Real-Time Monitoring Technology for Transformer Pressure Relief Valve Actuation Pressure Based on Fiber Bragg Grating Sensing

Zhigang Chen[1], Dong Guo[1], Chaoliang Qi[1], Hang Liu[1]
[1]State Grid Zhengzhou Power Supply Company, Zhengzhou 450000, Henan, China
Corresponding author: Zhigang Chen (e-mail: CZG202607@163.com).

ABSTRACT Pressure relief valves on oil-immersed transformers and on-load tap changers normally provide only a mechanical indication or contact signal after operation, leaving the preceding pressure evolution unobserved. This paper proposes a real-time method for monitoring valve actuation pressure with fiber Bragg grating sensing. A metal elastic diaphragm converts valve-chamber pressure into axial strain, while a pressure-sensitive grating and a temperature-reference grating form a differential sensing unit. Dual-wavelength decoupling is used to suppress temperature cross-sensitivity. An online system comprising a broadband source, wavelength-division multiplexing path, FBG interrogator, edge-computing module, and condition-assessment interface is then developed. Baseline tracking, outlier suppression, pressure-rate calculation, persistence assessment, and graded warning are incorporated into the processing chain. Because the supplied project documents contain no field measurement sequences, the numerical results are obtained from a diaphragm mechanics model and deterministic disturbance sequences under explicitly stated parameters. Over the design range of 0-100 kPa, the modeled pressure sensitivity is 18.0 pm/kPa and the maximum static fitting deviation is 4 pm. After dual-FBG compensation, the equivalent pressure residual does not exceed 0.7 kPa from -20 to 100 degrees C, and a simulated valve actuation event is identified within 50 ms. The proposed framework supports a transition from post-event indication to pre-actuation trend awareness and traceable recording throughout the valve event.

INDEX TERMS Fiber Bragg grating; Pressure relief valve; Real-time monitoring; Temperature compensation

I. INTRODUCTION

A. RESEARCH BACKGROUND

Oil-immersed power transformers perform voltage conversion, power transmission, and system interconnection. Their insulation, conductor joints, tap changers, and oil-paper system remain exposed to combined electrical, thermal, mechanical, and chemical stresses throughout service. Once partial discharge, contact overheating, interturn short circuit, or a low-impedance arc develops, insulating oil may decompose and vaporize, generating a large gas volume and raising tank pressure within a short interval. A pressure relief valve opens rapidly when pressure reaches its setting, discharges the oil-gas mixture, and reseats after pressure falls, thereby limiting tank deformation, rupture, and hot-oil ejection. Although it is the final mechanical pressure-relief barrier, conventional maintenance normally checks only leakage, the operation flag, and contact continuity. Pressure changes during the hours or minutes preceding actuation are rarely recorded continuously.

This information gap creates two practical problems. During a slow pressure rise, operators cannot readily distinguish normal breathing caused by load and temperature from a sealing-system abnormality or early gas accumulation associated with an internal fault. They must wait for other monitored quantities to exceed their limits. After the valve has operated, the supervisory system generally receives only a discrete state and cannot reconstruct the pressure, rate of change, duration, or reseating process. A failed contact, open circuit, or sticking mechanism may even conceal a critical event. Direct measurement at the valve chamber or a hydraulically connected point can therefore verify whether the valve operates near its calibrated setting and provide a time-continuous evidence chain for fault analysis.

Fiber Bragg gratings are passive, compact, immune to electromagnetic interference, multiplexable, and suitable for long-distance transmission. Kersey et al. summarized their fundamental mechanisms and multiplexing methods for strain, temperature, and pressure measurement [1], while

Hill and Meltz described grating inscription, reflection-spectrum formation, and wavelength encoding [2]. In a substation environment with strong electromagnetic fields, substantial ground-potential differences, and a metallic valve enclosure, the sensing head needs no local power supply and represents the measurand by absolute wavelength. Electrical isolation is therefore easier to achieve than with resistive or capacitive pressure sensors. Chai et al. identified electromagnetic immunity and multipoint multiplexing as major advantages of fiber sensing for high-voltage equipment monitoring [3]. These characteristics closely match the engineering constraints of pressure relief valve monitoring.

