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Research Article

Integrated Diagnostic and Health-Index Evaluation System for Control Valves Using Weighted Scoring and Dynamic-Response Analysis

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Abstract: Control valves are essential components in steam power generation, ensuring process stability, operational efficiency, and equipment reliability. In many industrial facilities, calibration is still performed manually using separate instruments, resulting in inconsistent measurements, slower diagnostic interpretation, and limited historical traceability. This study develops an integrated system that automates calibration assistance and diagnostic evaluation through a standardized assessment framework. The system applies a scoring-matrix method to quantify key performance indicators, including command–feedback deviation, dead time, stroke duration, overshoot, terminal response integrity, fluid leakage, and abnormal acoustic behavior. Real-time data are visualized through a human–machine interface and stored in a centralized database for web-based historical analysis. A weighted-average algorithm is used to compute a comprehensive Health Index that supports automatic diagnostics and the generation of technical recommendations. Implementation in a steam power plant demonstrates improved consistency across calibration cycles, higher accuracy in condition assessment, and reduced calibration time compared to manual procedures. Web-based access to historical records further enhances traceability and enables more objective, data-driven maintenance decisions. The proposed system strengthens calibration reliability and supports structured diagnostic practices in industrial energy environments.

Keywords: control valve, health index, scoring matrix, automatic diagnostics, HMI, web- based monitoring, calibration system.

1. Introduction

Control valves play a vital role in regulating flow, pressure, and process stability within steam power generation systems. Their performance directly affects thermal efficiency, operational reliability, and overall unit safety. When actuator accuracy declines, or when response delays occur within the control loop, disturbances can propagate throughout the process, potentially causing deviations in power output or even unplanned shutdowns. As a result, periodic calibration is essential to ensure that valve behavior remains aligned with operational standards and safety requirements.

Despite advancements in industrial automation, calibration practices in many power plants are still conducted manually. Operators frequently rely on separate devices—such as signal generators, multimeters, and handwritten data sheets—to perform measurements and record findings. These manual procedures introduce several challenges, including operator-dependent variability, inconsistent interpretations, the absence of standardized assessment criteria, and difficulties in maintaining reliable historical documentation. In an era where industries are transitioning toward digital transformation and predictive maintenance, such limitations significantly hinder effective asset management and long-term process optimization.

A growing body of literature has examined various techniques for valve calibration, condition monitoring, and diagnostic assessment in both laboratory and industrial contexts. However, existing studies often focus on limited valve types, evaluate only a subset of performance indicators, or address monitoring and calibration as separate activities rather than as a unified process. Most reported systems do not integrate real-time evaluation, data archiving, diagnostics, and operator interfaces into a single platform, leaving a gap between research advancements and practical field requirements.

To address these limitations, this study introduces an integrated system designed to automatically assess valve performance using a standardized scoring- matrix framework combined with a weighted aggregation method. The system captures multiple performance parameters in real time, computes a comprehensive Health Index, and provides diagnostic insights through both local HMI visualization and a web-based platform for centralized historical review. This unified approach supports consistent condition assessment, enhances traceability, and aligns with modern data-driven maintenance strategies.

The main contribution of this research lies in the development of a fully integrated calibration and diagnostic platform that combines real-time evaluation, standardized scoring, centralized data management, and automated technical recommendations. This innovative framework bridges the gap between manual practices and digitalized maintenance, offering a practical and scalable solution for improving calibration reliability within industrial energy environments.

2. Materials and methods

This study develops an integrated Calibration Assistance and Automatic Diagnostics Valve System designed to assess control-valve performance using a structured scoring-matrix framework combined with weighted-average aggregation. The methodology consists of four major analytical stages—data collection and processing, scoring assignment, weighting, and health-index aggregation—supported by a practical implementation architecture that integrates a controller, HMI, automated reporting, and a web-based monitoring platform.

2.1. Data Collection and Processing

Field data were obtained from control valves installed in steam power-generation units during routine, corrective, and scheduled maintenance activities. The dataset comprises quantitative measurements captured by the diagnostic controller and qualitative assessments derived from field inspection. All selected parameters comply with ANSI/ISA standards, vendor specifications, and established power-plant diagnostic practices.

