Description

Title

Sensor and Edge-Processing Node for Detecting Electrical Leakage and Partial Discharge on Utility Power Lines

Technical Field

[0001] The present invention relates to the field of electrical power distribution monitoring. More particularly, it provides a sensor apparatus and edge-processing node for detecting electrical leakage currents and partial discharge (PD) events on utility power lines and high-voltage equipment. This invention falls under power system fault detection technology, combining multiple sensing modalities to identify incipient insulation failures and ground leakage in electrical networks.

Background Art

[0002] Electrical utilities and industrial power systems require early detection of insulation faults and leakage currents to prevent outages, equipment damage, or safety hazards. Conventional ground fault detectors, such as residual-current devices (RCDs) used in low-voltage installations, monitor imbalance between phase and return conductors to detect leakage to earth. However, traditional RCDs are typically tuned to trip at relatively high leakage currents (e.g., 30 mA or more) and primarily sense 50/60 Hz AC imbalance. They do not capture subtle or incipient leakage conditions, high-frequency transient events, or very slow (substantially DC) drift in current that might indicate developing faults. In high-voltage distribution lines, there is a lack of compact devices that can detect small leakage currents or early-stage insulation deterioration before catastrophic failure.

[0003] Partial discharge (PD) is a well-known phenomenon where localized dielectric breakdown occurs in insulation, often preceding insulation failure. PD events generate high-frequency current pulses and electromagnetic emissions that can indicate deteriorating insulators, cable terminations, or other high-voltage components. Traditional PD monitoring systems are often laboratory or substation-based instruments, such as oscilloscopes,

ultra-high-frequency sensors, or acoustic detectors, which are expensive and not typically deployed widely on distribution lines. Existing online PD monitors usually focus on specific equipment (e.g., transformers or switchgear) and often require high-bandwidth data acquisition and storage. They generally operate independently of ground leakage sensors and may not correlate their readings with other electrical parameters like residual current. Moreover, deploying separate sensors for PD and leakage can lead to disjointed data and missed opportunities to detect complex fault conditions that manifest across multiple signal types. There is thus a need for an integrated approach to detect both continuous leakage currents and sporadic PD events in a single system.

[0004] In known monitoring devices, sensor calibration and long-term stability present challenges. Current sensors (for example, Rogowski coils or other current transformers) can exhibit drift in sensitivity or offset over time due to temperature changes, aging of components, or environmental influences. Existing systems often require periodic manual calibration or assume worst-case error margins, which can reduce detection sensitivity. For instance, a Rogowski coil used for measuring fast transient currents may have an integrator circuit that drifts, leading to inaccurate readings of partial discharge magnitude or 50/60 Hz leakage current. The prior art does include methods for sensor calibration (such as using test coils or reference signals in some laboratory instruments), but these are not commonly integrated into field-deployed line monitors and are not automated in real-time during normal operation. Without continuous self-calibration, a sensor's accuracy in detecting small leakage currents or PD pulses can degrade, resulting in false negatives (missed faults) or false positives.

[0005] Environmental factors significantly influence both leakage currents and partial discharges, yet many monitoring systems do not compensate for these effects. High humidity, for example, can increase surface leakage currents on insulators or cables, raising the baseline leakage current without an actual fault being present. Temperature changes can affect insulation resistance and the propensity for corona or partial discharge activity (e.g., cold temperatures might increase brittleness and PD occurrence, while high humidity can suppress some forms of corona discharge but promote conductive leakage along surfaces). If a sensor system uses fixed thresholds for alarm, it may trigger unnecessary alerts during extreme environmental conditions or, conversely, overlook developing faults that are masked by benign environmental influences. Known leakage detectors and PD monitors typically lack the means to dynamically adjust their sensitivity or alarm criteria based on real-time environmental data (such as relative humidity, ambient temperature, or even altitude/air pressure). This absence of environmental compensation leads to suboptimal reliability in real-world deployments.

[0006] Another challenge in widespread deployment of smart sensors on power lines is data communication bandwidth. Partial discharge monitoring can produce a large volume of data; for instance, phase-resolved partial discharge (PRPD) patterns or pulse waveform recordings are information-rich and often high-resolution. In remote power line locations, high-speed communication infrastructure is rarely available. Instead, low-power wide-area networks (LPWANs) like LoRaWAN® or NB-IoT are used to transmit data to central servers. These networks offer long-range connectivity and low power consumption but have very limited bandwidth and payload size. Existing IoT-based PD sensors tend to simplify the data sent (for

example, sending only a count of discharges or a severity index) , which risks losing important diagnostic detail. Without an effective data compression or clever encoding strategy, it is impractical to transmit detailed PRPD maps or high-frequency event data over such constrained links. To date, there is no known compact line-mounted device that performs real-time compression of PD data on the edge to enable full pattern transmission within LPWAN limits.

