level (that is, path loss)

In the first test, a prototype backscatter sensor was located in the vault, and the interrogator system was used to read it from ground level above the manhole with different manhole covers installed. In the second test, the interrogator system was taken into the vault, and the RF signal level received on a portable spectrum analyzer was measured from ground level above the manhole, again with different manhole covers installed.

Tests were run with the sensor and interrogator antennas in the best-case orientations. The sensor was positioned in the 14-ft (4-m) deep vault facing straight up from the bottom center of the manhole. The interrogator antenna was positioned a few inches (several centimeters) above the manhole cover facing straight down toward the sensor. For the spectrum analyzer measurements, an antenna identical to the interrogator antenna was used.

The sensor was moved away from the bottom center of the manhole, but the ability to read the sensor was quickly lost (even with no manhole cover) when the sensor was just a few feet (approximately 1 or 2 m) offset from the manhole. This is unfortunate and indicates that potentially helpful radio signal reflections within the vault are minimal—which means that for reliable wireless data collection, the sensor antenna will need to be located in the manhole area and optimally oriented.

The measurements taken at the EPRI Lenox facility under representative conditions indicate that it is technically possible to communicate with a sensor located inside an underground concrete vault using radio backscatter technology. Based on these initial findings, it appears that the wireless sensor concept is technically feasible and an effective design solution could be engineered if the development is merited.

In order for the sensor system to be commercially viable, the sensor wireless communications link needs to be robust with the manhole cover closed. To achieve this, the sensor and interrogator antennas will need to be optimally designed, configured, and oriented. Even with an optimal design, there may be some cover types and installation conditions that cannot be accommodated with the manhole cover closed. Therefore, it may be important as part of the analysis of cost, benefit, and requirements to identify installations in which sensors are desired and to categorize the conditions of these installations if the sensors will need to operate without modification to the installation site.

Test results are summarized in **Table 1-1**, and components of the testing are shown in **Figures 1-1** through **1-6**.

Table 1-1
Test Results

Cover Condition	One-Way Path Loss	Sensor Readings
Baseline reference; no cover	54 dB (ref)	Reads reliably but not 100%
Composite cover	54 dB (0 dB ref)	Reads reliably, but interrogator antenna positioning is more critical
Steel cover; slotted, no clogging	74 dB (-20 dB ref)	Reads reliably, but interrogator antenna positioning is even more critical (need to find the "sweet spot")
Steel cover; ventilation holes completely clogged	79 dB (-25 dB ref)	Unable to read sensor
Steel cover; no ventilation holes but three small grip holes	84 dB (-30 dB ref)	Able to read sensor only when the interrogator antenna is positioned directly over the grip holes

Figure 1-1
Composite Cover

The one-way path loss measurements provide a quantified measure of the differences between the manhole cover types and conditions. The numbers in **Table 1-1** are believable because the baseline measurement agrees with the free-space path loss calculation. The transmit power was 30 dBm (1 watt), the antenna gain was 24 dB (12-dB transmit + 12-dB receive), and the received power level on the spectrum analyzer was 0 dBm (30-dBm transmit power + 24-dB antenna gain – 54-dB path loss = 0 dBm received power). The path loss for free space is approximately 20logF + 20logD + 32.4 dB, where F is in megahertz (MHz) and D is in kilometers (km). Therefore, for 2450 MHz and 0.005 km, the path loss comes to 54 dB—which is exactly what was measured.

The backscatter interrogator system accommodates approximately 90 dB of path loss. For backscatter communications, the signal travels to the sensor and then back to the interrogator; therefore, 6 dB

Figure 1-2
Steel Cover with Clogged Vent Holes

Figure 1-3
Solid Steel Cover with Only Grip Holes

Figure 1-4
Steel Cover with Unclogged Slots

Figure 1-5
Sensor at the Bottom of the Manhole

Figure 1-6
Reader with Antennas Positioned Above the Slotted Steel Manhole Cover

(2x in linear terms) must be added to the one-way path loss measurements. This indicates that the steel manhole cover configurations present a system path loss in the range of 80 to 90 dB, which is within the system capability but marginal. The impact of the manhole cover on the radio signal propagation is more complicated than the path loss measurement indicates because the path is indirect, relying on diffraction. This means that although the signal level is within the range of the system, extra effort may be required to develop a reliable design. Initial thoughts are that interrogator antenna diversity and an increased sensor message transmission rate could improve wireless communication performance to an acceptable level of reliability.