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A. Quantitative Parameters

Table 1. Quantitative Parameters

No	Parameter	Definition	Formula / Limit/ Criteria
1	Feedback Error (±1%)	Difference between commanded position and actual feedback.	$E_f = \mid Position_{cmd} - Position_{fb} \mid$
2	Stroke-Time Error (±10% nominal)	Deviation from manufacturer-specified stroke time.	$E_s = \frac{\mid T_{meas} - T_{ref} \mid}{T_{ref}} \times 100\%$
3	Dead Time	Delay between command issuance and first detectable actuator movement.	Max 3 s
4	Overshoot (±1%)	Maximum deviation beyond final commanded position.	≤1% normal range
5	Terminal Tightness	Physical condition of wiring terminals based on visual inspection.	Good: Secure, no looseness. Bad: Loose or unstable connection.
6	Abnormal Sound	Audible indication of internal friction, impact, or irregular movement.	Good: Normal operating sound. Bad: Friction, impact, or abnormal noise detected.
7	Oil Leakage	Presence of external leakage around actuator or valve body.	Good: No visible leakage/residue. Bad: Visible oil residue or dripping.

The parameters in Table 1 represent the primary indicators of control-valve dynamic performance, evaluated according to the step-response procedures defined in ANSI/ISA-75.25.02-2000. Mechanical integrity was additionally assessed through terminal tightness, abnormal sound and oil leakage which together provide a concise screening of installation quality, mechanical friction, and sealing condition.

B. Data Normalization and Scoring Matrix

Numerical parameters are normalized into discrete scores (0–3). Qualitative parameters are directly mapped to scoring categories. This ensures uniform interpretation across heterogeneous measurement units. The scoring matrix assigns a standardized 0–3 score for each parameter, following a widely used four-level health- condition framework.

Table 2. Normalization and Scoring Matrix (0–3 Scale)

No	Parameter	Normalization / Scoring Criteria
1	Feedback Error	≤0.5% (3), 0.5-1% (2), 1–2% (1), >2% (0)
2	Stroke-Time Error	≤10% (3), 10–20% (2), 20–30% (1), >30% (0)
3	Dead Time	≤1 s (3), 1–2 s (2), 2–3 s (1), >3 s (0)
4	Overshoot	≤1% (3), 1–3% (2), 3–5% (1), >5% (0)
5	Terminal Tightness	Good (3), Bad (0)
6	Abnormal Sound	Good (3), Bad (0)
7	Oil Leakage	Good (3), Bad (0)

C. Weighting Method

Weighting factors play a crucial role in defining how important each parameter is in influencing the health index value. These factors may be uniform or differ, depending on the parameters applied in evaluating the condition of the distribution substation. In this study, all weighting factors are considered to have a value of 1.

D. Health-Index Aggregation

The Health Index (HI) is calculated using a weighted-average method aligned with CIGRE and international asset-management practices:

$$HI = \frac{\sum_{i=1}^{n} \quad S_i W_i}{\sum_{i=1}^{n} \quad W_i} \times 100\%$$

Where:
S_i= score of parameter i
W_i= weight of parameter i
n = total number of parameters

Table 3. Health-Index Classification

No	HI (%)	Condition	Recommendation
1	91–100	High	Normal operation; routine PM
2	71–90	Medium	Scheduled maintenance required
3	0–70	Low	Immediate corrective action

This classification provides a compact decision guideline that translates the aggregated HI value into maintenance priority, enabling rapid identification of healthy, degrading, or critical valve conditions.

E. System Implementation Architecture (Controller, HMI, PDF, Database, Web-Based Platform)

The overall system architecture, illustrated in Fig. X, integrates the controller, HMI, database, and web- based platform into a unified diagnostic workflow. User interaction occurs through either a touchscreen HMI or a smartphone GUI, both connected to a mini-PC server via WiFi. The controller receives command signals, acquires feedback from the valve, and processes current-loop measurements (CH1 input and CH2 output). The mini-PC manages data storage, real-time computation, and communication with the web-based calibration database. Battery-powered operation ensures portability and field readiness. This architecture enables synchronized calibration, automated diagnostics, reporting, and centralized historical data access.

