Validation of Pressure Transmitter Input/Output Loop Testing Based on Hybrid Analog and Digital HART Communication

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***Abstract*— The use of the 4–20 mA analog signal remains a foundational standard in industrial measurement and control systems, despite the continuous advancement of digital communication technologies. This study implements a hybrid validation approach that integrates the conventional 4–20 mA analog signal with HART (Highway Addressable Remote Transducer) digital communication for conducting Input/Output (I/O) loop testing on pressure transmitters. The primary objective is to ensure the accuracy and reliability of signal transmission from field instruments to control systems such as Programmable Logic Controllers (PLCs) or Flow Computers. Utilizing a HART modem and FieldMate software, analog signals are injected and digitally monitored to verify transmitter output against predefined tolerance standards. Test results indicate that all evaluated transmitters maintained an error level below the 0.25% threshold, in compliance with standards set by the Directorate of Metrology and ASTM/API guidelines. The integration of HART communication significantly enhances testing efficiency, diagnostic capability, and remote configuration flexibility, underscoring the critical role of hybrid validation approaches in modern industrial instrumentation systems.**

Keywords*— *Pressure transmitter, I/O loop testing, analog signal, HART communication, hybrid validation, error analysis

I. Introduction

Modern industrial instrumentation systems rely heavily on accurate and reliable signal transmission to ensure operational efficiency, safety, and product quality [1]. Instruments such as sensors, transmitters, and actuators function to collect, transmit, and control process data in real time.

As technology evolves, digital communication protocols such as Fieldbus, Profibus, and Ethernet/IP are increasingly adopted [2]. However, the 4–20 mA analog signal remains a preferred standard due to its robustness against electromagnetic interference, ease of installation, low cost, and broad compatibility with a wide range of control systems.

To address the growing need for complex data integration, the Highway Addressable Remote Transducer (HART) protocol was developed. HART enables the transmission of digital data over existing analog signal lines without disrupting the core function of the analog signal itself [3], [4]. With this technology, field devices can not only transmit measured values but also provide diagnostic information, device status, and remote configuration parameters. In practical applications, HART-based systems significantly streamline commissioning, maintenance, and troubleshooting processes in industrial installations. Operators are able to monitor device conditions online, perform remote resets, or read internal parameters without interrupting ongoing operations.

This technology has been widely implemented across various industrial sectors. In the oil and gas industry, HART-enabled pressure transmitters are employed to monitor pressure in pipeline networks while simultaneously tracking equipment condition in real time from control centers—enhancing measurement accuracy and reducing operational failure risks. In the chemical industry, temperature and pressure transmitters with HART communication provide additional sensor condition data, such as fault detection or recalibration alerts—critical for maintaining process stability. Similarly, in the energy sector, particularly in power plants, HART-based transmitters are used in boiler monitoring systems to improve temperature and pressure measurement accuracy and reduce potential downtime due to equipment failures.

Despite these advantages, both 4–20 mA analog signals and HART communication have inherent limitations. Analog signals can only transmit a single variable per line, requiring dedicated wiring for each parameter, and are incapable of carrying complex data structures. Meanwhile, HART communication is constrained by relatively low data transfer speeds, dependency on additional devices such as HART modems, and limited compatibility with fully digital systems.

To bridge these limitations, technologies such as WirelessHART and HART-IP have emerged. WirelessHART is an extension of the traditional HART protocol that facilitates wireless data transmission through mesh networks, reducing the need for physical cabling and increasing system flexibility in hard-to-access environments [4], [5]. HART-IP, on the other hand, allows HART data to be transported over standard Ethernet networks, paving the way for integrating instrumentation systems into the Internet of Things (IoT) ecosystem [6]–[11]. While the early concept of IoT focused on universal internet-based device connectivity [12], the industrial adaptation of this paradigm has evolved into the Industrial Internet of Things (IIoT). IIoT emphasizes the application of IoT technologies in manufacturing and process industries to enhance operational efficiency, process control accuracy, and predictive

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ISSN 0216-8685 (print); 2528-6889 (online)

maintenance capabilities through big data analytics and artificial intelligence [8], [13]–[18].