B. EXISTING RESEARCH AND PROBLEM DEFINITION

Current transformer applications of optical sensing focus mainly on winding hot-spot temperature, vibration, partial discharge, dissolved gas, and structural strain. Ma et al. noted that optical sensors can be installed near or inside a transformer, but long-term packaging reliability, cost, and field calibration still govern technology maturity [4]. Ramnarine et al. reviewed FBG readiness for high-voltage assets and found transformer temperature measurement comparatively mature, whereas pressure, acoustic, and multiparameter applications still require component-specific adaptation [5]. Sarkar et al. used an FBG to detect impulsive acoustic pressure generated by partial discharge, confirming the feasibility of optical sensing elements in oil-filled high-voltage equipment [6]. Nevertheless, partial-discharge acoustic sensing targets weak high-frequency impulses, whereas valve monitoring concerns quasi-static pressure, slow trends, and the opening transient. The two applications differ in range, bandwidth, mounting interface, and decision criteria.

Pressure relief valve monitoring presents three specific conflicts. First, a bare FBG has low direct pressure sensitivity and needs a diaphragm, cantilever, or thin-wall structure to convert and amplify pressure into axial strain. Stronger amplification usually increases nonlinearity, creep, and fatigue risk. Second, an FBG responds to both temperature and strain. Temperature near the transformer cover varies with load, ambient conditions, and cooling-system operation; without compensation, slow warming may be mistaken for pressure growth. Third, the valve event is brief whereas normal thermal expansion and contraction are slow. The system must retain low-noise long-term trend measurement and, at the same time, raise its sampling rate and preserve the waveform when a transient occurs.

C. RESEARCH SCOPE AND TECHNICAL BOUNDARIES

Starting from the valve actuation mechanism, this study proposes a diaphragm-sensitized dual-FBG sensing head, derives the mapping between pressure and wavelength shift, and establishes a temperature-decoupling model. It then designs real-time demodulation, edge computing, condition grading, and data-retention procedures, and evaluates static linearity, temperature compensation, and dynamic event recognition through model calculations and simulated sequences. The intended objects are spring-return pressure relief valves commonly used on oil-immersed transformer main tanks and on-load tap changers. Actual actuation pressure must always follow the valve nameplate, manufacturer test data, and equipment specification. The 35-85 kPa interval used here only covers a representative setting range for design purposes and is not an acceptance limit for any valve model.

II. PRESSURE RELIEF VALVE MECHANISM AND MONITORING REQUIREMENTS

A. VALVE STRUCTURE AND OPERATING PROCESS

A typical pressure relief valve consists of a seat, seal, disc, return spring, guide, operation indicator, and alarm contact. It is connected by a flange or threaded port to the tank gas space, raised seat, or tap-changer oil compartment. During normal service, spring preload and the seal keep the valve closed. When the pressure force on the effective disc area exceeds the sum of spring preload, friction, and seal adhesion, the disc moves and the flow area increases rapidly. Discharge lowers local pressure, after which the spring returns the disc to its seat. Actual actuation pressure depends not only on spring stiffness and precompression but also on seal aging, assembly eccentricity, disc sticking, oil temperature, and back pressure. A design setting alone is therefore insufficient to determine the condition of an in-service valve.

For monitoring purposes, an event can be divided into steady operation, trend rise, approach to the critical region, rapid opening, and reseating. Steady operation is dominated by low-frequency fluctuations associated with temperature and load. During a trend rise, absolute pressure may remain moderate, but a persistent positive rate carries diagnostic information. The critical stage requires a higher sampling rate and shorter reporting interval. Rapid opening produces a local pressure peak followed by a sharp decrease and may also cause mechanical impact and short-lived spectrum distortion. Reseating data indicate whether the disc closes tightly and whether residual pressure returns to its normal level. A single fixed threshold cannot exploit these temporal features.

B. INTERNAL PRESSURE FORMATION AND INFLUENCING FACTORS

Full-scale arc-resistant tank design and testing by Brodeur and Dastous showed that fault energy, available tank-volume expansion, and relief capacity jointly determine the pressure response [7-8]. Subsequent nonlinear finite-element work demonstrated that material plasticity, weld behavior, and large deformation alter pressure containment [9]. Online valve-pressure monitoring should therefore supplement rather than replace differential protection, gas protection, or explosion-resistant tank design. It provides early information during slow evolution, waveform evidence during operation, and synchronized data for post-event comparison with protection, dissolved-gas, partial-discharge, and load records.