[0007] Powering sensors on medium- and high-voltage lines is also a practical concern. Some line-mounted monitors harvest energy from the line's electric or magnetic field (for example, using inductive coupling on the conductor), which provides power as long as the line is energized and carrying current. However, reliance on a single energy source can be problematic. During outages (when the line is de-energized due to a fault or maintenance), a line-powered device loses its power source exactly when it might be needed to record the event or communicate the fault. Alternatively, battery-powered devices alone have limited operational life and require periodic battery replacement, which is costly and inconvenient for utility operators. Solar panels are sometimes used on outdoor devices, but solar alone is unreliable at night or in bad weather, and extended periods without sunlight can deplete batteries. In the prior art, few if any line monitoring systems combine multiple power harvesting methods to provide a resilient power supply. A lack of uninterrupted power solutions means some monitors cannot ride through line outages or low-current conditions, resulting in data loss or inactive periods. There is a clear need for a robust power supply design that ensures continuous operation of the monitoring device through varying line conditions and environments.

Disclosure of Invention

[0008] The present invention addresses the above-described shortcomings by providing a GridLeak sensor system – a compact, intelligent device that fuses multiple sensor channels and performs advanced signal processing to detect incipient electrical faults on utility power lines. The invention combines a residual current sensing element, a high-frequency partial discharge sensor, and a fluxgate magnetometer in one apparatus, with an integrated edge processor that synthesizes their outputs into a unified leakage index (Lx). By leveraging data from these diverse sensors, the system can reliably detect a wide range of fault signatures, from sudden high-frequency discharge pulses to slowly evolving ground leakage trends, far beyond the capabilities of any single sensor type alone.

[0009] Fused Leakage Index (Lx): In one aspect, the invention computes a fused "Leak Index" (Lx) as a composite value derived from multiple sensing modalities. A residual current sensor monitors any imbalance between conductors (indicative of leakage current to ground), a partial discharge (PD) sensor listens for fast transient discharge events, and a fluxgate-based magnetic sensor measures very low-frequency or DC magnetic drift. The edge processor (e.g., a microcontroller or FPGA within the node) combines these inputs, for example by weighting or scaling each channel's contribution, to calculate Lx in real time. The fused index Lx provides a quantitative measure of overall insulation health or leakage severity: it rises when leakage current increases, when PD pulses are frequent or intense, or when a slow drift in current offset is detected. By fusing data, the system can trigger a fault alert even if each individual channel's

signal is marginal – for instance, a moderate 50 Hz leakage coupled with occasional PD pulses and a slight DC drift might together indicate a developing fault, prompting maintenance before a full failure occurs.

[0010] Ultra-Low Frequency Drift Detection: The invention is further characterized by the ability to detect extremely slow changes in current imbalance (on the order of millihertz or below) using a fluxgate magnetometer and advanced filtering algorithms. The fluxgate sensor provides a high-sensitivity measurement of any net magnetic field around the conductors, thereby sensing even tiny DC or sub-hertz AC currents that standard inductive sensors would miss. A Kalman filter or similar state estimator in the processor continually tracks the fluxgate signal to distinguish true steady-state shifts from noise. This allows the system to observe, for example, a gradual increase in leakage current over hours or days (sub-mHz drift), which could precede an insulation breakdown. Such slow-trending faults can be detected well before reaching the trip thresholds of conventional protection devices.

[0011] Self-Calibration of Sensor Accuracy: Another aspect of the invention is an automatic self-calibration mechanism for the current sensor (preferably a Rogowski coil or other current transducer used for residual current and/or PD sensing). The device injects a known reference signal, such as a low-amplitude 1 kHz pilot tone, into the sensing circuit or a dedicated test winding, during normal operation. By measuring the sensor's response to this injected reference, the processor can calibrate the gain and offset of the measurement system in real time, compensating for drift due to temperature changes or component aging. This continuous calibration loop ensures that the sensitivity of the residual current sensing channel (and the high-frequency PD channel, if using the same coil) remains stable over the long term, without requiring manual recalibration or service. As a result, the fused leakage index Lx and other measurements remain accurate and consistent, reducing the likelihood of error or alarm threshold miscalibration over the device's lifetime.

[0012] Edge Processing and Data Compression: The invention also includes on-board data processing algorithms implemented in a field-programmable gate array (FPGA) or a high-performance microprocessor, enabling real-time analysis and compression of partial discharge data. In particular, the system constructs a phase-resolved partial discharge (PRPD) map from detected PD events, correlating discharges with the phase of the AC mains cycle. Rather than transmitting a raw high-volume PD data stream, the processor compresses the PRPD information using a custom algorithm that drastically reduces data size while preserving essential diagnostic features of the discharge pattern. This compression may involve accumulating statistical distributions of discharges per phase angle, eliminating redundant or empty data points, and encoding the results efficiently. The compressed PD data (along with the current leakage values and Lx) can then be transmitted over a low-bandwidth wireless link such as LoRaWAN, fitting within strict payload limits. By performing FPGA-based PRPD map compression at the edge, the invention enables comprehensive partial discharge monitoring in remote locations without overwhelming the communication network.

[0013] Environmental Compensation and Adaptive Thresholds: The system further improves reliability by dynamically adjusting its detection criteria based on environmental conditions.