With the advent of WirelessHART, HART-IP, and the broader shift toward IIoT, industry faces new opportunities for accelerating the digitalization of control systems. However, investment costs, high reliability requirements, and the persistence of analog-based infrastructures lead many sectors to retain conventional systems. In this context, a hybrid approach—combining the 4–20 mA analog signal with digital communication via HART—emerges as a strategic solution. This approach enables the transmission of core process variables, such as pressure or temperature, via the analog channel to ensure signal reliability, interference resistance, and legacy system compatibility. Concurrently, additional data such as diagnostic information, device configuration, and health status are delivered through the HART digital channel [19]. This hybrid model thus blends the stability and simplicity of analog transmission with the rich, flexible capabilities of digital communication. It allows for a gradual transition to data-driven automation without the need to replace entire existing infrastructures—ensuring operational continuity while enhancing efficiency through enriched data flow.

In alignment with these conditions, the purpose of this study is to validate the implementation of an analog-digital hybrid approach in I/O loop testing of pressure transmitters, and to analyze the accuracy of signal transmission and the effectiveness of HART communication in supporting the modernization of industrial instrumentation systems.

II. Methods

This study was conducted on pressure transmitters installed within an industrial metering system. An experimental approach was employed by performing direct I/O loop testing on the field devices.

The testing procedure began with the development of a system architecture diagram and a detailed I/O loop diagram. The system architecture diagram provides a general overview of the hardware and software interconnections within the instrumentation network. It illustrates the physical location of the pressure transmitters, the analog signal communication paths, and their integration with control systems such as Programmable Logic Controllers (PLCs) or Flow Computers.

Subsequently, a detailed I/O loop diagram was created, representing the input and output connections from the transmitters to the control system. This diagram includes information such as terminal wiring, device tag numbers, expected signal ranges, and critical measurement points. Its primary purpose is to verify that all connections between devices conform to the system design and to ensure that both analog and digital signal transmission paths are clearly identified.

Following the diagram development, physical verification was carried out through direct inspection of terminal blocks, signal cables, and the transmitter devices. Each cable connection was checked for correctness based on terminal numbers and the I/O loop diagram. A continuity tester was used to ensure there were no breaks or miswiring in the cables. Additionally, signal line resistance was measured to detect any abnormal resistance that could affect signal transmission integrity.

In the next phase, FieldMate software was installed on a laptop and connected to a HART modem, which was then linked to the 4–20 mA signal loop. Using the auto-scan feature in FieldMate, the system detected connected field devices. Successful detection of the transmitters served as an initial indicator of correct wiring.

Once the system setup was confirmed, the I/O loop test procedure was executed by injecting a 4–20 mA analog signal from FieldMate into the transmitter, and then monitoring the output using a multifunction calibrator (CA71). Additionally, digital data communicated over the HART channel were read to verify device status, configuration parameters, and internal diagnostics.

Error calculation was performed using the following formula:

$$Error(\%) = \left(\frac{|a-b|}{c}\right)x100 \quad (1)$$

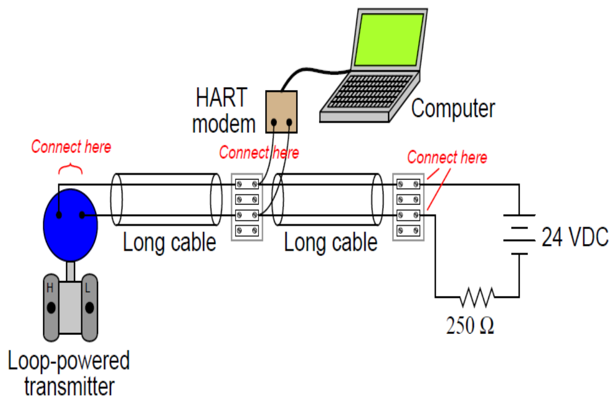
Where a represents the actual measured value, b is the reference value, and c is the defined measurement range. The test was considered valid if the calculated error did not exceed the tolerance threshold of 0.25%, in accordance with technical guidelines adopted from regulations set by the Directorate of Metrology of Indonesia regarding measurement system accuracy.

III. Results and Discussion

A. Results

The I/O loop testing procedure was carried out on pressure transmitters installed in an industrial metering system. The purpose of this testing was twofold: to verify the accuracy of the transmitted 4–20 mA analog signal to the flow computer and to assess the reliability of HART communication.

The initial preparation involved the development of a System Architecture Diagram and an I/O Loop Diagram to provide both physical and logical insights into device connectivity. Fig. 1. presents the system architecture used in this study, illustrating the connections between the transmitter, terminal block, HART modem, FieldMate laptop, and the flow computer. This diagram guided the operators in validating the correctness of both signal and communication paths before commencing the tests.