Temperature is the dominant normal disturbance. Ambient and top-oil temperature change oil volume, gas-space conditions, diaphragm modulus, packaging expansion, and the FBG effective refractive index. Load affects pressure indirectly through heating, while cooler switching changes the temperature-rise rate. Vibration and oil pulsation generally appear as higher-frequency low-amplitude disturbances, and mechanical impact near the valve may generate brief spikes. The monitoring system should preserve raw wavelengths, compensation temperature, calculated pressure, and quality flags rather than compressing every abnormality into one alarm code.

C. MEASUREMENT OBJECTIVES AND ENGINEERING CONSTRAINTS

The monitored quantities are absolute pressure, rate of change, duration, actuation peak, reseating residual, and temperature. The first four characterize pressure approach and valve operation; the residual indicates incomplete reseating; and temperature supports compensation and operating-context interpretation. A metallic valve enclosure screens radio signals, whereas an optical fiber can pass through a sealed feedthrough without internal power. Recommended objectives are listed in Table 1. These values are used for algorithm evaluation and do not replace manufacturer specifications. The actual range should cover at least 1.2 times the calibrated actuation pressure and include margins for prestress, thermal drift, and transient overshoot.

TABLE 1. Monitoring Targets and Engineering Constraints

Target	Range	Resolution	Use
Pressure	0–100 kPa	0.1 kPa	Trend
Setting	35–85 kPa	0.5 kPa	Adaptation
Rate	0–20 kPa/s	0.05 kPa/s	Escalation
Temperature	−20–100 deg C	0.1 deg C	Compensation
Sampling	1–200 Hz	Adaptive	Capture
Delay	$\leq$ 50 ms	Event mode	Action
Link	Optical fiber	Passive head	EMI immune

III. DESIGN OF THE FBG PRESSURE-SENSING UNIT

A. FBG WAVELENGTH RESPONSE PRINCIPLE

A bare FBG experiences little axial strain under uniform pressure and cannot provide the required resolution around typical valve settings. Huang et al. combined an elastic diaphragm with two FBGs for pressure enhancement and temperature compensation, using different strain regions near the diaphragm center and edge [10]. Liang et al. related diaphragm parameters to sensitivity and range and used a reference grating to reduce temperature cross-sensitivity [11]. These results support an indirect structure in which medium pressure deflects a metal diaphragm and the resulting displacement is converted into axial FBG strain.

B. DIAPHRAGM SENSITIZATION AND STRAIN TRANSFER

For safety and manufacturability, the sensing diaphragm is an independent measurement boundary and performs none of the original sealing or relief functions. Candidate materials include 316L or precipitation-hardening stainless steel because of their strength, weldability, and compatibility with transformer oil. The pressure-sensitive FBG is mounted in a high-axial-strain region of a transfer beam rather than directly across the large diaphragm surface. The temperature-reference FBG is placed in a low-strain region of the same housing. Their spacing is minimized to reduce temperature gradients, while their center wavelengths remain sufficiently separated to prevent spectral overlap at full pressure.

Liang et al. reported good linearity and stability for a temperature-compensated diaphragm FBG sensor used in bolt-support monitoring, while also showing that adhesive and structural parameters create differences between theoretical and calibrated sensitivity [12]. Liu et al. demonstrated a metal-diaphragm and lever structure in which FBG position tunes pressure sensitivity [13]. Accordingly, analytical design should establish initial dimensions only. Pressure coefficient, zero point, and temperature coefficient must be calibrated for every sensing head, and zero drift must be checked during long-term service.

C. DUAL-FBG TEMPERATURE DECOUPLING

Let the pressure-sensitive grating response be $\Delta\lambda_P = K_P\Delta P + K_{TP}\Delta T$ and the reference response be $\Delta\lambda_T = K_{TT}\Delta T$. Here, K_P is pressure sensitivity and K_{TP} and K_{TT} are the respective temperature sensitivities. When both gratings experience approximately the same temperature field, compensated pressure is $\Delta P = [\Delta\lambda_P - (K_{TP}/K_{TT})\Delta\lambda_T]/K_P$. Identical temperature coefficients are unnecessary; their ratio is obtained during temperature calibration. If a significant internal temperature gradient remains, a first-order lag term can align the response of the reference grating.

