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Encoded Sensors and Analog Sensors in High-Voltage Testing Applications

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Abstract: High-voltage testing is an essential part of testing the insulation of power equipment. Encounter persistent trouble with much strong electromagnetic interference (EMI>=120dBμV/m), much long distance cabling(>50m), quite strict many channel synchronization precision(\<5ns), difficulty in catching high frequency abrupt signals from partial discharge(PD). Based on the real world measurement data collected from six UHV test bases in China from 2024 to 2025, this paper sets up a four-dimensional quantitative evaluation model including SNR, amplitude relative error εa, temporal jitter Δtjitter, and temperature drift coefficient αt to comprehensively compare the encoded and analog sensors (RS-485 and fiber optic CAN types) and analog sensors (passive dividers, Rogowski coils, etc.) under power-frequency withstanding, lightning impulse (1.2/50 μs), switching impulse (250/2500 μs), and PD testing conditions. Sensors with codes do a better job of EMI resistance, thermal stability - α t = 12ppm / °C as well as faraway signal transmission reliability, synchronization precision (+ - 0.43ns). There's no way to replace analog sensors for PD pulse front edge fidelity, since their bandwidth is up to 150 MHz. To solve this complementarity, we put forward the "primary-auxiliary collaborative" hybrid sensing architecture: the encoded sensors serve as the primary channel for steady metrological measurement and hardware-level triggering; high-speed analog front-ends are used as the auxiliary channel for the purpose of nanosecond-level waveform construction. Hardware timestamping in used for sub-nanosecond alignment and it connects closely with the IEEE 1588v2 time synchronization. Field validation for ±800 kV UHVDC station shows:(1)Lightning impulse peak voltage expanded uncertainty(k=2)reduces from ±3.2% to ±0.86%; (2) Compression of PD rise-time measurement error from ±1.6 ns to ±0.43 ns—a full compliance with both GB/T 16927.1–2022 and IEC 60060-1:2023 requirements.

Keywords: High-voltage Testing; Encoded Sensor; Analog Sensor; Partial Discharge.

1. Introduction

High-voltage testing is undergoing a huge change, because there are more test rooms, we need more automation, and because we can see from far away now [1]. In this process, it very clearly shows the basic problems with the old way we send information, which is using old analog signals, and that has been the main way to take these big electrical signals for many, many years. Analog signals as continuous voltage/current, suffer greatly from attenuation and distortion over large cable lengths, are very prone to ground potential rise (GPR) and common-mode interference in electrically noisy environments, hold no inherent information about their own calibration status or identity, and rely completely on external often jittery-time-keeping trigger systems for multiple-channel time alignment[2]. And it is becoming more and more contrary to the requirements of next generation of intelligent test: the data can be traced, it is possible to be managed effectively after a long time, and tests must be reproducible[3].

2. Four-dimensional Quantitative Evaluation Model and Experimental Investigation

To break out the qualitative claims and have an objective data driven benchmark for both of the sensors we developed a complete four dimensional evaluation model. Model looks at performance from these main angles concerning HV testing: quality of signals, how correct measurements are, if times stay on schedule and how steady it is in the surroundings[4]. All comparative tests employ the exact same high voltage test item a 110kV GIS busbarsection and take place under identical controlled environment conditions Ambient temperature 23C ± 1C Humidity 45% ± 5% No forced air flow. We used standardized, top-notch cabling (shielded twisted pair for analog and specific fiber for digital) with single-point grounding techniques. All reported data are the average of 3 independent repeat trials for statistical significance[5].

Model's four components are defined as below:SNR: This is a metric which tests how easy it is for the sensor to get a weak signal like PD when the sensor is surrounded with lots of strong electromag interferences It is defined as: SNR (dB) = 10 * log10(P_signal/P_noise) where P_signal is the power of the signal of interest within its relevant bandwith and P_noise is the root-mean-square noise power measured over a certain quiet band such as 500 KHz - 100MHz when no intentional test signal is applied[6].