2 POWER HARVESTING

2.1 Power-Harvesting Circuit Enhancement for the Existing EPRI Backscatter Sensor

The EPRI conductor/splice backscatter sensor measures the temperature of the conductor/splice to which it is attached as well as the current that is flowing through the line. This sensor has been in development since 2004 and is approaching commercialization. It is from this baseline that similar sensors for specific underground distribution applications are envisioned.

A key feature of the splice sensor is that the power to operate the sensor is harvested from the magnetic field that is generated from the current flowing through the line. A short coil on a ferrite rod is used along with a rectifying circuit. This arrangement is effective for the high currents that flow in transmission lines (100–2000 amperes [A]). For underground distribution applications, currents levels will be lower, and so extending the performance limits is desired. Efforts taken to optimize the circuit, which are documented in this section, do not address the re-design of the coil because that depends on size and form-factor constraints that have not yet been determined. This means that additional performance can later be achieved by addressing the coil design as well.

The objective of this task was to minimize the conductor current threshold that is required to operate the sensor by improving the power rectification and conversion circuitry that are part of the sensor. The coil and sensing circuitry will remain the same. A line-current-sensing signal must be provided so that the sensor can monitor the line current; the circuit components must be rated for continuous line currents up to 2000 A.

The design approach is as follows:

1. Characterize the existing coil.
2. Examine the potential for increasing coil output.
3. Optimize the power-harvesting electronics.
4. Ensure that the line current monitoring function worked effectively.

The details of the investigation and electronics development are not documented because the sensor technology is currently being patented and licensed.

Several conclusions were reached as a result of this project. A new electronic power-harvesting circuit was developed that improved the power-harvesting performance of the EPRI splice sensor. The changes should reduce the operating threshold from ~100 A to ~30 A or less. These performance improvements will also open up more applications for the use of these sensors. The actual operating-threshold needs for underground distribution applications have not yet been identified but are anticipated to be on this order or possibly even more stringent (that is, the applications must work with less line current flowing). Any additional performance enhancement can be addressed in other parts of the power-harvesting system design.

3 SENSOR APPLICATION

3.1 Sensor Application Recommendations for Underground Diagnostic Applications

Application insight from experts in the field is necessary in order to identify practical sensor concepts for development. Insight is needed into component failure modes, symptoms that could be monitored for and detected, the probability and consequence of failures, and the quantity of fielded components as well as their physical distribution and accessibility. Working groups to gain this insight have been identified but need to be further pursued. Potential sensor needs must be matched to the appropriate enabling technology. The expectation is that application insight, coupled with an understanding of technology capabilities and limitations, will enable effective wireless sensing solutions to be engineered in order to improve the reliability and availability of underground distribution systems.

One possibility for the diagnostic monitoring of underground distribution components is a temperature sensor. The temperature of critical components can be monitored with a direct-contact sensor in order to detect overheating conditions. A challenge based on experience in overhead-transmission-line temperature sensing is to establish a suitable physical interface that is mechanically robust and secure while providing good measurement sensitivity without heat-sinking effects. The elbow or separable connectors in pad-mount transformer enclosures as well as the medium-voltage joints or splices in underground vaults are components that are susceptible to overheating. With the attachment of an appropriate temperature sensor to these components, thresholds could be established to identify abnormally hot conditions, and maintenance personnel could be wirelessly alerted without having to open the enclosure or vault.

Another possibility is a radio frequency interference (RFI) sensor. Electrical or partial discharges occur within damaged or failing components in underground distribution systems. Depending on environmental conditions, these conditions are often intermittent. At least one commercial product is used from a hotstick to detect RFI from elbow connectors in underground distribution systems (Radar Engineers Model 70 Partial Discharge Detector). Instead of a labor-intensive manual operation, this type of instrument could be designed as a low-cost wireless sensor that is stationed in close proximity to critical components. With continuous or (to conserve power) near-continuous monitoring, a comprehensive statistical measurement of the RFI emissions could be obtained. Similar to the temperature sensor, thresholds could be established to identify abnormal RFI conditions, and maintenance personnel could be wirelessly alerted without having to open the enclosure or vault.