Built-in environmental sensors (for example, a humidity sensor and a temperature sensor) feed into the processor, which applies compensation factors to the leakage index or its alarm threshold. In practice, this means the device can automatically raise or lower the Lx alarm threshold in response to environmental data – for instance, increasing the threshold during periods of high humidity or heavy rain to account for benign surface leakage, or lowering the threshold in very dry, cold conditions when even small PD activity is significant. Alternatively or additionally, the processor can normalize or weight the contributions to Lx so that, say, PD pulses in high humidity are given greater significance (recognizing that humidity might suppress PD, so any observed PD under such conditions is more alarming). This environmental weighting scheme minimizes nuisance alarms and maintains sensitivity across a wide range of real-world operating conditions.

[0014] Dual-Source Power Harvesting with Failover: In a further aspect, the invention includes a dual-source power supply for autonomous operation on live power lines. The device is equipped with both an inductive power harvester (or similar coupling) that draws energy from the electromagnetic field of the line and a small photovoltaic solar panel. Under normal conditions, the line harvester provides continuous power to the system's electronics and charges a backup battery. In daylight or when line current is low, the solar panel supplements charging. A rechargeable lithium iron phosphate ($LiFePO_4$) battery is integrated to serve as a fail-safe uninterruptible power source (UPS). This battery automatically takes over when harvested power is insufficient – for example, during a line outage at night – ensuring that the sensor node remains powered to capture critical fault data and send alerts. $LiFePO_4$ chemistry is chosen for its long cycle life, thermal stability, and ability to operate across wide temperature ranges, making it ideal for field deployment. The power management module intelligently switches between power sources and prevents deep discharge of the battery, thereby enabling continuous 24/7 operation of the monitoring device with minimal maintenance.

[0015] In summary, the GridLeak system provides a comprehensive solution for monitoring leakage currents and partial discharges on power lines. By combining multi-channel sensing, self-calibration, advanced signal processing, environmental adaptability, and robust power harvesting, the invention substantially improves early fault detection and reliability in power distribution networks. These and other features and advantages of the invention will be apparent from the following detailed description of exemplary embodiments, taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

[0016] Fig. 7A is a schematic block diagram illustrating the fusion of multiple sensor channels in the GridLeak system. As shown in Fig. 7A, the device incorporates a residual current sensor, a partial discharge sensor, and a fluxgate magnetometer, all providing inputs to a central processing unit. These inputs are combined to produce a unified leakage index (Lx) indicative of a fault condition.

[0017] Fig. 7B is an exemplary graphical representation illustrating contributions of different sensor channels to the fused leakage index Lx. Fig. 7B shows, for example, how the residual current, partial discharge pulses, and slow magnetic drift signals each influence the overall Lx value over time or over an AC cycle. A threshold level for Lx is also depicted, above which the system would register an alarm for a probable leakage or discharge fault.

[0018] Fig. 8 is a block diagram showing the pilot tone injection and calibration feedback loop for the Rogowski coil current sensor. In Fig. 8, a calibration signal generator injects a known 1 kHz pilot signal into a test winding of the Rogowski coil (or into its sensing circuit), and the processing unit measures the coil's response. This figure illustrates how the system adjusts the sensor's calibration parameters in real time based on the feedback, thereby self-calibrating the residual current measurement channel.

[0019] Fig. 9 is a flow diagram illustrating the phase-resolved partial discharge (PRPD) data processing and compression pipeline implemented in the device. As shown in Fig. 9, the high-frequency PD sensor output is sampled and correlated with the power frequency phase to accumulate a PRPD map. An FPGA or processor then compresses this map (reducing resolution or encoding only significant discharge data) before forwarding the compressed data to a low-bandwidth wireless transmitter (e.g., a LoRaWAN module) for communication to a remote monitoring center.

[0020] Fig. 10 is a schematic diagram illustrating the environmental weighting of the leak index threshold. Fig. 10 depicts environmental sensors (such as a humidity sensor and a temperature sensor) providing inputs to the processor, which in turn adjusts the Lx threshold or weighting algorithm. The figure exemplifies how under different environmental conditions (for instance, high humidity vs. low humidity) the threshold for triggering a leak alert is dynamically modified to maintain accurate fault detection.

Detailed Description of Preferred Embodiments

[0021] Overall System Architecture (Fig. 7A and 7B): Referring to Fig. 7A, the sensor and edge-processing node (hereafter also referred to simply as "the device") is designed to be installed on or near an electrical power line conductor to monitor its condition. The device comprises multiple sensing components: a residual current sensor (701) configured to detect any imbalance between line and return currents (or between phases in a multi-phase system), a partial discharge sensor (702) sensitive to high-frequency current spikes or electromagnetic transients associated with partial discharges, and a fluxgate magnetometer (703) positioned to measure low-frequency or static magnetic fields around the conductor. In one embodiment, the residual current sensor 701 is a Rogowski coil wound around the line and neutral (or around all phase conductors and neutral, in a three-phase system) so that it directly measures the net current (difference) flowing to ground. The partial discharge sensor 702 can be implemented as a high-frequency current transformer (HFCT) clamped on the line, or as a coupling capacitor or antenna near the high-voltage insulation – any means that can pick up the fast sub-microsecond pulses of partial discharge. The fluxgate sensor 703 is a magnetic field sensor capable of

detecting DC and very low-frequency magnetic flux; it may be integrated into the same core as the Rogowski coil or located adjacent to the conductors to specifically monitor any constant or slowly varying magnetic bias. Each of these sensors is connected to an analog front-end and analog-to-digital converter (not separately numbered) within the device, which conditions and digitizes their signals for processing.

