GridLeak IDE: Multi-Sensor Monitoring System Using Interdigitated Electrode Sensors for Partial Discharge, Impedance, and Coolant Purity

Description

Technical Field

This invention relates to sensor systems for electrical power and thermal management infrastructure. Specifically, it concerns a multi-sensor monitoring system employing interdigitated electrode (IDE) sensors to detect partial discharge events on high-voltage conductors, to monitor impedance characteristics of electrochemical energy storage devices, and to assess the dielectric quality of cooling fluids. The system is applicable to data centers, power distribution units, uninterruptible power supplies (UPS), and to utility transmission- and distribution-network assets where early detection of leakage currents, ground faults, or corona discharge is essential for public-safety compliance and outage prevention, and other installations where early detection of electrical insulation failures, capacitor aging, or coolant contamination is critical for safe and efficient operation.

Background

High-reliability electrical systems (such as those in data centers or industrial power distribution) demand continuous monitoring to preempt failures. Partial discharge (PD) is a phenomenon where localized dielectric breakdown occurs in high-voltage insulation, often due to defects or stress, without immediately bridging the electrodes. PD activity degrades insulation over time and can lead to catastrophic failures if undetected . PD magnitude is typically quantified in pico-coulombs (pC) of apparent charge . In practice, partial discharge events can range roughly from 1 pC up to several thousand pC , indicating extremely small discharges. These events manifest as fast, high-frequency current pulses (on the order of only a few nanoseconds in duration) superimposed on the conductor's signal . Traditional PD detection techniques use specialized couplers or antennas to capture these rapid transients, often requiring sensitive equipment and careful noise filtering . Permanent PD monitoring systems exist for large assets (e.g. transformers, switchgear), but they can be expensive and are not commonly applied to busbar-style DC power distribution within data centers. Moreover, conventional sensors may not be physically adaptable to the geometric constraints of busbars or may require complex installation. There is a need for a compact, flexible sensor that can be attached directly to busbars to continuously monitor partial discharge activity at the point of origin, with minimal installation downtime.

In parallel, operators of UPS systems and battery banks face challenges in monitoring the health of electrochemical energy storage modules. Over time, capacitors (whether supercapacitors or electrolytic capacitors) and lithium-ion cells exhibit drift in key parameters – notably a decrease in capacitance and an increase in ESR as they age . For example, electrolyte evaporation or electrode degradation in capacitors leads to higher internal resistance (ESR) and lower charge storage capacity . Industry end-of-life guidelines often specify that a capacitor should be considered failed when its capacitance has fallen by more than ~20% of its initial value or when its ESR has doubled (100% increase) from the original spec . Such changes can result in excessive heating, reduced power delivery, and ultimately device failure. However, continuous online measurement of ESR and capacitance in the field is not commonly available – maintenance crews typically rely on periodic manual tests or simply on runtime indicators and failure events. Existing monitoring solutions (e.g. simple voltage or temperature sensing in battery management systems) may not directly measure impedance changes at multiple frequencies, which provide richer diagnostic information about the state-of-health of the capacitive or battery elements. A dedicated impedance sensor module that can be integrated into each energy storage string or module, performing automatic frequency-sweep tests (from low Hz to kHz) to track ESR growth and capacitance loss, would enable predictive maintenance by identifying degrading units before they fail.

Another area of concern is the quality of dielectric coolant in immersion-cooled systems. Modern high-density data centers increasingly use immersion cooling, where servers and power electronics are submerged in electrically insulating fluids. The coolant must remain electrically non-conductive; any ingress of water or accumulation of ionic contaminants can drastically raise the fluid’s conductivity, defeating its dielectric properties and potentially causing corrosion or short-circuits . For instance, dissolved metals leached from components or moisture intrusion can introduce ions that increase fluid conductivity to harmful levels . Monitoring coolant health typically involves periodic sampling and laboratory analysis of fluid, or at best, bulk property sensors (like conductivity probes) in the reservoir. Such approaches may not detect early contamination or localized changes. An in-situ dielectric purity sensor that continuously measures the coolant’s dielectric constant and conductivity would provide immediate warning of coolant degradation. Interdigitated electrodes are well-suited for this task: when immersed, the capacitance between the electrodes depends on the fluid’s dielectric permittivity, and any ionic content causes a measurable increase in conductance between the electrodes. Prior research has shown that carefully designed IDE sensors can be extremely sensitive to changes in fluid properties – for example, detecting conductivity changes on the order of 10^–11 S/m (picoSiemens per meter) in insulating oils . This level of sensitivity enables detection of minute contamination levels (far below the threshold of causing a cooling failure), allowing operators to take corrective action (like filtering or replacing coolant) well before damage occurs.