Amplitude Relative Error (ε_a): This number represents how close the sensor's amplitude measuring is to the traceable standard on a deterministic, steady state. ε_α (%) = |V_m - V_t| / V_t × 100% V_m is the sensor's measured values from the sensor under test and V_t is the actual value given the laser interferometric voltage calibration system which is traceable back to national standards (NIM-Traceable with a k =2 and a expanded uncertainty of U =±0.05%). And monitor the drift accumulation for a long 24- hour time.[7]

Temporal Jitter (Δt_{jitter}): It's about how well the sensor can synchronize and when the timing is uncertain if a flashing event takes place It is obtained by doing cross-correlation analysis on the same lightning impulse waveform recorded at two synchronized measuring channels. The width of cross-correlation peak can be regarded as a direct measurement of the system level timing jitter which comprises all the sources included from trigger to that of the sampling clock stability[8].

Temperature Drift Coefficient (α_t): This metric indicates the sensor's sensitivity toward external changes of temperature, which is a major factor for outdoor applications and extended duration tests. αt(ppm/°C) = [G(θ2) - G(θ1)] / [Gn * (θ2 - θ1)] * 10^6, where G(θ) represents the gain when measured at temperature θ, G_n is the gain at reference temp(23°C) The sensor was put through a temperature range of -25°C to +70°C in 5°C steps and any non- linearity was fitted and reported[9].

The main experimental results of this model are: Under a power frequency withstand voltage of one hour at 1.3 times the rated voltage, encoded sensors kept stable at an amplitude error of εa = + 0.32C (σ = 0.07). But analog sensors, especially the electromagnetic VTs, showed a much more significant difference, the drift got bigger when their temperature rose to 38 K and this made their measurements less accurate[10].

For the standard 1.2/50 μs lightning impulse, the sensors with encoded sensors equipped with hardware timestamps have an intra-channel temporal jitter of Δt_{jitter} = 1.8 ns where σ = 0.3 ns. The analog sensors with external trigger distribution system was far more uncertain with their timing, around plus-or minus 5 nano seconds, because of the trigger jitter as well as the different amount of dispersion in the analog cables[11].

During evaluation at -25°C cold start performance, the encoded sensors with integrated temperature compensation had a small drift coefficient a-t = 12 ppm °C and a remaining non-linearity less than 0.08%. As far as the analog reference sensors go, their sensitivity αt is much greater, at 50ppm/°C, and the hysteresis can be observed with each heating-cooling cycle.

It is a four dimensional model. This is rejecting idealized laboratories. Every one of those is from physically measurable, field reproducable amounts which take into account all of the "signal origin -> sensor system -> environment interaction" links. So it has strong engineering validity and can be easily transferred for performance evaluation among different platforms and enterprises.

3. Design and Engineering Validation of the "Primary-Auxiliary Collaborative" Hybrid Sensing Architecture (HSA)

In order to bridge these identified gaps in performance, to be better than the sum of its parts, we herein propose the proposed hybrid sensing model called as Hybrid Sensing Architecture (HSA) Stragey The architecture relies on 3 basic logical layers:

Paradigm Shift Layer: Don't chase that one-sensor-fits-all any longer. Adopt the philosophy that the proper task requires a heterogeneous sensor, one that has the appropriate technology for a given measurement.

Functional Decoupling Layer: Partition the entire measurement task according to time scale and physical nature. Steady-state-dominant params (e.g., power freq voltage mag, harmonics, THD), transient-dominant (e.g., PD pulse rise time, osc freq, wavefront shp):

Channel Coupling Layer: Keep similar wrod count, do AI trace removal re writing with a human style, make it easier to read academically, no matter what the user writes: Time and Data of decoupled channels are consistent with synchronization and data protocols at the hardware level. Do not lose the functionally separated that brings the best from each channel

Details of HSA implementation: Main channel (Steady-state Metrology & trig Systems): This channel uses a high-performance encoded sensor, namely a fiber optic CAN voltage sensor. Key points: temperature range is full-range of - 40 ℃ ～ + 85 ℃ with self - calibration function and compensation algorithm stored in non - volatile memory, low - noise 16 - bit SAR ADC takes sampling rate of 5MS/s, which can be used to correctly measure harmonics to the 25th order - according to the IEC 61850 - 9 - 2; digital output is a stream of 16 - bit unsigned integer values. Critically, each data sample is tagged with a nanosecond-resolution hardware timestamp generated at the ADC sample- and - hold instant. Data transmission by means of single mode optical fiber can supply complete galvanic separation, ground loops and common mode interference can be removed completely. This channel provides the system's official measurement for both steady-state and slow transient values and creates an ultra-low-jitter hardware trigger sign.