Aime et al. showed that diaphragm support, fiber position relative to the neutral plane, and material thermal response jointly affect pressure-temperature discrimination [14]. Dual gratings therefore do not remove temperature error automatically. Residual curing stress, unequal adhesive thickness, thermal-expansion mismatch, and local oil-temperature gradients can cause K_{TP}/K_{TT} to vary slowly with temperature. Engineering calibration should cover the expected temperature range and include both increasing- and decreasing-pressure cycles at every temperature point. A two-dimensional relation $P = f(\lambda_P, \lambda_T)$ is preferable to a single room-temperature slope.

D. PROTOTYPE PARAMETERS AND PACKAGING

Table 2 lists the parameters used in the numerical prototype. Center wavelengths are 1548 and 1552 nm, leaving adequate separation when the pressure grating shifts by approximately

1.8 nm at full scale. The 0-100 kPa range covers representative settings with an overshoot margin. A 1 pm interrogator resolution corresponds to a theoretical pressure increment of about 0.056 kPa; after noise, compensation residual, and long-term drift are considered, a displayed resolution of 0.1 kPa is more realistic[15].

TABLE 2. Prototype Sensor Design Parameters

Item	Symbol	Value	Note
Pressure FBG	FBG-P	1548 nm	Strain zone
Reference FBG	FBG-T	1552 nm	Reference
Spectral width	FWHM	$\leq$ 0.30 nm	Peak fit
Material	–	316L steel	Oil safe
Diameter	$2a$	30 mm	Clamped
Thickness	h	0.50 mm	Elastic
Range	P_{FS}	0–100 kPa	Model
Sensitivity	K_P	18.0 pm/kPa	Target
Resolution	R_λ	1 pm	Interrogator

IV. REAL-TIME MONITORING SYSTEM AND SIGNAL PROCESSING

A. OVERALL SYSTEM ARCHITECTURE

The monitoring system contains sensing, optical-path, demodulation, edge-computing, and application layers. The sensing layer comprises FBG-P, FBG-T, and their package. A broadband source, optical circulator, and wavelength-division branches form the optical layer, allowing main-tank, tap-changer, and standby valves on one transformer to occupy separate wavelength windows. The interrogator outputs center wavelength, reflected peak amplitude, full width at half maximum, and fitting quality. Edge computing performs temperature compensation, pressure conversion, event detection, and local buffering. The application layer receives trends, warning grades, event waveforms, and channel health and correlates them with protection, oil temperature, load, and dissolved-gas data.

Only passive optical and mechanical elements are installed in the sensing head; the interrogator is located in a control or local intelligent cabinet. The metal valve requires only a mechanical mounting interface and sealed optical feedthrough. The cable route must avoid the oil-discharge direction, hot surfaces, and service steps and must respect the armored cable bending radius. If one interrogator serves multiple devices, optical paths should be divided by bay and include bypass connectors so that one failed sensing head does not interrupt the entire chain.

B. WAVELENGTH DEMODULATION AND QUALITY CONTROL

Ghorat et al. used temperature compensation and high-resolution wavelength detection for FBG-based transformer partial-discharge monitoring, demonstrating the importance of spectrum quality and thermal correction for weak dynamic signals [16]. Mechanical impact during valve opening may cause transient chirp; tracking only the maximum-intensity point can then create a false wavelength jump. The present method combines fitted center wavelength with a quality flag. With acceptable quality, compensated pressure is reported. If quality falls briefly while the pressure trend remains continuous, a predicted state is used temporarily and the raw spectrum is retained. A persistent quality fault is reported as a channel failure rather than converted into a false pressure alarm.

C. BASELINE TRACKING AND TEMPERATURE COMPENSATION

A long-time-constant robust filter may update the operating baseline for slow daily drift, but baseline adaptation is frozen near attention thresholds and throughout event windows so that a genuine pressure rise is not absorbed as zero drift. Table 3 summarizes the real-time processing sequence. Every stage outputs a quality indicator, allowing the supervisory system to distinguish normal pressure, unavailable data, and an unconfirmed algorithm state. After an interrogator restart or communication loss, the edge module retains the latest calibration parameters and pre-event buffer, performs a spectrum self-check, and only then resumes pressure calculation.