In summary, there is a convergence of needs across power distribution, energy storage, and cooling domains for integrated, real-time monitoring. Existing solutions tend to be fragmented – one might deploy separate PD monitors, battery management systems, and coolant sensors, each working in isolation. The background art lacks a unified system that combines these sensing capabilities into a single platform with a common data hub. Such integration can reduce complexity and provide a more holistic view of infrastructure health, correlating events (e.g. a power surge causing both a partial discharge and a momentary stress on capacitors, or a cooling issue coinciding with increased electrical stress). The present invention addresses these needs by providing a multi-sensor system with novel IDE-based sensors for each parameter and a central node to intelligently process and report the aggregated data.

Summary of the Invention

The invention provides a multi-sensor monitoring system that unifies three distinct sensing functions — partial discharge detection, impedance spectroscopy of energy storage devices, and dielectric fluid purity monitoring — within a single integrated platform. Each sensor module leverages interdigitated electrode (IDE) structures for sensitivity and compact form factor, and each is designed to tackle a specific maintenance challenge:

- Partial Discharge Sensor Module: A flexible IDE strip sensor (e.g. a thin polyimide film with conductive interdigitated traces) that can be bonded or wrapped directly onto a high-voltage DC busbar or conductor. This sensor acts as a high-frequency capacitive coupler to capture transient pulses caused by partial discharge events. The module includes on-board electronics for signal conditioning, such as a high-bandwidth amplifier and a band-pass filter tuned to the characteristic frequency range of PD pulses (which are typically fast-rise transients with frequency content in the MHz range). A microcontroller or signal processor analyzes the pulses, rejecting noise and computing an anomaly score or PD magnitude for each event. By setting thresholds on discharge activity (e.g. number of pulses or apparent charge in pC over time), the module can flag insulation deterioration before catastrophic failure. The use of a flexible, adhesive-backed IDE sensor allows for non-invasive retrofitting onto existing busbars and provides intimate coupling to the electric field of the conductor.

- Impedance Sensing Module: A printed circuit board (PCB) based sensor with multiple interdigitated electrode pairs or dedicated connector interfaces that attach across individual cells or modules in a battery/supercapacitor string. The module incorporates a programmable AC signal generator capable of sweeping frequencies from about 10 Hz up to 10 kHz, and a measurement subsystem to record the voltage/current response. Through this multi-frequency impedance spectroscopy, the module can compute each unit's effective capacitance and ESR at different frequencies. A microcontroller on the module (or in the central node) uses the sweep data to derive health indicators — for example, a rising ESR at 1 kHz and a dropping capacitance at 10 Hz may indicate drying electrolyte or electrode degradation. The module can run periodic tests (e.g. on a schedule or triggered by the central node) and compare results to baseline values (stored from commissioning or last maintenance) to detect trends. It can monitor multiple energy storage components by either time-multiplexing the measurements through analog switches to different cells or by having multiple IDE sensing sub-elements, each tuned or connected to a particular cell. The design emphasizes isolation and safety, given the direct connection to potentially high DC voltages (e.g. a string of supercapacitors in series). By integrating this onto or near the battery/supercapacitor pack, continuous state-of-health assessment is achieved without removing the devices from service.

- Dielectric Coolant Purity Sensor: A “bookmark”-shaped probe with interdigitated sensor traces on an insulating substrate, designed to be inserted into the coolant bath or coolant circulation loop of an immersion-cooled system. The IDE pattern forms a fringing field capacitor whose capacitance is a function of the coolant’s dielectric constant. Simultaneously, any conductive contaminants in the fluid create a resistive leakage path between the traces, which can be measured as increased conductance (or decreased resistance). The sensor module includes an excitation source (which may be a low-frequency AC or a DC bias with AC perturbation) and measurement circuitry to derive the fluid’s permittivity and conductivity. For example, a small AC excitation at a fixed frequency can be used to measure the fluid’s impedance; from the real and imaginary parts, the module calculates the dielectric constant (related to the capacitance) and loss factor or conductivity (related to resistive current through the fluid). Sudden changes in these parameters indicate contamination: water ingress would significantly raise the dielectric constant and conductivity, while ionic contamination (from metal leaching or decomposition of fluid) would primarily raise conductivity. The probe is designed to tolerate the fluid environment (e.g. using corrosion-resistant electrode coatings or an encapsulation that still permits capacitive sensing of the fluid). Its shape and size (akin to a slim card) allow it to be placed in tight spaces like between server boards or in the coolant reservoir. Optionally, multiple such probes can be placed at different locations in the system (for instance, at the inlet and outlet of a coolant path) for spatial monitoring; they can all be networked into the same central node.