Auxiliary Channel (High Fidelity Transient Capture): This channel is all about perfect waveform. It uses its own analog sensor, which is a high-frequency analog sensor like a differential output Rogowski coil made of a nanocrystalline alloy with a bandwidth from 3 MHz to 150 MHz (−3 dB) and a rise time of <=2.3 ns. This sensor is hooked up directly (very little intervening cable) to a dedicated FPGA-thing that makes it able to get samples super-fast, like 10 billion per second! And instead of the usual 12, oh so important little numbers, they get 12 bits each. Máy card dropout from deep pre-trigger: It is generated by an item which is connected straight to a different hardware interrupt pin present on the primary channel sensor's fpga: This physical touch establishes an immediate and direct link, completely avoiding any software delay or network fluctuation that is common when using command-based triggers, it should be noted that the timing is precise to within less than one nanosecond.

Time synchronization Mechanism(double-level): Precise timing alinement is reached by a two tier structure:

Level 1 (Network Synchronization): IEEE 1588v2 (Precision Time Protocol) boundary clock is deployed at the primary data gateway node with high-stability oscillator to provide a common time reference of better than ±100 ns accuracy across the measurement network.

Level 2 (Hardware Timestamping): The trace engine, which is an FPGA-embedded timestamp engine, gives extremely exact hardware timestamps to every data frame from the first channel and, at an even greater level of precision, to each sample point collected by the auxiliary high-speed card, with a resolution as low as 100 ps. In the final step, post-processing uses a Kalman filter to refine the inter-channel time offset down to a stable, synchronized time difference of (+/-)0.43ns (95% CI).

Six month field validation at an 800kv UHVDC converter station:

The HSA went through a thorough six month field test in a large UHVDC station. It included normal tests and fault simulations.

Lightning Impulse Testing (1.2/50 μs): The expanded measurement uncertainty (k=2), for the impulse peak voltage dropped from plus or minus 3.2 percent using the stations' legacy analog measurement system to plus or minus 0.86 percent using the HSA Regarding the waveform detail, it was also observed containing 3. 8 time greater fidelity in pictures and spectra also overshoot, The high frequency ringing was captured, It was also captured

Partial Discharge Detection (IEC60270): The standard deviation for measuring PD pulse rise-time(10% to 90%) went down from 1.6ns to 0.43ns. After this improved timing is used inside a dual channel of time of flight (TOF) localization algorithm then the 3D spatial error for finding out PD sources connected to a transformer tank goes from plus or minus 1.8m to plus or minus 0.35m.

Long-Term Stability Assessment: The primary channels (encoded) and the auxiliary (analog) display a very steady baseline with less than 0.8 mV RMS and no significant drift under a 40°C @ 95% RH continuous 72hr soak test (The drift is <=0.21%)

The most important thing about the HSA is its data management system. All raw and processed data are saved in csv files in a standard format. The metadata has header lines with strict adherence to the PQDIF v2.0 format standard as well as the IEEE C37.118.2-2016 (Synchrophasor Data Transfer) standard. Make it possible to index millisecond-level date, allow for retrospective analysis across different platforms, and provide “plug-in / insert” sets of data ready for training AI models for the recognition of patterns and predictive diagnosis. So this architecture does live up to the claim on operational intelligence: acquire-on-the-fly; use-on-the-fly; trace-on-the-fly; decide-on-the-fly, As shown in Tables 1–4 below.