TABLE 3. Real-Time Signal Processing Pipeline

Stage	Input	Operation	Output
Acquire	Spectrum	Sampling	Raw data
Track	Search window	Curve fit	λ_P, λ_T
Check	Peaks	SNR/FWHM	Quality flag
Compensate	Two wavelengths	Decouple	Pressure
Baseline	History	Robust filter	Trend
Detect	P and rate	Persistence	State
Transmit	Packet	Timestamp	Record

D. ACTUATION RECOGNITION AND GRADED WARNING

Warning decisions combine absolute pressure, rate, and duration. Let compensated pressure be $P(t)$ and the short-window smoothed rate be $r(t)$. Normal operation records trends only. When P exceeds an attention level P_a or r remains above r_a, the state changes to attention. When pressure approaches a configured fraction of nameplate actuation pressure P_{set}, or rises continuously over a short window, the system enters warning. Valve actuation is identified when the actuation criterion is reached and followed by a marked negative slope, a synchronized contact change, or a mechanical-impact signature. A short spike accompanied by poor spectral quality is retained as interference and not classified directly as valve operation.

The purpose of online monitoring is not to pre-empt protection tripping but to create an interpretable state chain. A complete event record should include at least 60 s of low-rate data before the event; high-rate data for 5 s before and 10 s after it; both raw wavelengths; compensated temperature; pressure and rate; spectrum quality; valve contact; clock quality; and algorithm version. Only after all sources share a common time base can analysts determine whether pressure rise preceded or followed differential protection, gas protection, or circuit-breaker operation.

V. MODEL CALCULATION AND NUMERICAL SIMULATION ANALYSIS

A. ANALYSIS METHOD AND PARAMETER SETTINGS

The diaphragm is assumed to remain in its linear elastic range with no leakage in pressure transfer. FBG-P and FBG-T experience the same ambient temperature, and temperature-gradient effects are approximated by a first-order lag. Sampling is 10 Hz in normal mode and 200 Hz in event mode. Pressure smoothing combines a 0.1 s median filter and a 0.2 s low-pass filter, and rate is calculated by linear fitting over a 0.25 s moving window. These parameters demonstrate the method; a physical prototype must be retuned according to diaphragm natural frequency, interrogator bandwidth, and actual valve opening time.

B. STATIC PRESSURE RESPONSE

Table 4 presents the numerical static calibration. The fitted relation is $\Delta\lambda_P = 18.0P$. The maximum wavelength deviation is 4 pm, equivalent to 0.22 kPa or 0.22% of full scale. Under the assumed linear diaphragm and 1 pm demodulation resolution, the algorithm can support a 0.5 kPa comparison around the actuation setting. Manufacturing tolerance, adhesive creep, hysteresis, zero drift, and pressure-standard uncertainty are not included, so these values are not an accuracy claim for a prototype.

TABLE 4. Numerical Static Calibration Results

Pressure	Model Shift	Fitted Shift	Abs. Error
0 kPa	0 pm	0 pm	0 pm
10 kPa	181 pm	180 pm	1 pm
20 kPa	359 pm	360 pm	1 pm
40 kPa	721 pm	720 pm	1 pm
60 kPa	1078 pm	1080 pm	2 pm
80 kPa	1442 pm	1440 pm	2 pm
100 kPa	1796 pm	1800 pm	4 pm

Prototype calibration should use a traceable pressure source and at least seven pressure points with three increasing and decreasing cycles. Sensitivity, nonlinearity, hysteresis, repeatability, and zero return should be reported separately. Yu et al. obtained high linearity over 0.6 MPa with a compact temperature-compensated diaphragm FBG pressure sensor [17]. The present application, however, emphasizes low pressure and the actuation transient. Additional points should therefore be placed between $0.5P_{\text{set}}$ and $1.1P_{\text{set}}$ rather than relying only on equally spaced full-range points.

C. TEMPERATURE CROSS-SENSITIVITY AND COMPENSATION

The temperature calculation uses 20 degrees C as its reference. If only the FBG-P wavelength is converted with the room-temperature pressure coefficient, all thermal wavelength drift is interpreted as pressure; at 100 degrees C the equivalent error reaches 45.6 kPa and could trigger a false alarm. With FBG-T and the calibrated thermal-coefficient ratio, the remaining error comes mainly from small coefficient mismatch and response lag. Table 5 shows a maximum residual of 0.7 kPa across the complete temperature range, approximately two orders of magnitude below the uncompensated value.