- Leakage-Current / Ground-Fault Sensor Module: A split-core clamp or flexible IDE wrap that encircles a live conductor, cable sheath, or grounded structure. – Operating principle. The IDE array forms a high-impedance capacitive shunt to sense displacement current between conductor and earth (50 Hz – 10 kHz), enabling detection down to ~50 µA.– Built-in injection check. Periodically sources a known test-pulse to verify gain and phase calibration.
- – Field use. Snap-fits around overhead-line phases, UG-cable terminations, or substation buswork to reveal insulation breakdown, animal-induced faults, or damaged arrestors long before protective relays operate.

- – Data fusion. When the leakage module reports rising ground current that temporally correlates with partial-discharge spikes, the central node escalates the event as an emergent insulation failure.

All three sensor modules are tied together by the central processing node. This central node provides power and data interfaces to the sensors (e.g. via wired connections or a wireless link, depending on the installation). It is responsible for aggregating sensor readings and applying higher-level analysis. Key functions of the central node include:

- Time-stamping and Synchronization: As data comes in from the partial discharge sensor, impedance module, and coolant sensor, the central node assigns accurate timestamps to each measurement. This allows correlation of events (for example, a spike in partial discharges coinciding with a dip in bus voltage and a momentary change in supercapacitor impedance could indicate a broader power disturbance). A real-time clock or network time protocol (NTP) source may be used for synchronization if multiple nodes are deployed.

- Calibration and Normalization: The central node stores calibration data for each sensor channel. For instance, the baseline capacitance of the coolant sensor in clean fluid, or the initial ESR of a brand-new capacitor module, or the noise floor of the PD sensor. Incoming data is adjusted using these calibration factors to correct for sensor tolerances and environmental factors (temperature, etc.). This ensures that alarms are triggered on true deviations rather than manufacturing variances or benign fluctuations. The node may periodically prompt the sensors to perform self-calibration sequences (such as open-circuit readings, short-circuit readings, or reference checks using internal standards).

- Data Fusion and Thresholding: The central node runs algorithms to interpret the data in context. It compares the processed readings against predetermined thresholds or dynamic models. For the PD sensor, it might accumulate an “insulation stress index” over time – e.g. count of discharges per day above a severity level – and trigger an alert if the trend is upward or exceeds a safe limit. For the impedance module, the node can compute state-of-health metrics for each energy storage unit (perhaps expressed as remaining lifetime percentage) and flag any unit that crosses a warning threshold (for example, ESR >2× its baseline or capacitance <80% of initial). For the coolant sensor, it can trip an alarm if fluid conductivity rises above a set limit (indicating contamination that requires service). The threshold logic can be adaptive: the node might adjust limits based on temperature (since, for example, capacitor ESR and fluid permittivity are temperature-dependent) to reduce false positives .

- Communication Interface: The central processing node communicates the sensor data and any alerts to external systems. This can be via standard protocols such as Ethernet (TCP/IP), industrial fieldbus (Modbus, CAN bus), or wireless (Wi-Fi, BLE) depending on the deployment. In a data center scenario, the node would connect to the Building Management System (BMS) or Data Center Infrastructure Management (DCIM) software. It may publish both real-time telemetry and alarm notifications. For example, it could issue an SNMP trap or REST API call when an anomaly is detected, or log time-stamped data to a database for trend analysis. The system can integrate with maintenance workflows – e.g., send email/SMS alerts to operators or create maintenance tickets when certain sensor readings go out of range.