[0022] All sensor outputs are fed into a central processing unit (720) as shown in Fig. 7A. The processing unit 720 typically comprises a microcontroller or digital signal processor working in concert with an FPGA or other logic circuitry to handle both low-speed and high-speed data streams. The firmware or logic in the processing unit executes algorithms to combine the sensor data and calculate the fused leakage index Lx in real time. In one embodiment, the leakage index Lx is computed by aggregating normalized contributions from each sensor channel. For example, the processor may continuously integrate or RMS-measure the 50/60 Hz residual current magnitude from sensor 701, count or quantify the magnitude of PD pulses from sensor 702, and estimate any steady offset from sensor 703. These values can be weighted and summed (or processed through a more complex fusion algorithm) to yield Lx. Mathematically, the leak index could be expressed as:

$$Lx = w_1 \cdot f(\text{leakage current}) + w_2 \cdot g(\text{PD activity}) + w_3 \cdot h(\text{magnetic drift}) ,$$

where w_1, w_2, w_3 are weighting coefficients and f, g, h are functions that scale each sensor's raw measurement into a dimensionless score. For instance, $f(\text{leakage current})$ might be a ratio of the measured ground current to a nominal safe limit, $g(\text{PD activity})$ could be related to the pulse count or amplitude within a time window, and $h(\text{magnetic drift})$ might represent the magnitude of any DC bias detected. The result Lx is a unitless index that increases with greater fault severity.

[0023] As illustrated conceptually in Fig. 7B, each sensor channel's contribution to Lx can vary over time or over each AC cycle. Partial discharge events (shown as sharp spikes in Fig. 7B) occur at specific phase angles and cause momentary jumps in the leak index. The residual 50 Hz leakage current (illustrated as a smoother periodic waveform in Fig. 7B) raises the baseline level of Lx whenever a non-zero ground current flows. The fluxgate drift contribution is depicted as a slow trend (a gently rising line in Fig. 7B) that gradually elevates the index if, for example, a long-term increase in leakage is present. The processor (720) continuously monitors Lx against a preset or adaptive threshold level (shown as a horizontal dashed line in Fig. 7B). If the Lx value exceeds the threshold, the system interprets this as an indication of a likely fault (significant insulation leakage or discharge activity) and can trigger an alert or trip signal. In practice, the device may communicate an alarm to a central system or locally activate an indicator when Lx is above threshold for a sustained duration. The threshold itself may be dynamic as discussed later (see environmental compensation, Fig. 10). By way of example, the device might detect that Lx remains low (below threshold) under normal conditions (only negligible leakage and no PD), but as soon as a combination of a moderate ground current and repeated PD pulses pushes Lx over the threshold, an alarm flag is raised for maintenance crews to investigate that segment of the line.

[0024] Fluxgate Sensor and Sub-mHz Drift Detection: A unique feature of this invention is its ability to detect extremely low-frequency changes in current that conventional AC sensors cannot reliably capture. The fluxgate magnetometer 703 continuously senses the net magnetic field around the conductors. In a perfectly balanced system with no leakage, the magnetic fields from the outgoing and return currents cancel out (for example, equal current in line and neutral yields near zero net field within the sensor's core). Any small net field indicates an imbalance – this could be due to a DC component or asymmetry in current, or a very slow-varying leakage current. The output of fluxgate 703 is provided to a specialized algorithm in the processing unit 720, preferably implemented as a Kalman filter or an equivalent low-bandwidth tracking filter. The Kalman filter is configured to estimate the true underlying DC or low-frequency current offset while filtering out higher-frequency noise and short-term fluctuations. Over time, the filter accumulates evidence of any drift. For instance, if a porcelain insulator on a distribution line becomes wet or contaminated, a tiny DC leakage or half-wave rectified current may start flowing to ground. Such a current could be on the order of milliamps or less and change over tens of minutes – effectively below 0.001 Hz (1 millihertz) in terms of frequency content. The fluxgate sensor 703 will pick up this small net magnetic bias; the Kalman filter distinguishes it from measurement noise and slowly varying external influences (like geomagnetic variations or nearby current-carrying lines) by virtue of its statistical filtering. Eventually, the filter converges on a measured drift value that represents the leakage build-up. This information is incorporated into the Lx index (via function h() as noted above) or can separately trigger an alert if a significant trend is observed. By detecting such sub-mHz current drift, the system can forewarn of conditions like insulation aging, moisture ingress, or other gradual fault mechanisms well before they escalate into high-magnitude faults detectable by ordinary means.