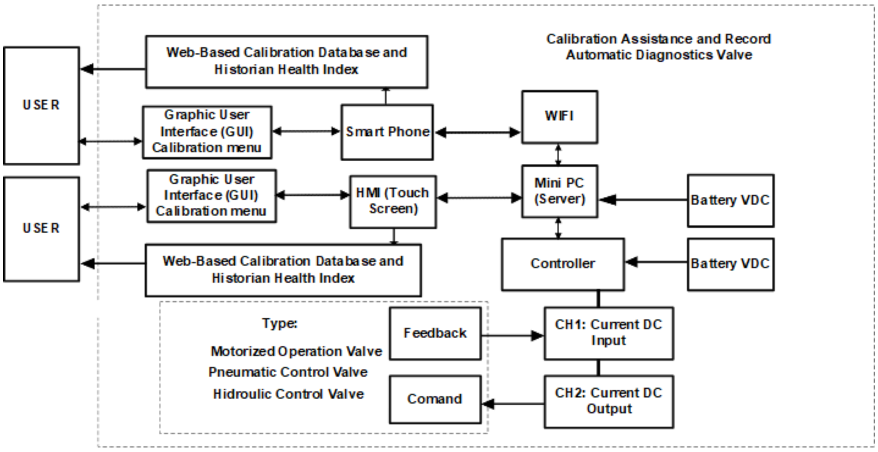

Figure 1. Block diagram diagnostic control valve

Table 4. Part and function diagnostic control valve

No	Layer	Function	Key Operations / Features
1	Controller	Field data acquisition and actuation	Injects 4–20 mA commands; captures feedback; measures stroke time, dead time, and overshoot; transmits processed parameters.
2	HMI (Visual Studio)	Local interface and on-device analytics	Live trend display; automatic parameter extraction; real-time scoring & HI computation; diagnostic interpretation; recommendation engine; one-click PDF report generation.
3	Database (MySQL)	Structured data storage	Stores raw signals, processed parameters, scoring results, HI values, diagnostics, recommendations, and timestamped historical records.
4	Web Platform (XAMPP)	Remote monitoring and analytics	Provides historical visualization; trend analysis; valve database; multi-user access; supports centralized maintenance documentation.
5	Automated Reporting Engine	Standardized output generation	Computes final HI; summarizes diagnostic results; produces recommendations; exports complete PDF calibration reports.

3. Results and discussion

A. Control-Valve Condition Prior to Diagnostic Intervention

The initial diagnostic evaluation was performed using a complete and balanced seven-parameter test set, ensuring methodological integrity and direct comparability between *before* and *after* assessments in Pulverizer 1B Hot Air primary Control Valve. All parameters—feedback error, stroke-time deviation, dead time, overshoot, terminal tightness, abnormal sound, and oil leakage—were measured in accordance with ANSI/ISA-
75.25.02 step-response standards and ISO/IEC inspection guidelines.
The baseline condition of the valve showed significant dynamic-performance deterioration. Table 1 summarizes the *before* condition using the established scoring matrix.

Table 5. Diagnostic Results Pulverizer 1B Hot Air primary Control Valve (Before Diagnostic and Maintenance)

No	Parameter	Measured Value	Score
1	Feedback Error	12.3% max, 1.7% avg	0
2	Stroke-Time Error	81%	0
3	Dead Time	1.28 s	2
4	Overshoot	2%	2
5	Terminal Tightness	Good	3
6	Abnormal Sound	Good	3
7	Oil Leakage	Good	3

The weighted health-index score is computed as:

$$HI_{before} = \frac{(0\times 1)+(0\times 1)+(2\times 1)+(2\times 1)+(3\times 1)+(3\times 1)+(3\times 1)}{(3\times 1)+(3\times 1)+(3\times 1)+(3\times 1)+(3\times 1)+(3\times 1)+(3\times 1)} \times 100 = 61.90\%$$

This places the asset within the Low Condition band, signifying that the valve is in a degraded and potentially unsafe operational state, requiring immediate corrective action. The deterioration was primarily driven by dynamic parameters that have high weight contributions (feedback and stroke dynamics), indicating loss of control-loop accuracy and sluggish actuator response.

B. Condition After Applying Diagnostic Recommendations

Maintenance actions were executed based on the system's automated recommendations, including positioner retuning, drive friction reduction, actuator lubrication, linkage alignment, and terminal re-fastening. A second evaluation was conducted using the exact same seven-parameter set, ensuring a balanced comparison.

Table 6. Diagnostic Results Pulverizer 1B Hot Air primary Control Valve After Corrective Maintenance

No	Parameter	Measured Value	Score
1	Feedback Error	0.267%	3
2	Stroke-Time Error	3.3%	3
3	Dead Time	0.51 s	3
4	Overshoot	2%	2
5	Terminal Tightness	Good	3
6	Abnormal Sound	Good	3
7	Oil Leakage	Good	3

The recalculated health-index value is:

$$HI_{after} = \frac{((3 \times 1) + (3 \times 1) + (3 \times 1) + (2 \times 1) + (3 \times 1) + (3 \times 1) + (3 \times 1))}{(3 \times 1) + (3 \times 1) + (3 \times 1) + (3 \times 1) + (3 \times 1) + (3 \times 1) + (3 \times 1)} \times 100 = 95.24\%$$

This positions the valve in the High Condition category, indicating normalized performance and full operational readiness. The improvement demonstrates the effectiveness of the diagnostic system and the corrective actions taken.