In essence, the invention marries three monitoring functions that are conventionally separate, into one cohesive system. By using IDE-based sensors, the solution achieves high sensitivity and compact, embeddable form factors: the comb-like electrodes maximize surface area and capacitive interaction with the environment, enabling detection of subtle changes (such as pico-coulomb discharge pulses or minute conductivity in fluid) that would otherwise be missed . The detailed description and accompanying figure descriptions below illustrate example embodiments of each module and the overall system architecture.

Brief Description of the Drawings

- Fig. 1 is a block diagram of the integrated multi-sensor monitoring system (100) according to an embodiment of the invention, showing the partial discharge sensor (110) on a busbar, the impedance sensing module (120) connected to an energy storage unit, the coolant purity sensor probe (130) in an immersion cooling tank, and the central processing node (140) that aggregates data from the sensors and interfaces with external management systems.

- Fig. 2A shows a perspective view of the partial discharge strip sensor (200) attached to a high-voltage DC busbar (202) according to an embodiment. The sensor's flexible substrate (210) with interdigitated electrode pattern (212) is wrapped around or affixed to the flat surface of the busbar. Conductive traces lead to a supporting electronics module (220) mounted at one end of the strip.

- Fig. 2B is a schematic circuit diagram of the partial discharge sensor module (200) electronics, including the interdigitated sensor electrodes (212) capacitively coupled to the busbar, a high-frequency amplifier (222), a band-pass filter (224), an analog-to-digital converter (226), and a microcontroller (228) that processes discharge pulses and communicates results.

- Fig. 3 illustrates an example impedance sensing module (300) for a supercapacitor or battery string. The PCB (310) carries interdigitated electrode pairs (312a, 312b) forming test lead contacts to a capacitor (314). The module includes a frequency sweep generator (320), a measurement circuit (322) (for measuring impedance response), and a local microcontroller (330) that calculates ESR and capacitance from the measured data.

- Fig. 4 depicts a dielectric coolant purity probe (400) immersed in a coolant bath (430). The probe has a flat substrate (410) with interdigitated sensor traces (412) exposed to the fluid. A small on-board conditioning circuit (420) applies an AC excitation and measures the fluid's capacitive and conductive properties. The probe connects to the central node for power and data.

- Fig. 5A illustrates a split-core clamp (500) containing a semi-cylindrical IDE array (512) that surrounds a power conductor (502). The IDE traces couple to the axial electric field; a trans-impedance amplifier (522) converts the displacement current to voltage. A programmable notch filter (524) rejects harmonic noise and provides separate RMS leakage and high-frequency corona channels. In underground applications, a flexible IDE "bandage" (Fig. 5B) conforms to cable jackets or pot-heads; its guarded return electrode permits µA-resolution even with sheath-current imbalance. The microcontroller (528) computes true-RMS leakage, THD, and rate-of-change metrics, forwarding them to the central node for alarming or trend analysis.

(In the figures, like numerals refer to like elements. For instance, item 212 in Fig. 2A is the same interdigitated electrode structure 212 shown in the Fig. 2B circuit schematic. Subscript letters (e.g., 312a, 312b) denote multiple instances of similar components in a figure.)

Detailed Description of Embodiments

Overall System Architecture (Fig. 1): Referring to Fig. 1, the multi-sensor monitoring system (100) comprises a network of sensor modules communicating with a central processing node (140). In an example deployment for a data center power system, a partial discharge sensor 110 is installed on a high-voltage DC busbar 112, an impedance sensing module 120 is connected across a bank of supercapacitor energy storage units 122, and a dielectric fluid sensor probe 130 is submerged in the coolant within an immersion cooling tank 132. Each sensor module (110, 120, 130) is linked to the central processing node 140 via a suitable communication link 115 (which could be a wired bus or wireless connection). The central node 140 coordinates the sensors, providing excitation signals, timing, and power as needed, and it collects measurements for analysis. The central node 140 in this embodiment interfaces with the facility's management network 150 (e.g., an Ethernet LAN to a building management system or cloud platform), enabling remote monitoring and data analysis.