4 FUNCTIONAL SPECIFICATION

4.1 Draft Functional Specification: Backscatter Sensor System for Electric Power Utility Diagnostics

The functional specification for the system, sensors, and portable interrogator for the envisioned underground distribution component diagnostic sensing application is provided in this section. The specification will continue to evolve and be refined throughout the development process.

4.1.1 Background

Radio frequency identification (RFID) systems consisting of readers and tags commonly use backscatter communication techniques in which the reader illuminates a local area with an RF carrier in order to read tag identification codes. These codes are scattered back as modulating signals on the carrier. The following are the primary benefits of an RF backscatter system:

- Low-cost, low-power tags: Only an antenna modulator, rather than an RF transmitter, is required.
- Minimal RF interference concerns: Tags do not transmit RF, rather, the reader does.
- Wide operating range: The system has an operating range of a few hundred feet (approximately 60 meters) with micro-power tags.

4.1.2 Scope

An RF backscatter system is envisioned for component diagnostic sensor applications within the electric power industry. In this case, the tags (hereafter referred to as *sensors*) communicate a data payload (that is, sensor readings) in addition to an identification code. A key feature of backscatter technology is the potential for sensors to harvest power from the local environment (for example, solar, vibration, magnetic field, and electric field), enabling a battery-free, maintenance-free, multi-decade sensor life. Many electric power utility sensor applications are located in remote areas and near energized lines where periodic drive-by or fly-by data collection can be performed quickly and at a safe standoff distance using backscatter technology.

In this section, functional system specifications for the underground distribution component sensor application are organized as follows:

- Section 4.2, "System Protocol": The generic sensor communications protocol.
- Section 4.3, "Underground Distribution Component Sensor": A sensor that measures temperature and current and attaches to underground distribution components, such as separable connectors inside pad-mount transformer enclosures and medium-voltage joints and cable sections inside underground concrete vaults with manhole access.
- Section 4.3, "Interrogator": A portable device that is used to read sensors and that can be interfaced with a computer or personal digital assistant (PDA) for control and display purposes.

Figure 4-1 illustrates the sensor system architecture.

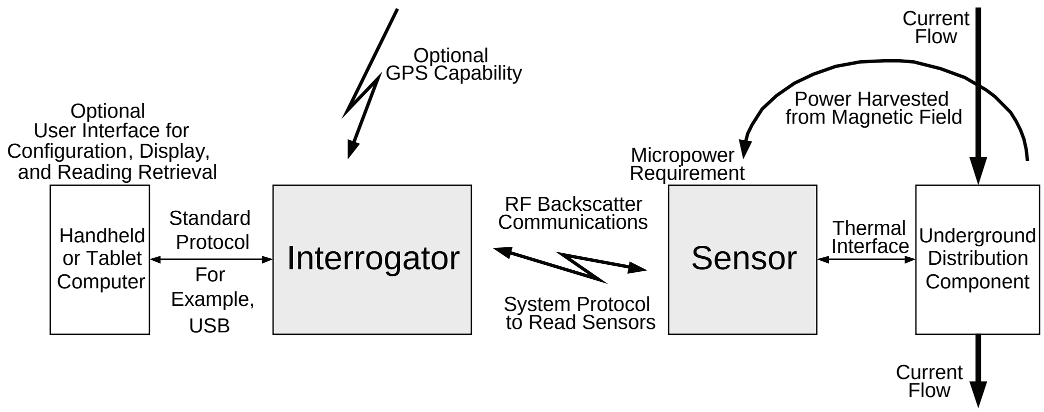

Figure 4-1
Sensor System Architecture

Specification compliance may be verified during engineering development using the following variety of methods:

- Analysis: theoretical proof based on accepted principles of math and science
- Review: design review based on engineering drawings and source code
- Inspection: physical inspection of a specimen
- Demonstration: functional demonstration of a specimen in a realistic scenario
- Test: measurements taken using calibrated instrumentation

The expected compliance verification method is listed in brackets at the end of each specification description, for example, [Test].