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ISSN 0216-8685 (print); 2528-6889 (online)

Fig. 1. System architecture diagram of the transmitter testing setup.

Subsequently, Fig. 2. depicts a more detailed I/O loop diagram, representing the current flow path (4–20 mA) from the transmitter to the control system. This diagram was utilized in the field to verify actual wiring, confirm terminal connections, and detect any errors in signal cable installation.

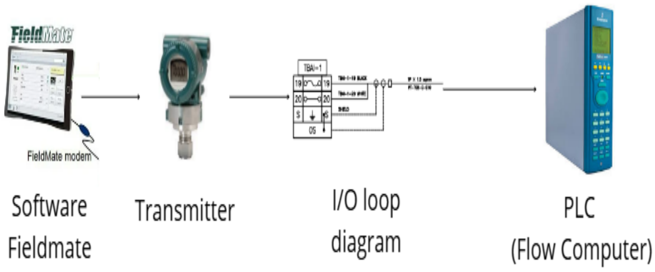

Fig. 2. Transmitter wiring I/O loop diagram.

Once the diagrams were verified, the testing proceeded in the field. Fig. 3. shows the FieldMate software interface on a laptop, used to inject analog signals into the transmitter. The software interface allowed the operator to set the desired current value and monitor the transmitter's real-time response.

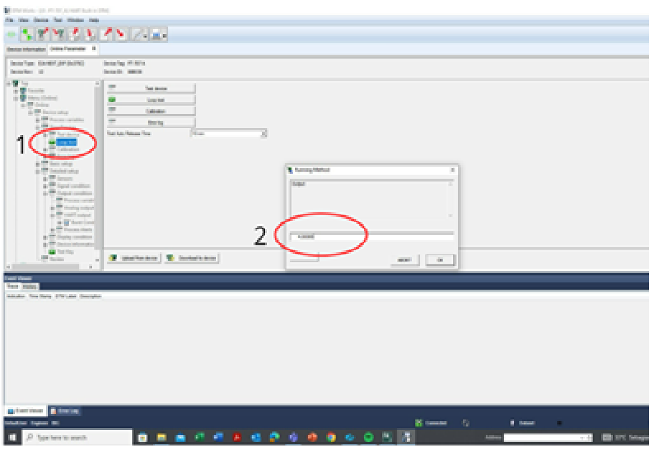

Fig. 3. FieldMate interface for 4–20 mA current injection.

In parallel, the actual output of the transmitter was read using a multifunction calibrator CA71, as shown in Fig. 4. This device captured the analog output signal generated by the transmitter in response to the injected current.

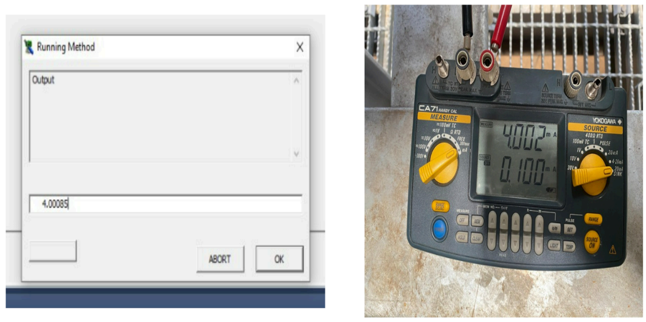

Fig. 4. Output signal reading using CA71 calibrator.

The loop test was conducted by injecting discrete current values of 4 mA, 8 mA, 12 mA, 16 mA, and 20 mA through FieldMate. These points were selected based on the principles of **linearity testing** and **span verification**. The 4 mA value represents the zero or minimum operating point, while 20 mA represents the maximum or full-scale span. Intermediate points—8 mA, 12 mA, and 16 mA—were included to evaluate the transmitter's performance across the entire operating range. This five-point verification method aligns with standard calibration practices and ensures both linear and nonlinear deviations are detected across the span.

The 4–20 mA range was used as it is the universal standard for analog signal transmission in industrial control systems—where 4 mA typically denotes zero process level and 20 mA indicates full-scale process value.

The test data are summarized in Table 1, which includes three key variables: the injected current value, the actual measured value, and the calculated percentage error.

- Injected Current refers to the deliberate analog input supplied via FieldMate to simulate varying process conditions (e.g., from low to full-scale pressure).
- Measured Value is the actual analog output recorded by the calibrator.
- Error (%) quantifies the deviation between the injected and measured values, calculated based on the total signal span.