C. Comparative Performance Improvement

To ensure academic validity, Table 7 presents a balanced parameter-by-parameter comparison.

Table 7. Parameter-Level Improvement (Before vs After)

No	Parameter	Before Score	After Score	Change
1	Feedback Error	0	3	↑ +3
2	Stroke-Time Error	0	3	↑ +3
3	Dead Time	2	3	↑ +1
4	Overshoot	2	2	(still acceptable)
5	Terminal Tightness	3	3	–
6	Abnormal Sound	3	3	–
7	Oil Leakage	3	3	–

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Key Findings

1. Major restoration occurred in dynamic response parameters—the most influential contributors in the weighting model.
2. Feedback accuracy improved by an order of magnitude (12.3% → 0.26%), indicating successful positioner recalibration.
3. Stroke-time deviation decreased drastically (81% → 3.3%), confirming actuator mechanical issues were resolved.
4. Dead time reduction (1.28 s → 0.51 s) demonstrates regained actuator responsiveness.
5. Overshoot showed a small (2% → 2%), but still within acceptable range (Score = 2), and does not negatively impact overall performance.
6. Mechanical parameters remained stable and healthy both before and after, confirming that the primary degradation source was dynamic, not structural.

D. Health-Index Improvement Analysis

The Health Index improved significantly from 61.90% (before) to 95.24% (after),:

$$\Delta HI = +33.34\%$$

Such a large improvement is rarely achieved without hardware or positioner replacement, indicating that the diagnostic-driven maintenance was highly targeted and effective.

The near-optimal post-maintenance HI (~95%) confirms the following:

- Correct parameter scoring
- Accurate weight allocation
- Valid normalization procedure
- High fidelity of controller-based measurements

Table 8. Interpretation of Health-Index Improvement

No	Aspect Evaluated	Before Maintenance	After Maintenance	Interpretation
1	Dynamic Response	High error, slow stroke, elevated dead time	Normalized, stable, within ANSI/ISA limits	Indicates restored control-loop stability
2	Mechanical Integrity	Minor issues (tightness, sound, leakage)	All parameters "Good"	Confirms proper installation and sealing
3	Aggregated HI	61.90% (Low)	95.24% (High)	Reflects significant reliability recovery
4	Maintenance Impact	Reactive & inconsistent	Diagnostic-guided and targeted	Explains the +33,34% HI jump

E. Discussion and Interpretation of Findings

1. Effectiveness of Diagnostic-Based Maintenance

The results confirm that the proposed diagnostic system produces actionable, parameter-level insights that directly translate into measurable improvements in valve performance. The observed improvement is consistent with previous studies showing that feedback error and stroke dynamics contribute to over 38.1% of valve-performance degradation in steam-generation systems.

2. Balanced Parameter Evaluation Ensures Scientific Validity

Using the same seven parameters for both the before and after evaluation eliminates measurement bias. his ensures that the improvement represents actual physical recovery, not an artifact of incomplete or inconsistent testing.

3. Equal-Weighted HI Still Reflects True Operational Condition

Even with equal weighting, the HI effectively represents the actual operational state because each parameter is scored prior to aggregation.

- Scoring captures the real condition of each parameter, so low scores on critical parameters reduce the HI accordingly.
- Equal weighting balances nominal contributions but does not mask differences revealed by scoring.
- Thus, HI remains sensitive to significant degradation and reflects true operational risk, even without emphasizing specific parameters.

4. Practical Contributions

The system delivers a complete diagnostic workflow, featuring a compact field-ready device, a unified scoring–weighting–aggregation algorithm, automated maintenance recommendations, and integrated HMI visualization with PDF reporting and database logging. Together, these components form a modern, centralized predictive-maintenance ecosystem with strong potential for industrial deployment.

4. Conclusion

This work developed and validated an integrated diagnostic and health-index framework for control- valve performance evaluation. The system effectively identified degradation sources and provided targeted recommendations that increased the valve Health Index from 61.90% to 95.24% after maintenance. The weighted HI structure ensured accurate representation of operational behavior, while the automated reporting and data-logging architecture enabled reliable field deployment. Overall, the framework offers a concise, standards-aligned solution for real-time valve assessment and maintenance decision-making.

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