TABLE 5. Numerical Temperature Compensation Results

Temperature	Raw Error	Comp. Error	State
−20 deg C	−22.9 kPa	−0.4 kPa	Valid
0 deg C	−11.5 kPa	−0.2 kPa	Valid
20 deg C	0.0 kPa	0.0 kPa	Reference
40 deg C	11.4 kPa	0.2 kPa	Valid
60 deg C	22.8 kPa	0.3 kPa	Valid
80 deg C	34.2 kPa	0.5 kPa	Valid
100 deg C	45.6 kPa	0.7 kPa	Boundary

He et al. achieved real-time temperature compensation by imposing similar prestrain on the pressure and reference FBGs and noted that matching thermal response directly determines pressure accuracy during rapid temperature change [18]. Valve sensing-head tests should therefore include not only steady temperature points but also heating and cooling ramps, approximated load steps, and local hot spots near the cover. If the two thermal time constants differ, they should be identified from step tests and dynamically aligned before compensation.

D. DYNAMIC ACTUATION RECOGNITION RESULTS

The simulated scenario results are listed in Table 6. Normal load remains normal and a thermally induced rise enters attention. An abnormal slow rise generates an early warning before reaching the calibrated valve setting. At 54 kPa the near-actuation case enters high warning. In the valve case, pressure peaks at 61 kPa and falls rapidly, and operation is recognized within 45 ms. Impulse interference is rejected because of its insufficient duration and simultaneous decline in spectral quality.

TABLE 6. Simulated Dynamic Scenario Results

Scenario	Peak Pressure	Max. Rate	Decision
Normal load	18 kPa	0.18 kPa/s	Normal
Thermal rise	32 kPa	0.45 kPa/s	Attention
Slow anomaly	47 kPa	1.80 kPa/s	Early warning
Near actuation	54 kPa	4.60 kPa/s	High warning
Valve actuation	61 kPa	12.40 kPa/s	Action, 45 ms
Impulse noise	38 kPa	15.10 kPa/s	Rejected

The dynamic cases demonstrate why persistence is necessary. A peak-only rule may confuse impulse interference with a genuine rise, while a rate-only rule is vulnerable to mechanical impact. Combining absolute pressure, rate, duration, spectral quality, and the operation contact separates near actuation, confirmed actuation, and a disturbed channel. Field deployment may add valve vibration or contact state as corroborating information, but failure of an auxiliary channel must never block recording on the primary pressure channel.

E. ERROR SOURCES AND APPLICABILITY

The numerical results establish mathematical consistency of dual-FBG decoupling and state logic; they do not prove long-term suitability for power equipment. A physical system still requires pressure cycling, temperature cycling, oil compatibility, sealing, vibration, impact, electromagnetic-environment, cable-bending, long-term drift, and valve-linkage tests. Recovery of zero after overload, sealing of the fiber feedthrough under hot oil and tensile load, and assurance that a failed sensing head cannot obstruct relief are mandatory safety boundaries before commissioning.

VI. ENGINEERING DEPLOYMENT AND FAULT-WARNING STRATEGY

A. INSTALLATION AND FIELD RETROFIT

For a new transformer, an independent pressure-tapping chamber should be placed near the valve inlet, with a short channel that does not trap gas. The sensing diaphragm and the main valve then experience pressure in parallel. The sensing head may be removable, provided an isolation arrangement preserves tank sealing during removal. Existing equipment should use an original test port or a manufacturer-approved connection; drilling the valve body or tank without authorization is prohibited. Retrofit review must confirm valve model, actuation pressure, interface dimensions, oil-level relationship, discharge direction, and service clearance and must be approved by the manufacturer or responsible equipment authority.

The mounting orientation should prevent long-term gas trapping, sediment blockage, and direct discharge impact on the fiber feedthrough. The cable route from valve to cabinet requires mechanical protection, clear identification, service slack, and no tight coils. Connectors should be placed in dry, low-vibration locations; unavoidable outdoor joints need waterproof, dustproof, and anti-condensation protection. Zero should be recorded both before energization and after stable operation. Their difference indicates assembly stress and initial oil-pressure conditions.

B. GRADED WARNING AND MULTISOURCE INFORMATION FUSION

Warning has four levels: advisory, attention, warning, and actuation. Advisory denotes a slight abnormality in zero, optical power, or compensation residual and does not directly indicate a transformer fault. Attention denotes pressure above its long-term baseline or a persistent slow rise and requires checking load, top-oil temperature, and the breathing system. Warning denotes pressure approaching the valve setting, a pronounced rate increase, or simultaneous abnormalities in several sources and requires closer inspection and response preparation. Actuation confirms valve opening or an emergency pressure level, latches the waveform, and enters the established incident procedure.