The central processing node (140) typically contains a processor or microcontroller, memory for data and calibration storage, and network interface hardware. It may also house analog front-end circuitry for any sensors that require centralized signal processing (alternatively, each sensor can preprocess data and send digital results). In some designs, the central node provides a unified power supply to all sensors, such as a low-voltage DC rail or Power over Ethernet (PoE) if networked, simplifying wiring. The central node (140) time-synchronizes data streams and can fuse information: for example, if partial discharge sensor 110 and impedance module 120 both detect anomalies at the same timestamp, the node can correlate these events as potentially related to a common cause (like a power transient). The network interface (150) of the node supports protocols to transmit sensor readings and alarms. For instance, it could support an SNMP agent sending traps on alarms, a REST API for the DCIM to poll data, or an MQTT client publishing to a monitoring dashboard. The system may further support local interfaces like a display or indicators on the node itself to show status (e.g., an LED for "PD alarm" or "capacitor fault").

Partial Discharge Sensor Construction (Fig. 2A & 2B): As shown in Fig. 2A, the partial discharge sensor module (200) consists of a flexible sensing strip that can conform to the shape of a busbar (202) or other conductor. In one embodiment, the strip has a polyimide film substrate (210) (for example, Kapton® or similar high-dielectric strength polymer) about 50–125 µm thick, which carries a pattern of interdigitated copper or gold electrodes (212) on one side. These interdigitated electrodes form a comb-like structure – multiple fingers from two opposing electrodes interlocking without touching, separated by a small gap (e.g. 0.5 mm gap, with finger lengths of a few cm). This structure creates a high capacitance coupling with the underlying busbar and a broad electrostatic pickup area. The sensor strip (210) can be attached to the busbar via a thin insulating adhesive layer (216) on its back side, or by mechanical means like tape or clamps, ensuring the IDE pattern faces the busbar to maximize coupling. Because the substrate is flexible, it can wrap around a flat or round busbar surface, or even around an insulation layer on the bus if direct attachment to a live conductor is not possible (the sensor can detect through insulation via capacitive coupling). The end of the strip terminates in a small printed circuit segment (which may be rigid or flex) that hosts the support electronics (220).

Fig. 2B schematically illustrates the electronics of the PD sensor module (200). The interdigitated electrodes (212) are connected as the input of a high-frequency amplifier (222). The design of the amplifier 222 prioritizes a wide bandwidth (e.g., 1 MHz to 100 MHz range) and low-noise performance, so that nanosecond PD pulses can be amplified without distortion . In one embodiment, a two-stage amplifier is used: a charge-sensitive preamplifier followed by a broadband gain stage. The output of the amplifier feeds a band-pass filter (224) – for example, a filter centered around a few MHz with a bandwidth of a few MHz, to reject frequencies outside the typical PD pulse spectrum and to attenuate mains frequency or other low-frequency interference. The filtered signal then goes to an analog-to-digital converter (ADC) (226) or a high-speed comparator, depending on the design. If using an ADC, the microcontroller (228) can digitize the waveform of each pulse for further analysis (such as extracting apparent charge via time integration, or identifying pulse shape patterns). If using a simpler threshold detector, the microcontroller 228 can count pulses that exceed a set threshold.

The microcontroller (228) (or an FPGA or DSP in higher-end variants) on the PD module processes the incoming transient data. It can implement algorithms to discriminate true partial discharge events from noise. For example, it might require the pulse to have a specific rise-time and decay signature or occur coincident on multiple sensors (if multiple strips are used) to count as PD. The firmware accumulates statistics such as PD pulse count rate, average magnitude, and max magnitude over a sliding window. From these, it computes an anomaly score or health index. One simple metric is the total apparent charge per minute; a more complex one could weight discharges by magnitude and persistence. When the PD activity exceeds predefined criteria (either set by standards or learned from baseline operation), the module or central node can generate an alert. The microcontroller 228 communicates these results (e.g., via a digital bus interface) back to the central node 140. In some embodiments, to reduce data load, the PD module might only send summary statistics or alarm flags, rather than streaming every pulse waveform.

Notably, the PD sensor is highly sensitive: thanks to the large surface area of interdigitated electrodes and the amplifier design, it can detect very small discharges. In practice, the system can register partial discharge pulses corresponding to only a few pico-coulombs of charge transfer . Such sensitivity is on par with laboratory-grade PD detectors, which can go below 1 pC in controlled setups . Achieving this in situ on a busbar is facilitated by placing the sensor close to the source of discharge (the busbar's insulation defects) and using a low-noise front-end. The flexible IDE sensor essentially acts as a localized capacitive antenna for the electromagnetic emission of the PD, capturing the fast transient before it dissipates along the power network. This is advantageous over remote ultrasonic or RF monitors which might miss small events or struggle in electrically noisy environments.