4.2 System Protocol

4.2.1 Messages

The sensor shall modulate its backscatter antenna with a digital message that includes a sensor ID code and a data payload. [Review]

4.2.2 Sensor Identifications

Sensor ID codes shall be 24 bits, providing more than 16 million unique IDs. [Review]

4.2.3 Sensor Data Payloads

Data payloads shall be a fixed size between 0 bits ("ID only") and 32 bytes (256 bits), depending on the sensor specification. Readers shall be able to accommodate this range of payload sizes. [Review]

4.2.4 Message Data Rate

The data rate shall be 10 kHz nominal. [Test]

4.2.5 Message Modulation

When modulating a message, the sensor shall digitally switch its backscatter antenna between two states—incident energy reflecting and incident energy absorbing—at the following rates:

Data bit = logical "0": 149.3 kHz nominal
Data bit = logical "1": 95.2 kHz nominal [Test]

4.2.6 Message Quieting

When not modulating a message, the sensor shall hold its backscatter antenna in a fixed unmodulated state in order to eliminate noise potential. [Test]

4.2.7 Message Interval

After modulating a message, the sensor shall wait before modulating another message. The length of the wait period depends on the sensor specification and allows time for multiple sensors in close physical proximity to be read without interfering with one another. [Review]

4.2.8 Radio Frequency Spectrum

The interrogating reader and sensors shall be designed to operate in the 2400- to 2483.5-MHz radio spectrum, which is an unlicensed band that is available nearly worldwide. [Review]

4.3 Underground Distribution Component Sensor

These specifications were adapted from sensor specifications originally developed for overhead transmission line applications. Specification tailoring will be required as the underground distribution sensor concepts develop and the technical details and requirements are resolved.

4.3.1 Temperature Sensing Function

The sensor shall directly measure the temperature of the underground distribution component to which it is attached with a range of 0–255°C and a resolution of 1°C. [Review]

Notes:

This range is based on overhead transmission line applications but can be re-scaled as necessary for underground distribution applications.

The range of 0–255°C is matched to the range of an 8-bit digital value (that is, 1-byte data payload) to provide exactly 1°C resolution. Other ranges, resolutions, and bit widths are possible.

4.3.2 Temperature Accuracy

The sensor temperature monitoring accuracy shall be within 5% or 3°C, whichever is greater (see **Figure 4-2**). [Test]

4.3.3 Line Current Sensing Function

The sensor shall measure the line loading (in amperes) at the time of the temperature measurement with a range of 0–2550 A and a resolution of 10 A. The line loading is measured by sensing the strength of the magnetic field that is induced by the line current. [Review]

Notes:

This range is based on overhead transmission line applications but can be re-scaled as necessary for underground distribution applications. For example, 0–255 A may be more appropriate.

The range of 0–2550 is matched to the range of an 8-bit digital value (1-byte data payload) to provide exactly 10-A resolution. Other ranges, resolutions, and bit widths are possible.

4.3.4 Line Current Accuracy

The sensor line current monitoring accuracy shall be within 5% or 10 A, whichever is greater (see **Figure 4-3**). [Test]