Multisource fusion should not be a simple majority vote. A slow pressure increase that follows top-oil temperature and load can be assigned lower abnormal confidence. Pressure that continues to rise while temperature and load remain stable, or that precedes gas, partial-discharge, or dissolved-gas abnormalities, deserves greater attention. A contact indication without pressure entering the setting region may imply a contact defect, external mechanical trigger, or pressure-channel fault. A characteristic pressure peak and drop without contact operation calls for inspection of the contact circuit and valve mechanism. As Ma et al. emphasized, optical sensing creates value when integrated with the existing transformer diagnostic system rather than isolated as a separate data channel [4].

C. CALIBRATION, MAINTENANCE, AND DATA GOVERNANCE

Data are divided into raw, calculated, and event layers. The raw layer stores wavelengths and spectrum quality; the calculated layer stores temperature, pressure, rate, and baseline; and the event layer stores warnings, confirmation comments, response, and equipment defects. Every calibration or algorithm revision retains its effective time, and historical data are never silently overwritten with new parameters. Professionally reviewed event samples may refine rate and duration thresholds. Unconfirmed automatic alarms must not be treated directly as fault labels, because that would reinforce the algorithm's own errors.

D. RELIABILITY DESIGN AND IMPLEMENTATION PATH

The governing principle is that a monitoring failure cannot impair primary-equipment safety. A ruptured sensing diaphragm, broken fiber, de-energized interrogator, or communication loss must leave the original mechanical valve behavior unchanged. The monitor reports a channel fault but never blocks main protection or the relief mechanism. A reference reflector or spare fiber can supervise optical-path integrity, and key devices should provide local buffering and retention through a power interruption. When several valves share one interrogator, optical segmentation or standby channels should limit the consequence of a single failure.

Implementation proceeds through prototype, laboratory linkage, demonstration service, and scaled deployment. Prototype work verifies diaphragm strength, sensitivity, and temperature compensation. Laboratory linkage uses an actual valve model under controlled pressure and compares the reference pressure, FBG measurement, operation contact, and disc displacement. Demonstration service selects equipment with accessible maintenance and clear history and focuses on seasonal temperature, load cycles, and long-term drift. Only then should multipoint multiplexing, data interfaces, maintenance workload, and spares be standardized. Research on arc-resistant tanks by Brodeur et al. shows the strong dependence of pressure safety on structure and operating condition [9]; results from one demonstration cannot be copied to every valve without adaptation.

The technology has three main limitations. First, local valve-port pressure cannot represent the complete spatial pressure-wave field and cannot locate a fault. Second, compensation removes only common thermal effects described by the model; severe gradients, package damage, and plastic deformation still create residual error. Third, without long-term field samples, graded thresholds must be based on manufacturer information and laboratory testing, and no excessive promise can be made about warning lead time. The appropriate engineering role is to supplement discrete operation indication with continuous pressure records and provide reliable additional evidence for condition-based maintenance and event analysis.

VII. CONCLUSION

This paper addresses the absence of pre-actuation pressure visibility and continuous event records for pressure relief valves on oil-immersed transformers and on-load tap changers. It develops a real-time framework integrating a diaphragm-sensitized dual-FBG sensing head, wavelength-division demodulation, edge compensation, and graded warning. The pressure-sensitive FBG converts diaphragm motion into wavelength shift, while a colocated reference grating supplies temperature information for dual-wavelength pressure-temperature decoupling. A joint rule based on absolute pressure, rate, duration, spectral quality, and the valve contact distinguishes normal thermal variation, abnormal slow rise, near actuation, valve opening, and transient interference. Numerical analysis under explicit assumptions gives a modeled sensitivity of 18.0 pm/kPa over 0-100 kPa, a maximum static fitting deviation of 4 pm, a compensated equivalent pressure residual no greater than 0.7 kPa from -20 to 100 degrees C, and a 45 ms recognition time for the simulated valve event. These are model and algorithm results, not prototype measurements. Future work must test actual valve models under pressure cycling, temperature gradients, oil immersion, sealing, linkage operation, and long-term drift, with traceable calibration and assurance that monitoring failure cannot affect the original valve function as prerequisites for field deployment.

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