To further improve reliability, the PD sensor module (200) may incorporate calibration and self-test features. For example, the microcontroller 228 might include a calibration capacitor or pulse generator (not shown) that can inject a test pulse of known charge into the input to verify the chain's functionality and calibration. Periodic self-tests ensure that the sensor and amplifier are still working (important since these may be installed in high EMI environments for long durations). Environmental drift (temperature changes affecting the amplifier or permittivity of substrate) can be calibrated out by occasional baseline captures with no HV present, or by using a reference channel.

Impedance Sensing Module Design (Fig. 3): Turning to Fig. 3, the impedance monitoring module (300) is depicted. In this embodiment, the module is built on a PCB (310) that can either be integrated into a battery/capacitor management system or added onto existing modules. The PCB 310 has connectors or contact pads (312a, 312b) that attach across the terminals of the device under test, shown here as a supercapacitor (314) for illustration. In some designs, the contact pads are arranged as interdigitated fingers on the board that can be pressed against the terminals of a cell or bolted on, hence making a stable connection while also possibly measuring surface impedance. Alternatively, the board might connect via wires or a harness to multiple cells. Each pair of terminals 312a-b leads into the measurement circuit.

The module (300) includes a multi-frequency AC source (320). This can be a programmable signal generator chip or a microcontroller DAC that produces a low-amplitude sinusoidal voltage or current. The frequency is swept in the range of interest (approximately 10 Hz to 10 kHz in one embodiment, though other ranges can be used). The amplitude is chosen small enough not to disturb the normal operation of the device under test significantly (e.g., a 10 mA AC current injection or a 50 mV perturbation) yet large enough for a clear measurement. The AC excitation is applied through appropriate coupling networks to the test cell 314.

A measurement circuit (322) monitors the response. This often takes the form of sensing the voltage across and current through the device: for instance, using a small shunt resistor or a transimpedance amplifier for current, and a high impedance buffer for voltage. The gain/phase of the response at each frequency is recorded. This can be done sequentially (frequency sweep) or by a Fourier methods if multiple frequencies are injected at once. The local microcontroller (330) or an associated impedance analysis chip computes the complex impedance Z(f) for each frequency f. From these data points, the controller can extract parameters: the ESR is essentially the real part of impedance at a high frequency (where the capacitor's reactance is minimal), and the capacitance can be inferred from the imaginary part of impedance (for example, at 10 Hz or 120 Hz, the magnitude $|Z| \approx 1/(2\pi fC)$ for a large capacitor, so C can be derived). The sweep also allows detection of frequency-dependent behaviors (e.g., a gradual rise in ESR with frequency might indicate inductive effects or poor charge mobility in a supercapacitor).

In addition to measuring one capacitor or cell, the module (300) can be multiplexed. Suppose a UPS has a string of N supercapacitors; a single module 300 could cycle through each cell by connecting the source and measurement circuit sequentially (using analog multiplexers or relays) to each pair of terminals. In such cases, the board will have multiple contact pairs 312a/b and the microcontroller 330 will address them one by one. This reduces cost by using one set of electronics for many cells, at the expense of time (each sweep per cell takes a short duration). The microcontroller stores baseline impedance spectra for each cell (recorded when the cells were new or recently serviced). Over time, it compares new measurements to these baselines. A significant increase in ESR or drop in capacitance triggers an internal flag. For example, if ESR has increased by 50% and capacitance dropped by 10%, the controller might classify the cell's state-of-health as moderately degraded; beyond 100% ESR increase or 20% cap loss (the typical end-of-life criteria), it would flag the cell for replacement. The module can communicate such diagnostics to the central node 140 as periodic reports or immediately if an out-of-tolerance condition is found.

The impedance module's design emphasizes isolation and safety. Typically, the module 300 will include an isolation barrier (optocouplers, isolator ICs, or even an isolated power supply) because it connects to high DC potentials. The microcontroller 330 might be referenced to the same ground as the cell it measures; hence, isolation is needed to send data to the central node (unless the whole module is battery-powered and wireless). In one embodiment, the impedance module uses a small wireless microcontroller and battery, avoiding a direct wired connection to the central node, thereby floating at the cell potential and transmitting data via radio. However, a wired approach with proper isolation and transient protection is equally viable in industrial setups.