[0025] Pilot Tone Injection and Self-Calibration (Fig. 8): With reference to Fig. 8, the device employs an active calibration scheme to maintain sensor accuracy over time. The residual current sensor 701 in this embodiment is realized as a Rogowski coil encircling the conductor set. The Rogowski coil outputs a voltage proportional to the rate of change of the net current (dI/dt). An integrator circuit in the analog front-end converts this to a signal proportional to the actual current. Variations in temperature or component aging can alter the coil's sensitivity or the integrator's gain, leading to errors. To counteract this, a calibration signal generator (810) is included in the device. The generator 810 produces a stable reference signal, for example a 1 kHz sinusoidal or square-wave voltage. Through a switch or coupling network (812), this reference is periodically injected into a test winding (811) that is magnetically linked with the Rogowski coil 701. The test winding 811 effectively feeds a known small "pseudo-leakage" current through the Rogowski coil's magnetic circuit. Because the amplitude and frequency of the pilot tone are known, the processor 720 can measure the coil's output in response to this injected signal and compare it against the expected response. Any discrepancy (in amplitude or phase) reveals calibration drift.

[0026] The calibration routine operates continuously in the background or at regular intervals. For instance, the processor might inject the 1 kHz pilot tone for a few milliseconds each second (or a few cycles every minute) in a way that does not interfere with critical measurements. The pilot frequency of 1 kHz is chosen because it lies outside the spectrum of interest for power frequency (50/60 Hz) and typical PD pulses (which are very fast transients, >1 MHz, or

broad-band impulses). The processing unit 720 can easily filter out or distinguish the calibration tone from genuine PD events or 50 Hz leakage signals. Using a synchronous detection technique, the processor isolates the component of the sensor output at 1 kHz during the injection period. By analyzing the magnitude of this component, the system computes a calibration correction factor. If the measured 1 kHz response is weaker than expected, the processor knows the sensor's sensitivity has dropped (perhaps due to temperature) and it can digitally compensate by amplifying the sensor signal slightly more. Conversely, if the response is too strong, the sensitivity might have increased or the integrator gain drifted high, and the processor will adjust accordingly. Additionally, by monitoring the phase of the returned pilot signal, the system can correct any integrator timing errors or coil frequency response issues. This closed-loop calibration ensures that the effective transfer function of the Rogowski coil system is kept constant over time. As a result, both the 50/60 Hz residual current measurement and the high-frequency PD pulse measurements (if the same coil or front-end is used for those) remain accurate. The calibration sequence can also serve a diagnostic purpose: if the coil or analog front-end were to fail or fall far out of spec, the lack of a proper response to the pilot tone can be used to flag a sensor fault, prompting maintenance.

[0027] Partial Discharge Detection and PRPD Mapping: The partial discharge sensor 702 collects fast transient signals that correspond to PD events on the line. Each PD event typically lasts only nanoseconds to microseconds but can produce a measurable high-frequency pulse. The processing unit 720, potentially using an FPGA, monitors the output of sensor 702 for these pulses. To construct a phase-resolved partial discharge (PRPD) pattern, the system also needs a reference for the phase of the AC mains cycle. This can be obtained either from the line voltage (if the device includes a voltage sensor or coupling to the line) or from the 50/60 Hz residual current waveform itself as a phase reference. Using a phase-locked loop or zero-cross detection on the fundamental frequency, the processor synchronizes a phase counter to the AC cycle.

When a PD pulse is detected by sensor 702, the precise timing of that pulse within the AC cycle is recorded. Over many cycles, a distribution of PD occurrences versus phase angle can be built. For example, PDs might predominantly occur near the peak of the voltage waveform (a common pattern for void discharges in insulation) or near the zero-crossing (perhaps for surface discharges). The device accumulates this information into a PRPD map, which can be visualized as a two-dimensional histogram: one axis is the phase of the AC (0–360°) and the other is either the magnitude of the PD or simply a count of occurrences, sometimes with a third dimension or color indicating magnitude. Fig. 9 schematically illustrates this process, where raw PD pulses (921) are detected and binned by phase by a mapping module (922). The result is a data structure containing the distribution of PD events over the AC cycle. This PRPD data is invaluable for experts to diagnose the type and location of insulation defects. However, the raw PRPD map can contain hundreds or thousands of data points (depending on resolution, e.g., 360 phase bins × several magnitude levels). Transmitting this in full fidelity is impractical over a network like LoRaWAN, which might allow, for instance, only ~50 bytes of payload per message.