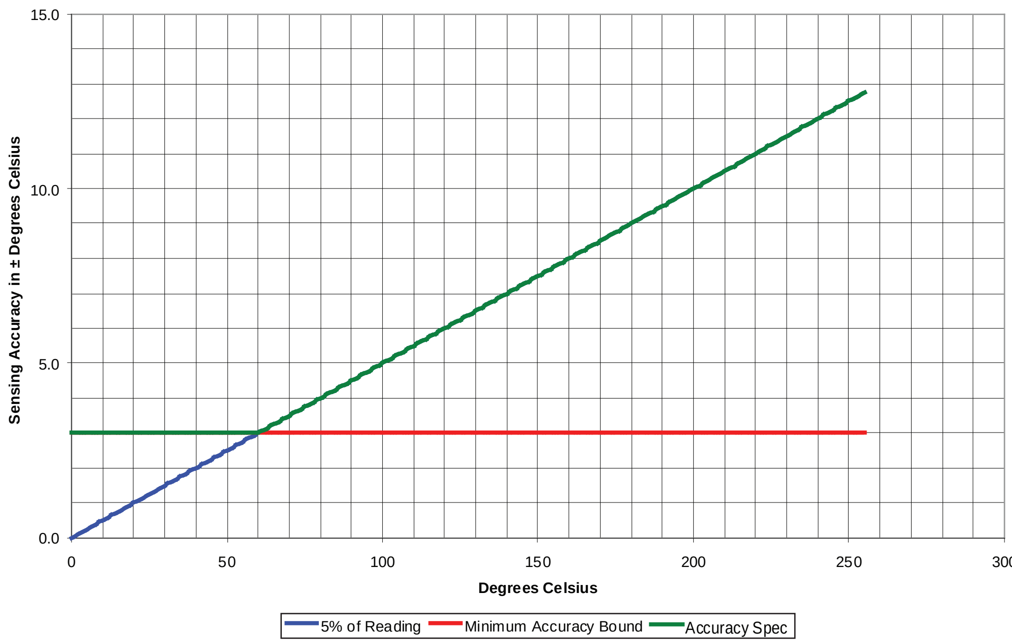

Figure 4-2
Sensor Temperature Monitoring Accuracy

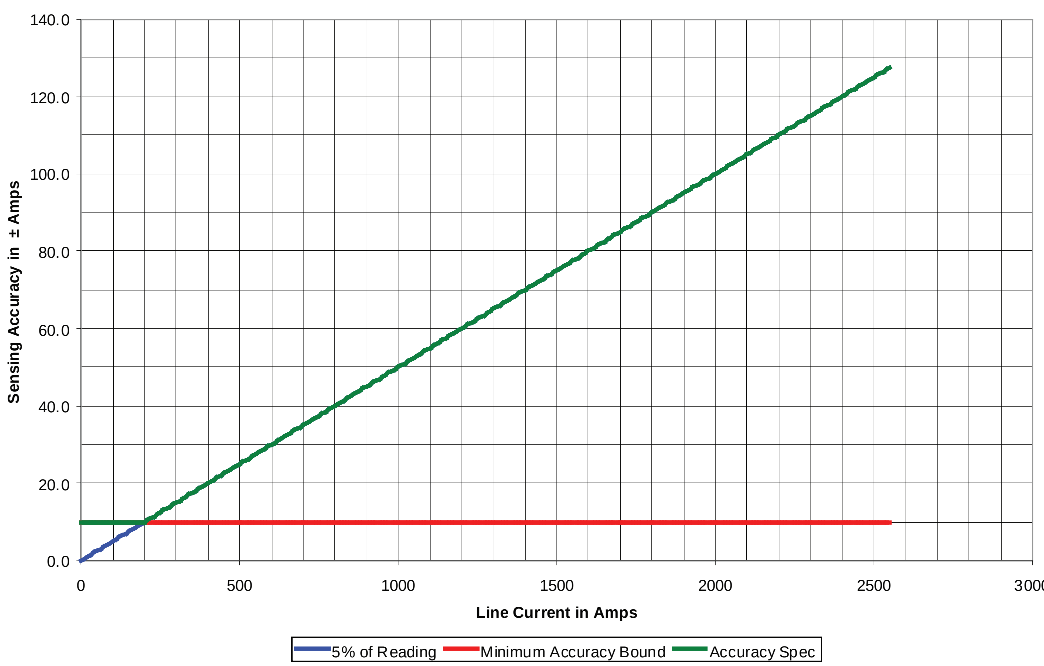

Figure 4-3
Sensor Line Current Monitoring Accuracy

4.3.5 Peak Reading

The sensor shall store in nonvolatile memory the peak temperature and the line loading at the time of the peak temperature reading. [Demonstration]

4.3.6 Peak Reset

The peak reading shall be reset by momentary closure of a set of switch contacts. This step may require operator access to the sensor. [Demonstration]

4.3.7 Measurement Interval

The sensor measurement interval shall be programmable at the time of manufacture over the range of 1–30 minutes. [Review]

4.3.8 Sensor Identification

The sensor 24-bit ID code shall be programmable at the time of manufacture. The same ID code shall be printed onto a barcode that is affixed to the sensor. [Demonstration]

4.3.9 Data Payload

The sensor data payload shall be 4 bytes: one byte each for the latest temperature reading, the latest line current reading, the peak temperature reading, and the line current at the peak temperature reading. [Demonstration]

4.3.10 Messaging

The sensor shall modulate its message (including the sensor ID and data payload) according to the system protocol specified in Section 1. [Review]

4.3.11 Message Interval

The sensor shall modulate its message and wait a somewhat random amount of time before modulating its next message; however, the message interval (on average) shall be kept at a constant that is programmable at the time of manufacture over the range of 0–30 seconds. The wait feature mitigates interference concerns when sensors are in close physical proximity. Increasing the message interval increases the number of sensors that can be read in a given area, but this also increases the average time required to read a sensor and could impact drive-by speed. [Test]