Table 1. Error analysis from defined current injection points

Injected Current (mA)	Measured Value (mA)	Error (%)
4.00	4.01	0.18
8.00	8.02	0.25
12.00	12.01	0.08
16.00	16.02	0.13
20.00	20.03	0.15

The objective of presenting this data is to quantitatively evaluate the transmitter's performance. If the error for each tested point remains below the tolerance threshold of 0.25%, the transmitter is deemed operationally reliable. This tolerance follows the standards outlined in API MPMS Chapter 21.1 and ASTM D1250—both widely adopted in custody transfer and petroleum measurement applications. In Indonesia, the Directorate of Metrology has adopted these

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ISSN 0216-8685 (print); 2528-6889 (online)

thresholds in practice, even though the latest national regulations do not explicitly state a fixed numerical limit.

- API MPMS Chapter 21.1 (American Petroleum Institute Manual of Petroleum Measurement Standards) defines accuracy limits for electronic gas measurement systems.
- ASTM D1250 (American Society for Testing and Materials) provides guidance on petroleum measurement tables and accuracy tolerances for liquid hydrocarbon transfers.

If all measured errors fall within the specified tolerance, the transmitter is considered compliant. Any deviation beyond this range would necessitate corrective actions such as recalibration, wiring inspection, or systematic error analysis.

The results presented in Table 1 provide strong evidence of the transmitter's consistent and accurate performance throughout the 4–20 mA operational range. The transmitter demonstrated linear and stable responsiveness to signal variations, indicating high measurement reliability—critical for precision-sensitive applications such as custody transfer, fluid flow monitoring, and advanced process control systems.

The practical benefits of this verification include enhanced process data integrity, increased operator confidence in decision-making, and reduced economic risks due to measurement errors. Furthermore, the documented results serve as a calibration record for audits, certifications, or regulatory compliance. These results can also be used in predictive maintenance programs, where error trends are tracked over time to anticipate performance degradation and preempt failures.

In summary, the testing results not only validate the technical accuracy of the transmitter but also reinforce the overall reliability of the instrumentation system in supporting safe, efficient, and regulation-compliant industrial operations.

Based on the test results presented in Table 1, all output readings from the pressure transmitter demonstrated consistent error values below the maximum tolerance threshold of 0.25%, as stipulated in API MPMS Chapter 21.1 and ASTM D1250. This outcome confirms that the transmitter successfully maintains both linearity and accuracy across the full 4–20 mA operating range, in accordance with the Five Point Verification principle commonly adopted in industrial calibration procedures.

The implementation of the hybrid validation approach in this study showcases an effective synergy between analog and digital communication channels. The 4–20 mA analog channel serves to transmit the primary process pressure values, while the HART digital channel provides access to internal parameters and diagnostic status of the transmitter. This integration ensures that not only are the process values verified for accuracy, but the overall health of the device is also continuously monitored.

The reliability of this transmission system is particularly crucial in high-stakes industrial applications such as custody transfer in oil and gas, where measurement precision directly impacts the validity of large-scale financial transactions. Even minor errors in wiring, transmitter configuration, or calibration can lead to significant cumulative deviations with economic implications. As such, a systematic I/O loop testing process, as conducted in this study, functions not only as a technical validation, but also as a compliance assurance mechanism and risk mitigation strategy.

Moreover, the test results underscore the operational advantages of the FieldMate software (as illustrated in Fig. 3). With its intuitive interface and auto-scan capabilities, FieldMate accelerates field device detection, simplifies signal injection, and enables simultaneous parameter configuration and diagnostic reading. Correct FieldMate setup played a pivotal role in this testing procedure, ensuring that current injection and process variable monitoring were precisely aligned with the transmitter's configuration. The initial configuration screen, including engineering units, minimum and maximum ranges, and loop status—as depicted in Fig. 5.—illustrates the foundational steps taken prior to signal injection.

Additionally, the use of the CA71 multifunction calibrator (Fig. 4) as an independent verification tool further validates the reliability of the test results. This device allows manual reading of the transmitter's analog output, independent of the FieldMate system, providing an important safeguard against potential software-based measurement biases or system errors during signal verification.