[0028] FPGA-Based Data Compression (Fig. 9): To solve the bandwidth challenge, the present invention compresses the PRPD data on the fly. In one embodiment depicted in Fig. 9, an FPGA

(930) is dedicated to performing the compression algorithm in real time as new PD events stream in. The compression strategy may be as follows: First, the PRPD map is distilled to essential features. If many phase bins have zero counts (no discharges in those bins), those can be efficiently encoded (e.g., by run-length encoding the zeros). If certain ranges of phase have similar discharge patterns, they can be grouped or described with parameters (for example, “10 discharges of roughly X magnitude occurred in the 90°–110° phase range”). The FPGA can also apply thresholding – e.g., ignoring very small pulses below a certain magnitude to reduce noise in the data. Another approach is converting the distribution into a parametric form: computing statistical moments or identifying peaks in the phase distribution and only sending those. In any case, the FPGA 930 reduces the data volume significantly, perhaps compressing a full PRPD pattern into a few tens of bytes. This compressed representation (933) is then passed to the device’s communication module (940). In a preferred embodiment, module 940 is a LoRaWAN radio transceiver that sends the data packets at periodic intervals or upon detecting an alarm. The compression algorithm ensures that even with the limited data rate of LoRaWAN (typically a few kilobits per second at most, with duty cycle limits), the key information about PD activity is conveyed. For example, the device could transmit once a day a summary of PRPD activity, or immediately send an alert packet if a sudden surge in PD is detected. Because the compression occurs locally on the edge device, there is no need for continuous high-speed streaming; this greatly conserves bandwidth and power. The phase-resolved nature of the data is preserved in the compressed output, enabling remote experts or automated analytics to reconstruct an approximate PD pattern and assess the severity and nature of the insulation defect.

[0029] Environmental Sensing and Adaptive Threshold (Fig. 10): In order to adapt to environmental conditions, the device integrates at least one environmental sensor (704 in Fig. 10), such as a relative humidity sensor and a temperature sensor, mounted either on the device enclosure or in a location where they can measure ambient conditions near the line. The outputs of these sensors are continually read by the processing unit 720. The device’s software maintains a dynamic adjustment factor for the leakage index threshold or for Lx computation itself, based on these readings. Fig. 10 illustrates an example logic: an environmental compensation module (1001) receives the measured humidity and temperature and outputs a threshold bias or adjustment. This can be implemented through a lookup table or empirical model stored in the device’s memory. For instance, a calibration table might indicate that at 90% relative humidity, the baseline leakage current could naturally be, say, 5 mA higher due to moisture, so the Lx threshold should be raised accordingly to avoid false alarms. Conversely, at 10% humidity (very dry air), even a small partial discharge might be significant, so the threshold for PD-related contributions could be lowered or the weighting of PD pulses in Lx increased. Similarly, temperature influences might be accounted for: high temperatures could increase leakage currents (by lowering insulation resistance), so thresholds adapt to that context. The environmental compensation (1001) modifies the effective threshold (1002) fed to the alarm decision block. In practice, this means the device might not trigger an alarm for a moderate Lx value if the humidity is extremely high and most of that Lx is coming from steady leakage current; whereas the same Lx value in dry conditions would trigger an alarm. This adaptive behavior dramatically improves the positive predictive value of alarms, meaning when the

system does issue a warning, it is more likely to be a true fault rather than a weather-induced transient. In one embodiment, the device can also log environmental data alongside electrical data, providing context to the utility's engineers when analyzing events (e.g., noting that a cluster of PD events occurred during an exceptionally cold night). The overall result is a smarter thresholding mechanism that tailors itself to the environment, ensuring sensitivity and specificity of fault detection are maintained.

[0030] Dual Power Harvesting and Power Management: The GridLeak device is designed for long-term field deployment without the need for external power or frequent battery replacements. An important embodiment of the invention is the dual-source power harvesting system, now described in detail (refer also to the system diagram of Fig. 7A where the power block is implicit). The device includes a line power harvester (not separately numbered) which may be an inductive coil or current transformer wrapped around the live conductor. This harvester converts a small fraction of the line's electromagnetic energy into usable electric power by induction. For example, a toroidal core with a secondary winding can be clipped around the line conductor; as load current flows through the line, the alternating magnetic field induces a voltage in the secondary, which is then rectified and regulated by the device's power electronics. This provides a primary power source whenever current is flowing (even a few amperes of line current can be sufficient to generate a few watts). In addition, the device features a solar panel (mounted on the device's exterior) that generates power from sunlight. The solar panel is connected through a charge controller to supplement the power system, especially during daytime or when line current is low. Both power sources charge a rechargeable $LiFePO_4$ battery (705) housed in the device. $LiFePO_4$ (lithium iron phosphate) cells are chosen for their excellent longevity and safety in outdoor conditions. The battery acts as a buffer and backup: a power management circuit (not shown) ensures that when harvested power (line + solar) exceeds the device's immediate needs, the excess charges the battery, and when the harvest is insufficient, the battery supplies the difference.

[0031] A key aspect of this design is that it forms a failover uninterruptible power supply (UPS) for the sensor node. If the power line goes down (due to a fault that the device might be in the process of detecting, or a scheduled outage), the inductive harvester no longer provides energy. In such cases, the system seamlessly switches to battery power. The battery, likely kept well-charged by the dual charging sources, has enough capacity to keep the device running through the outage – for example, it might sustain operation for several hours or days, depending on system power consumption and battery size. This ensures that the device can still record the event of the line de-energization, possibly capture any transient data at the moment of the outage, and continue to communicate an alarm through its wireless module. Similarly, at night, if line current is very low (e.g., a lightly loaded rural line with minimal current flow, not enough to harvest) and solar is obviously unavailable, the device will rely on battery. The next morning, solar charging resumes and replenishes the battery. The power management system includes protective features: it avoids overcharging the $LiFePO_4$ battery (using appropriate charge termination) and prevents deep discharge (by shedding non-critical loads or shutting down the radio temporarily if battery falls below a threshold). In effect, this dual-source harvesting with battery backup provides self-sustaining, maintenance-free power for the device over its operational life, which may span many years. This is crucial for practical deployment of

a large number of sensors across distribution networks, as it eliminates the need for frequent site visits for battery changes and guarantees that the monitoring function is not interrupted by external power variations.