Table 1. Basic Parameter Comparison Between Sensor Types

Parameter	Analog Sensor (Passive Divider)	Encoded Sensor (Fiber-Optic CAN Type)
Output Format	0–10 V analog voltage	16-bit digital code (0–65535)
Nominal Accuracy (23°C)	±1.0%	±0.2%
Operating Temperature Range	−25°C to +70°C	−40°C to +85°C
Temperature Drift Coefficient α_t	50 ppm/°C	12 ppm/°C
Maximum Reliable Transmission Distance	≤30 m (coaxial cable)	≥1000 m (single-mode fiber)
Common-Mode Interference Immunity	<80 dBμV/m	>120 dBμV/m

Table 2. Performance Comparison in Power-Frequency Withstand Test (750 kV, 50 Hz)

Item	Analog Sensor	Encoded Sensor
Amplitude Relative Error ε_a	±2.1%	±0.32%
Signal-to-Noise Ratio (SNR, dB)	58.3	76.9
Drift Over 8-Hour Continuous Run	+1.4% (due to heating)	+0.18%
Ground-Loop Interference Error	±1.8% (measured)	Immune

4. Conclusion

This paper portrays the core engineering impasse around sensor choice in high voltage testing without using theoretical discussion but instead with three empirical pillars: field collected info, an intense 4D quantification score, and hands-on proof of a fresh HSA (Hybrid Sensing Architecture). We can come to three clear conclusions:

1. Encoded sensors are not the plug-and-play replacement of analog sensors in every single situation. Decisive and transforming advantages in areas important for modern grid assets: stable solution with tunnel effect at more than 1000M, noise resistant data transmission solution at more than 120DBM, strong solution at high EMI, operation range is stable in a wide range from -40°C to +85°C, ultra precise measurement with hardware synchronization solution within -+0.43ns in multi channel. So they are good at power-frequency and peak impulse metrology, remote condition monitoring, and serving as a backbone for AI diagnosis data.

Table 3. Dynamic Performance Comparison in Lightning Impulse Test (1.2/50 μs)

Item	Analog Sensor	Encoded Sensor
Wavefront Time T_1 Measurement Error	±8.5%	±12.3% (sampling-limited)
Half-Peak Time T_2 Measurement Error	±6.2%	±9.7%
Peak Voltage Measurement Error	±2.9%	±0.86%
Temporal Jitter Δt_{jitter}	±5.0 ns (external trigger)	±1.8 ns (hardware timestamp)

Table 4. Key Metrics in Partial Discharge (IEC 60270) Test

Item	Analog Sensor (Rogowski + High-Speed ADC)	Encoded Sensor (Fiber-Optic CAN Type)
Equivalent Detection Bandwidth	3 MHz – 150 MHz	DC – 25 MHz
Minimum Detectable PD Charge (SNR=3)	3.2 pC	8.7 pC
Pulse Rise-Time Resolution	1.2 ns	15 ns
Multi-Channel Synchronization Accuracy	External trigger dependent (±5 ns)	IEEE 1588v2 + FPGA (±0.43 ns)

2. Analog sensors are still quite necessary in some diagnostic functions. Their native and broadband analog response (up to 150 MHz), genuine zero protocol latency figure plus direct-to-the-point millivolt grade signal fidelity make them exceptionally appropriated to finish work needing to hold onto nanoseconds worth of timing details wholly untouched along with all of the shades on the whole spectrum unchanged. This includes to extract the exact PD pulse rise times, to identify any sharp-front oscillations in the switching impulses, and to look at very high order harmonics as well.

3. The "primary-auxiliary cooperate ’s" hybrid spectroscopy architecture is by no means a technical compromise, but rather the strategic and most efficient route ahead for next-generation HV measurement systems. The HSA intelligently decouples the measurement tasks based on their physical requirements and temporal needs, assigns the sub task that is best suited for a sensor technology, and enforces strict sub-nanosecond alignment via hardware coupling. This is done by the HSA in order to transform the complementary benefits of encoded and analog sensors into verifiable system performance gains. Field validation results are definite: lightning impulse peak voltage measurement uncertainty drops 73%, and the spatial accuracy of PD source localization improves nearly 4 times. Such advanced

development satisfies all the highest accuracy class requirements set forth by the leading international and national standards, GB/T 16927.1-2022, IEC 60060 - 1:2023, and DL / T 1687 - 2017.

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