4.3.12 Power Harvesting

The sensor shall harvest power from the current that flows through the underground distribution component, if possible or practical. [Test]

4.3.13 Backup Power

The sensor shall include a backup power reservoir to enable sensor operation when the harvested power is inadequate. [Test + Analysis]

4.3.14 Battery Option

As a configuration option, the sensor shall be capable of being battery powered with a life expectancy of at least 10 years. [Test + Analysis]

4.3.15 Thermal Interface

The sensor shall be designed to attach to separable connectors for direct temperature measurement of the insulating boot and to medium-voltage joints and cable sections in a similar manner. [Review]

4.3.16 Size

The sensor envelope shall not exceed 5 × 5 × 5 in. (12.7 × 12.7 × 12.7 cm). [Inspection]

4.3.17 Weight

The sensor weight shall not exceed 16 oz (0.45 kg). [Inspection]

4.3.18 Compatible Underground Distribution Components

The sensor shall be attachable to standard separable connectors, medium-voltage joints, and cable sections. [Demonstration]

4.3.19 Connector Stress

The sensor shall attach directly to the underground distribution component without placing stress on it that results in premature failure. [Analysis]

4.3.20 Energized Installation

The sensor shall be installable on the underground distribution component under energized conditions. [Demonstration]

4.3.21 Energized Operation

The sensor shall be operable with line voltages up to 35 kV (within the pad-mount transformer box) and up to 69 kV (within underground concrete vaults) and with line currents up to 900 A. [Demonstration]

4.3.22 Corona Free

The sensor shall not produce corona activity under dry conditions when installed on the underground distribution component. [Demonstration]

4.3.23 Corona Withstanding

The sensor shall operate in the presence of foul-weather corona activity and the resulting by-products. [Demonstration]

4.3.24 Fault Current Exposure

The sensor shall withstand 5-kA, 7-cycle fault currents flowing through the underground distribution component to which it is attached. [Demonstration]

4.3.25 Current Impulse Exposure

The sensor shall withstand 20-kA, 8/20-μs current impulses flowing through the underground distribution component to which it is attached. [Demonstration]

4.3.26 Sheltered Outdoor Operation

The sensor shall be packaged to operate in a sheltered outdoor environment and shall be designed for an ingress protection (IP) level of IP55 according to International Electrotechnical Commission (IEC)/EN60529. [Review]

4.3.27 Service Life

The sensor shall be designed for a service life of at least 20 years. [Review]

4.3.28 FCC Compliance

The sensor shall be designed for compatibility with the United States Federal Communications Commission (FCC) regulations for unlicensed devices (47CFR). [Review]

4.4 Portable Interrogator

These specifications were adapted from portable interrogator specifications originally developed for overhead transmission line applications for which fly-by inspections are typically conducted. Specification tailoring will be required as underground distribution sensor concepts develop and the technical and logistical details and requirements regarding wireless sensor data collection are resolved.

4.4.1 Sensor Reading Function

The interrogator shall be able to read sensors that conform to the system protocol specified in Section 1. [Demonstration]

4.4.2 Reading Storage

The interrogator shall store valid readings to nonvolatile memory, including a date and time stamp in addition to the sensor ID and data payload. [Demonstration]

4.4.3 Minimum Interval Between Readings

The interrogator shall be user-configurable through the computer interface so that the minimum interval between readings of a common sensor ID can be set. This should reduce excess redundant data from accumulating in nonvolatile memory. For example, sensor readings may be decoded at a rate of 1 per second, and in five minutes 300 duplicate readings may be otherwise unnecessarily stored. [Demonstration]

4.4.4 Storage Capacity

The interrogator shall be able to store up to 1 million readings in a nonvolatile memory media such as a secure digital (SD) card. [Review + Analysis]

4.4.5 Global Positioning System Option

The interrogator shall include provisions to interface with a global positioning system (GPS) receiver, in which case GPS time and position data can be included with each stored reading. [Demonstration]

4.4.6 Computer Interface

The interrogator shall include provisions to interface with a handheld or tablet computer so that the user can configure operation, retrieve stored readings, display readings in real time, and display interrogator health status. [Demonstration]

4.4.7 Default Operation

If there is no computer host, the interrogator shall operate as it was last configured. Configuration settings shall be stored in nonvolatile memory so that they are not lost when the power is cycled. [Demonstration]