[0032] Communication and Alarm Reporting: In preferred embodiments, the device incorporates a low-power wireless communication module (such as a LoRaWAN radio 940 as mentioned earlier) to report data and alarms to utility back-end systems. Whenever the computed leakage index Lx exceeds the adaptive threshold or a significant PD event is detected, the processor can immediately format an alert message containing relevant information (e.g., the current Lx value, which component of it is dominant, recent PD counts, etc., as well as possibly the environmental readings) and transmit this message. Periodic status reports can also be sent, containing compressed PRPD data, current sensor readings, battery status, and the like. The use of LoRaWAN allows the device to communicate over several kilometers to a gateway, ensuring coverage even in remote line locations. Alternative communication means could include other LPWAN technologies or cellular IoT modems if bandwidth requirements dictate. The invention is not limited to a particular protocol, though the design of the data compression was explicitly to accommodate very constrained links. The combination of intelligent local processing and targeted communication means the system only uses the wireless channel when necessary, conserving energy and network capacity, yet never leaving the utility blind to critical developing faults.

[0033] It will be appreciated that the foregoing detailed description of embodiments is provided to enable a person skilled in the art to make and use the invention and is not intended to limit the scope of the invention. Various modifications and substitutions can be made without departing from the spirit of the invention. For example, different types of current sensors (e.g., a Hall effect sensor for DC coupled with a CT for AC) could be used instead of a Rogowski coil, and different pilot-tone frequencies or waveforms could be employed for calibration. The particular frequencies, threshold values, and algorithmic methods described may be adjusted to suit specific application requirements (such as monitoring underground cables versus overhead lines). The scope of the invention is defined by the claims that follow, and encompasses all equivalents of the features recited therein.

[002X] Alternate Retrofit Embodiment In yet another embodiment, the sensing and calibration circuitry (elements 110–150) is provided on a field-installable daughter board configured to mate with pre-existing residual-current IoT nodes. The daughter board receives power and data via the donor node's auxiliary header, while replacing only the donor's original current transformer module.

Industrial Applicability

[0034] The GridLeak system according to the present invention is industrially applicable in the monitoring and maintenance of electric power infrastructure. Electric utility companies can deploy the described sensor nodes on distribution lines, transmission lines, and substation equipment to continuously surveil the health of insulation and detect hazardous leakage currents. By providing early warning of partial discharges and slowly increasing ground currents, the invention enables condition-based maintenance – crews can be dispatched to repair or replace an insulator before it fails catastrophically, thus preventing unplanned outages. This improves the reliability of power delivery and reduces downtime and maintenance costs. The ability to detect minute leakage trends and PD activity also has safety implications, as it can prevent potential electric shock hazards or fire incidents (for example, detecting a deteriorating insulator on a high-voltage line in a wildfire-prone area before it arcs and ignites surrounding vegetation).

[0035] The invention's adaptive environmental compensation makes it suitable for real-world outdoor deployment across various climates. Whether in humid tropical regions, dry deserts, or cold alpine environments, the device adjusts its detection criteria, thereby maintaining accuracy and reducing false alarms that might otherwise desensitize operators. Its dual power harvesting capability allows installation in remote locations on the grid without any external power source or frequent battery changes. This self-powered feature is crucial for wide-area sensor networks covering thousands of kilometers of lines – the sensors can operate autonomously for years, leveraging the very infrastructure they monitor for energy. The lightweight, clamp-on design (in embodiments using Rogowski coils or clip-around CTs) means the device can be installed on live lines with minimal service interruption.

[0036] In industrial settings beyond utility power lines, the invention can be applied wherever electrical leakage and partial discharges are of concern. This includes large industrial plants, mines, or marine vessels where onboard power systems need monitoring for insulation faults. The system's ability to compress and communicate data through IoT networks means it integrates well with modern asset management platforms and cloud-based analytics. Utilities can aggregate data from many such nodes to perform fleet-wide analysis, identifying systemic issues (like a batch of insulators of the same age showing increasing leakage index) or pinpointing specific trouble spots on the grid. Thus, the invention provides a scalable solution for enhancing electrical grid resilience and safety, illustrating a clear industrial applicability in the energy sector and beyond.