The accuracy of measuring small changes in ESR is enhanced by multi-point calibration. The module may include known reference components (like a precision resistor and capacitor) that it measures to self-calibrate the gain/phase accuracy of the sweep each time. It can also correct for temperature influences; since ESR can vary with temperature, the module could have a temperature sensor and adjust the thresholds dynamically, or report temperature along with measurements for the central node to interpret .

Dielectric Purity Probe (Fig. 4): With reference to Fig. 4, the coolant sensor probe (400) is shown deployed in a tank or pipeline of dielectric fluid (430). The probe has a flat, elongated substrate (410), for example a FR4 PCB or ceramic strip, which can be a few millimeters thick and perhaps 1–2 cm wide by 10–20 cm long (similar to a bookmark). Along its length (or at its tip) are printed interdigitated electrode traces (412), typically made of copper, nickel, gold, or other corrosion-resistant conductor. The traces are arrayed with a gap (e.g. 0.5 mm to 2 mm) between fingers, forming a capacitive sensor area. The design may use a pair of interdigitated combs where one comb is driven by an excitation signal and the other is connected to a sensing amplifier, or it might measure the impedance between all the interdigitated fingers as one sensor. The large fringe field that extends from these traces into the surrounding liquid effectively measures the liquid's permittivity and conductivity.

The probe 400 connects to a small electronics module (420), which might be mounted on the same substrate (if space and temperature allow) or wired to a nearby enclosure. The circuit 420 can be quite simple: in one embodiment, it forms an RC oscillator where the liquid between electrodes is part of the capacitor, thus changes in fluid properties alter the oscillation frequency, which the microcontroller measures. In a more controlled approach, the circuit 420 contains an AC excitation source (possibly a fixed frequency sine wave or an impulse generator) and a measurement channel similar to the impedance module described earlier. A common choice is a ~1 kHz AC small signal to simultaneously sense capacitive and conductive currents. The microcontroller (or the central node via the probe interface) can separate the in-phase (conductive) component of the current from the quadrature (capacitive) component, thus yielding conductance and capacitance values of the fluid between electrodes.

When the coolant is clean and dry, its relative permittivity ε_r might be around 2.0 (for mineral oil or engineered fluids) and its conductivity extremely low (often <1 nS/m). The probe is calibrated to this baseline (perhaps during installation, a reference reading in known good fluid is taken). If water ingress occurs, even a small amount of water (ppm levels) can significantly increase the dielectric constant of the fluid (since water's ε_r ~ 80). Thus, the probe's measured capacitance will increase from the baseline. At the same time, dissolved ionic impurities from water (or other contaminants) will raise the conductivity, which is seen as an increase in the resistive (in-phase) current. Because the IDE sensor is sensitive, it can detect very small changes – for example, a change of a few picofarads in capacitance or a shift in conductivity on the order of 10^–11 to 10^–9 S/m could be detected . This corresponds to early-stage contamination that would not yet cause system failure, allowing preemptive filtration. If contamination continues to worsen (e.g. a major water leak into the tank), the conductivity might rise by orders of magnitude, which the probe would immediately sense, triggering an urgent alarm.

The probe's microcontroller or interface circuit (420) typically outputs the readings digitally to the central node 140. It may also implement local threshold detection for safety – for instance, if it ever measures conductivity above a critical threshold (indicating the coolant has possibly lost its insulating property), it can send an immediate discrete alarm signal that could even shut down power equipment to prevent damage. To maintain accuracy, the probe can have a small heater or temperature sensor on board, since fluid permittivity can vary with temperature. The system can either temperature-compensate the readings or report the raw values along with temperature for the central node to interpret. Some embodiments may use multiple frequency measurements here too, to distinguish different types of contaminants (much like a low-frequency measurement might pick up ionic conduction, while a higher-frequency measurement might focus on dipole polarization effects).

Material selection for the probe is important: the substrate 410 should ideally have a high glass transition temperature and low water absorption (if polymer) to remain stable in hot oil. The electrodes 412 might be coated with a thin protective layer (like a conformal coating or Parylene) to avoid direct metal exposure that could corrode; such coatings are thin enough (microns) that they negligibly impact capacitive sensing but protect the metal. Alternatively, using a noble metal for 412 (gold or platinum) avoids corrosion without a coating. The probe shape can be optimized for the specific application – e.g., it can be made longer to increase sensitivity (more surface area in contact with fluid) or made in a cylindrical form factor for insertion into pipe flow. Fig. 4 shows a basic flat form factor that is easy to fabricate and install.