4.4.8 Operating Configuration

Interrogator operation shall be user configurable through the computer interface as follows:

- Mode: standby (essentially off), on-air (collecting readings), or duty cycled
- Duty-cycled standby time: time duration of standby state in duty-cycled mode
- Duty-cycled on-air time: time duration of on-air state in duty-cycled mode
- Minimum interval between readings: as described in Section 4.4.3
- Clock settings: set on-board clock time and date (when no GPS is present) [Demonstration]

4.4.9 Reading Retrieval

Stored readings shall be retrievable through the computer interface for entry into an external spreadsheet or database. [Demonstration]

4.4.10 Reading Spooler

The interrogator shall spool sensor readings to the computer interface in near-real time as valid readings are decoded. [Demonstration]

4.4.11 Health Status Display

The interrogator shall include built-in test features to assist the user if troubleshooting is required. The health status shall be indicated with a status light-emitting diode (LED) as well as a health message that is periodically provided to the computer interface. At a minimum, the following built-in test features shall be provided:

- Battery voltage low
- Transmit antenna fault (when reflected transmit power is sensed)
- Receiver overload (when the antenna isolation between transmit and receive is inadequate)
- GPS status (when the GPS option is selected) [Demonstration]

4.4.12 Power On/Off Switch

The interrogator shall have a power on/off switch. [Demonstration]

4.4.13 Power Consumption

The interrogator power consumption shall not exceed 20 W. [Test]

4.4.14 Battery or Power Supply

The interrogator shall operate from a rechargeable battery with a minimum voltage (that is, end of life) of 5.5 V, a maximum voltage of 8 V, and a sustained peak current capability of 2.5 A. The interrogator shall also be operable using an ac-line powered supply with equivalent ratings. [Review + Demonstration]

4.4.15 Battery Life

The interrogator shall operate for at least 1 hour on its battery. [Test]

4.4.16 Battery Recharging

The interrogator battery shall be rechargeable from an ac-line powered source (110–120 V, 60 Hz). [Demonstration]

4.4.17 Portability

The interrogator shall be human portable. [Demonstration]

4.4.18 Size

The interrogator dimensions shall not exceed 12 × 9 × 3 in. (30 × 23 × 8 cm), not counting connector protrusions. [Inspection]

4.4.19 Weight

The interrogator weight shall not exceed 5 lb (2.3 kg). [Inspection]

4.4.20 Read Range

The interrogator shall be able to read sensors reliably (that is, with a >50% success rate) over a minimum standoff range of 0–150 ft (0–46 m) when there is a clear line of sight between the reader and the sensor. [Demonstration]

4.4.21 Doppler Tolerance

The interrogator shall be able to read sensors reliably (with a >50% success rate) over a relative velocity range of ±60 mph (97 kph [±88 ft/s ±27 ft/s) between the reader and the sensor. [Demonstration]

4.4.22 Corona Noise Tolerance

The interrogator shall be able to read sensors reliably (with a >50% success rate) in a substation or similar environment with corona and arcing activity in close proximity to the reader and/or the sensor. [Demonstration]

4.4.23 Reader Platform Flexibility

The interrogator shall be able to read sensors reliably (with a >50% success rate) whether the reader data collection takes place from a fixed station, an operator walk-by, a ground vehicle drive-by, or an aerial vehicle fly-by. [Demonstration]

4.4.24 Environmental Compatibility

The interrogator shall be able to read sensors reliably (with a >50% success rate) over normal terrestrial outdoor temperatures and weather conditions. Performance degradation is acceptable under conditions of heavy rain, sleet, snow, or when ice buildup is present on the sensors or reader equipment. [Review]

4.4.25 Exposed Weather Operation

The interrogator shall be packaged to operate under exposed outdoor weather conditions and shall be designed for an IP level of IP55 according to IEC/EN 60529. [Review]

4.4.26 Shock and Vibration

The interrogator shall be capable of being mounted to withstand shock and vibration experienced in vehicle transport, including helicopters, and shall be operable under these conditions. [Review]

4.4.27 FCC Compliance

The interrogator shall be designed for compatibility with FCC regulations for unlicensed devices (47CFR). [Review]

4.4.28 Safety Compliance

The interrogator shall meet Occupational Safety and Health Administration (OSHA) safety standards. [Review]

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