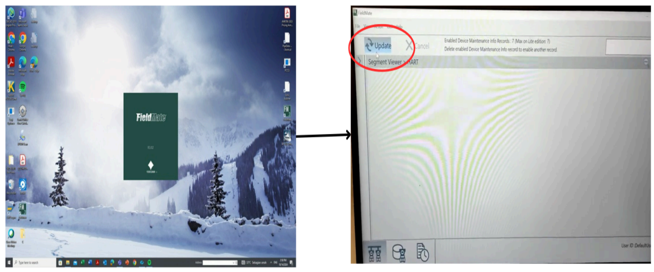

Fig. 5. Initial transmitter setup in FieldMate

A crucial component of this validation process also involved wiring inspection using a **continuity test**, as shown in Fig. 6. This verification step ensures that no installation errors—such as loose connections, excessive signal line resistance, or reversed polarity—compromise signal accuracy. The system's wiring layout, presented in Fig. 2, was cross-referenced with actual field installations to prevent misalignment that could distort measurement results.

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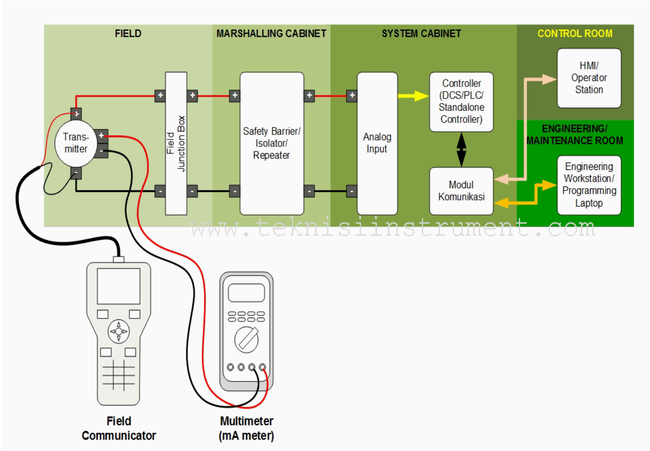

Fig. 6. Continuity test for cable connection

By meticulously developing an accurate wiring diagram, performing correct FieldMate configurations, and verifying the injection and output readings through an independent calibrator, the entire validation process was executed with systematic and layered precision. These procedures affirm that the analog-digital hybrid approach not only enhances the accuracy and efficiency of transmitter validation but also positions the system for seamless integration into the Industrial Internet of Things (IIoT). In the IIoT paradigm, device monitoring, control, and diagnostics are unified within a digital industrial network infrastructure—making hybrid readiness a vital stepping stone toward next-generation automation.

IV. Conclusion

Ensure The I/O loop testing of pressure transmitters using a hybrid approach that integrates 4–20 mA analog signaling and HART digital communication demonstrated that all tested transmitters maintained error levels below the 0.25% tolerance threshold, as stipulated in API MPMS Chapter 21.1 and ASTM D1250 standards. These findings confirm that the transmitters are capable of maintaining measurement accuracy and linearity across the full operating range, making them suitable for high-reliability industrial applications such as custody transfer systems in the oil and gas sector.

The hybrid approach applied in this validation exhibits clear advantages by combining the stability of analog signal transmission for primary process values with the flexibility of the HART digital channel for accessing device diagnostics and configuration parameters. This integration enriches system monitoring capabilities without compromising the integrity of the main signal path, and represents a key step toward supporting digital transformation under the Industrial Internet of Things (IIoT) paradigm.

The systematic testing procedure—comprising the development of the system architecture and I/O loop diagrams, wiring inspection through continuity testing, transmitter parameter setup via FieldMate, and output verification using an independent CA71 calibrator—ensured that all aspects of device installation and configuration were thoroughly validated. These results underscore that successful testing depends not only on the reliability of hardware components but also on the precision of technical procedures and the completeness of system documentation.

In conclusion, this study confirms that hybrid analog-digital loop validation is an effective method for enhancing the reliability of instrumentation systems, supporting predictive maintenance strategies, and accelerating the industrial transition toward integrated digital control systems.

Acknowledgment

The author would like to express sincere gratitude to PT Yokogawa Indonesia for providing the invaluable opportunity to participate in the industrial internship program. This experience has allowed the author to gain first-hand exposure to the latest technologies applied in the industrial sector, particularly in the fields of instrumentation and control systems. The support, guidance, and resources made available during the internship have greatly contributed to the successful completion of this study.

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ISSN 0216-8685 (print); 2528-6889 (online)