Central Node Data Processing: With all modules described, we revisit the central processing node (140, Fig. 1) to highlight how it handles the data from these sensors in practice. The central node runs firmware or software that implements a data acquisition loop for each sensor. For the PD sensor 110, it might receive either raw pulse data or summary metrics at regular intervals (e.g., PD count per second, largest pC in last minute). The node will maintain a log of these and possibly perform trending analysis – for example, comparing today's PD incidence to last week's to identify gradual worsening. Similarly, for each energy storage unit monitored by module 120, the node could record the ESR and capacitance readings over time, plotting slow changes that indicate aging. It could apply a model (like an exponential degradation curve or Arrhenius law adjustments for temperature) to project remaining useful life of capacitors, issuing notifications when a unit is approaching end-of-life criteria . For the coolant sensor 130, the central node can display real-time dielectric measurements and perhaps estimate contamination levels (e.g., "2% water by volume estimated" if the calibration for water is known, or "ionic contamination increasing at X units/week").

The alarm handling in the central node is configurable. Some thresholds are straightforward (if any PD event above, say, 50 pC is detected, that is a serious alarm; if coolant conductivity goes above 1 µS/m, immediate action required). Others might be trend-based (if ESR has increased 50% from baseline, schedule maintenance; at 100% increase , issue replace alert). The node can combine sensor inputs to reduce false alarms: for example, a single PD spike might be noise, but a PD spike accompanied by a sudden impedance change in capacitors might indicate an actual electrical fault – the node could be programmed to alarm only when multi-sensor corroboration occurs, or escalate the severity in that case.

To illustrate usage: imagine a scenario where a busbar joint starts developing a small insulation void causing partial discharges. The PD sensor 110 picks up intermittent 5 pC pulses . The system flags this as a warning level event (minor PD activity). Over weeks, the pulses become more frequent and larger (say 20 pC). The PD module and central node together recognize the trend and raise the alert to critical, suggesting an inspection of that busbar section. In another scenario, a set of supercapacitors in a UPS has been operating for 3 years. The impedance module 120 data shows one particular capacitor's ESR has climbed 2× from initial (and capacitance dropped ~25%). The system generates a predictive maintenance ticket to replace that capacitor bank at the next scheduled maintenance window, avoiding an unexpected UPS failure. Meanwhile, the coolant sensor 130 might continuously assure that the immersion fluid is clean – if one day a heat exchanger leak introduces water, the sensor quickly detects a rising conductance in the fluid and alerts operators to take immediate corrective action (such as removing and purifying the coolant before servers are damaged).

Alternative and Additional Embodiments: While the above description focuses on a data center use case (HVDC busbars, UPS banks, immersion cooling), the leakage-current module enables deployment across overhead transmission lines, pad-mounted transformers, and photovoltaic-array combiner boxes, complementing the partial-discharge sensor for a holistic grid-asset-health package.

the invention is not limited to that environment. The partial discharge sensor could be applied to any high-voltage apparatus, including AC switchgear or transformers – the flexible IDE design allows it to be mounted in places traditional PD sensors can't easily go. The impedance monitoring could be used for any electrochemical energy storage or conversion device, such as fuel cell stack health monitoring or even filter capacitors in power converters. The dielectric sensor could monitor transformer oil or even air quality (humidity or dust in air will change an air-gap capacitance slightly). The central node could be scaled down (for a single machine scenario) or scaled up (monitor dozens of sensors across a facility, essentially acting as a distributed sensor network manager). Additionally, the communication from sensors to the node could employ wireless mesh networking in some embodiments, which simplifies retrofits in existing facilities by avoiding long cable runs; each sensor module might be battery-powered or draw low power from the environment (for example, the PD sensor could harvest energy from the electric field of the busbar it's monitoring).

The descriptions of figures provided are intended to enable a skilled person to visualize and implement the various modules. Actual implementations can vary in circuitry and form so long as they achieve the stated functions. For instance, one could replace analog impedance measurement with a dedicated impedance analyzer ASIC, or implement the PD detection in an FPGA for higher fidelity. The scope of the invention encompasses these variations, as defined by the claims below.