[002X] Alternate Retrofit Embodiment

In yet another embodiment, the sensing and calibration circuitry (elements 110–150) are assembled on a compact daughter-board that is mechanically and electrically configured to mate with a pre-existing residual-current IoT transmitter. The daughter-board carries the Rogowski–IDE hybrid pickup, the pilot-tone generator, the integrator/PGA stage, the ADC, and the DSP/FPGA logic described above. A multi-pin board-edge connector plugs into an auxiliary header of the donor transmitter, receiving power and bidirectional data while replacing only the

donor's original current-transformer module. All other subsystems of the donor unit—enclosure, LPWAN radio, energy-harvesting supply, and environmental sensors—are thereby re-used without modification. Upon installation, the donor firmware is upgraded (over-the-air or via service port) to enable the fused-leakage algorithm of the present invention, after which the combined assembly operates as fully described for the self-contained GridLeak node.

Supplementary Specification – Power Architecture Options

Title

Alternative Induction Energizer vs. Solar-Battery Module for GridLeak Sensor Nodes

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1 · Purpose

This supplement expands the baseline GridLeak node specification to cover two interchangeable power subsystems:

1. **Induction Energizer (IE)** – contact-free, conductor-clamped AC harvester.
2. **Solar-Battery Module (SBM)** – photovoltaic harvester with fail-safe Li-titanate coin-cell buffer (0.5 Wh).

It documents architecture, component selections, safety rationale, blackout-coverage strategy, and a decision matrix for deployment teams.

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2 · Reference Design Constraints

Parameter	Target	Rationale

Continuous sensor runtime	15 yrs MTBF	Utility pole-top install; no scheduled service
Normal load draw	≤ 9 mW avg (27 mW peak)	IDE readout + BLE burst every 5 min
Ambient temp	–40 °C → +85 °C	IEEE Std C37.100-2019 compliance
Transient fault withstand	25 kA @ 2 ms	GridLeak housing already rated; power module must not add failure paths

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3 · Induction Energizer (IE) Architecture

3.1 Operating Principle

- Planar ferrite-backed Rogowski-like pickup wraps 120° around phase conductor.
- Harvests ~4–10 Vrms proportional to line current (≥ 50 A).
- Full-bridge AC/DC, supercap reservoir (5 F, 5.5 V), µPMIC with nano-power cold-start (e.g., LTC3588-1).
- **No battery by default**; supercap covers >3 h zero-current gap.

3.2 Optional Black-Out Buffer

Option	Component	Hold-up @ 9 mW	Safety Notes

Coin-cell Li-titanate	TLH-2450 (0.5 Wh)	24 h	Ti-doped anode → non-thermal runaway; UL 1642 pass >150 °C

3.3 EMC & Surge Path

- 600 V TVS (SM8S series) across harvester coil.
- IEC 61000-4-5 class 4 surge verified (±2 kV diff / ±4 kV common).

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4 · Solar-Battery Module (SBM) Architecture

4.1 Operating Principle

- 2-W mono-crystalline PV (40 mm × 80 mm, ETFE coated).
- Boost MPPT (BQ25570) charges 0.5 Wh Li-titanate.
- Deep-sleep MCU draws 2 µA; worst-case nighttime budget 0.17 Wh → 3× margin.

4.2 Fire-Risk Mitigation

- Li-titanate chemistry chosen to remain below 80 °C core even at full-sun 125 °C enclosure.
- Flame-retardant potting (UL 94 V-0) around cell.

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5 · Comparative Performance Metrics

Attribute	Induction Energizer	Solar-Battery Module

Installs with no live-line cut?	Yes – external clamp	Yes – external bracket
Nighttime autonomy	3 h (supercap) → 24 h (with coin cell)	60 h (2.2 Wh gross)
Line-current dependency	Needs ≥ 10 A avg	None
Wildfire ignition risk	Negligible (no Li)	Low (Li-titanate + potting)
Maintenance interval	15 yr	10 yr PV degradation

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6 · Integration Checklist

1. **PCB jumper JP1** selects IE or SBM voltage sense (4.8 V vs 4.2 V max).
2. **Firmware flag** `PWR_MODE` auto-detects start-up source; alters sleep duty.
3. Surge arrestor MOV differs (IE: >600 V) vs. (SBM: >60 V).

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7 · Qualification & Testing

Test	Standard	Pass / Fail Criteria

Induced-fault energy dump	ANSI C62.11, 10 kA 8/20 µs	Module <10 °C rise, functional
5-day thermal cycling –45 ↔ +90 °C	IEC 60068-2-14	ΔC<1 % (supercap) / ΔV<50 mV (cell)
Impedance drift snapshot	Internal EIS, 1 Hz–1 kHz	Δ

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8 · Decision Matrix (Field Deployment)

Site Type	Typical Load	Arbor Cover	Recommended Module
Urban feeder	180 A	Partial shade	**IE + coin cell**
Rural spur / solar farm	<15 A	Full sun	**SBM**
Wildfire corridor	120 A	Mixed	**IE (no Li)**

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9 · Bill-of-Materials Delta (per node)

Line Item	IE Cost (1k qty)	SBM Cost (1k qty)

Harvester coil + ferrite	$4.60	—
Supercap 5 F 5.5 V	$2.10	$2.10
PV panel 2 W	—	$5.80
Li-titanate cell 0.5 Wh	*opt* $3.40	$3.40
MPPT IC / PMIC	$4.90	$5.10
Total	**$11.60** (14.90 w/ coin)	**$16.40**