Advances in Valve Technologies and Drive Systems for Efficient Gas–Liquid Flow Regulation

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Abstract. In current chemical and bioengineering production processes, the transportation of gases and liquids is a critical component of the entire process. During the transmission process, the valve system used to regulate and control the flow rate and conductivity of gas-liquid mixtures serves as a vital control component. However, existing research has primarily focused on individual aspects of valves and their drive mechanisms, lacking a comprehensive comparison from both mechanical and automation perspectives. This gap has led to issues such as improper selection and poor performance in practical applications. To address this issue, this paper conducts a comprehensive analysis of mainstream valves and their integration with pneumatic, electric, and electro-hydraulic drive systems. Additionally, this paper focuses on the latest valve control methods, identifies their innovative aspects, and analyzes their advantages and disadvantages, providing new insights for industrial production with higher efficiency, offering practical guidance for making optimal choices in various industrial scenarios. This work not only aids in making more informed engineering decisions but also points the way toward the future development of smart fluids.

Keywords: Valve systems, Drive mechanisms, Flow control, Automation and performance optimization.

1. Introduction

The precise regulation of fluid flow is a fundamental requirement in chemical and bioengineering processes, ranging from large-scale continuous production to specialized batch operations. At the heart of these control systems lie valves, critical components whose performance dictates overall plant efficiency, product quality, and operational safety. The evolution of industrial automation has further elevated the role of valves from simple mechanical shut-off devices to integrated control elements, whose effectiveness is inherently tied to their actuation and control systems.

While significant research exists on the mechanical design of valves and the development of advanced actuators, a conspicuous gap remains in the literature regarding a systematic, integrated analysis of valve and actuator combinations. Existing studies often focus on isolated aspects, such as the sealing performance of a specific valve type or the dynamic response of a novel actuator without providing a cross-comparative framework from both mechanical and automation perspectives. This fragmented approach presents a practical challenge for engineers: the selection of an optimal valve and actuator system is often based on empirical knowledge or fragmented data, leading to issues like oversizing, under performance, inadequate response to control signals, and unnecessary energy consumption in complex industrial scenarios.

To bridge this gap, this paper provides a comprehensive evaluation of mainstream industrial valves, including gate, globe, ball, and butterfly valves, when integrated with three primary actuation technologies: pneumatic, electric, and electro-hydraulic systems (as shown in Table 1).

Furthermore, this work extends the analysis to emerging intelligent control methodologies, including IoT-enabled PID control, Programmable Logic Controller (PLC) based systems, and neural network enhanced algorithms. By critically examining the innovative aspects, advantages, and limitations of these approaches, this study offers new perspectives on achieving high precision, automated, and intelligent fluid control.

Table 1. Different valves comparing

Valve Type	Working Principle	Main Feature	Drawback
Gate valve	Gate valve is the valve driven by the disc and makes linear lifting movement along with the sealing face. In the process of opening or closing the gate, the disc moved in the vertical direction to that of the gas medium flow in the channe [1]	1. Fully open and fully close 2. Low flow resistance and low pressure loss. 3. Good sealing performance (metal hard seal or soft seal).	Long opening and closing time; Poor adjustment performance; Likely to cause water hammer; Large size and heavy weight
Ball Valve	A spherical body with a hole in the middle serves as the valve core, which can be rotated 90 degrees to open or close the fluid flow.	No openings where media can leak. Suitable for high-pressure applications. Direct control via electric (magnetic) field – fast response to demand [2]	Complex installation of the medium channel Unknown fixation of the rotating shaft without using a valve stem During use, a constant current is required to keep the ball in the proper position, which leads to permanent power consumption [2]
Butterfly Valve	rotating a valve stem to drive the butterfly disc, completing the opening and closing actions with a 90° rotation [3]	1. Simple structure, small size, and light weight. 2. Rapid opening and closing. 3.High cost performance in large diameter valves.	Relatively poor sealing (centerline type); not suitable for high pressure differential conditions; limited adjustment range.
Globe Valve	The valve disc moves up and down along the center line of the valve seat, regulating flow by changing the gap between the disc and the seat.	1. Excellent regulation characteristics. 2. Minimal wear on sealing surfaces.	High flow resistance; not suitable for particulate media; high opening and closing torque.

2. Types of Valves and Control Methods

2.1. Valve-controlled components

2.1.1 Classification of valves

There are many types of valves, and the mainstream types on the market include gate valves, globe valves, butterfly valves, ball valves, etc. The following table provides a brief description of their working principles and main features.

2.1.2 Valve controller

This paragraph will introduce three mainstream execution systems: electric execution systems, start-up execution systems, and electro-hydraulic execution systems.

First is Pneumatic Solenoid Valve. A pneumatic solenoid valve is an essential component used to control the direction, flow, or pressure of compressed air in automated machinery. It plays a critical role in converting electrical signals into mechanical movement, enabling seamless actuation of cylinders, grippers, and other pneumatic devices. The electrical current energizes the solenoid coil, which generates a magnetic field. This field then pulls or pushes a plunger to shift the valve's internal spool or poppet, changing the air pathway. This makes pneumatic solenoid valves highly responsive and suitable for rapid, repetitive cycles in industrial automation [4].

As shown in Fig. 1, the operation of the valve depends on its design (typically 2-position or 3-position) providing either a single stable state or a dual stable state. When the coil is activated, it moves the valve to allow air to enter the working port and release exhaust accordingly. When the coil is de-energized, the reset spring or a second coil returns the valve to its original state. This allows for precise timing and directional control, particularly in synchronized operations.

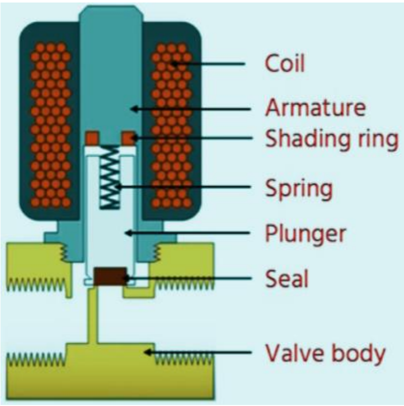

Figure 1. The structure of the pneumatic solenoid valve [4]

The second is Electro-Hydraulic Actuation as shown in Fig. 2. For valve actuator systems that require extreme amounts of force or fast open/close speeds, or where clean, dry compressed air is unavailable, electro-hydraulic actuation may be the best method for valve actuation. Like pneumatic actuation, electro-hydraulic systems use a fluid medium to control valve motion. Instead of compressed air, however, hydraulic actuation technology uses liquid fluid. In most cases, pressurized oil provides the necessary power to open and close the valve. he conversion between electrical and hydraulic variables allows the domain of hydraulic devices to be connected to the IoT (internet of things) framework by incorporating new features such as remote control, digital signal processing, application of advanced control strategies, real-time diagnostics and enhanced safety procedures [5].

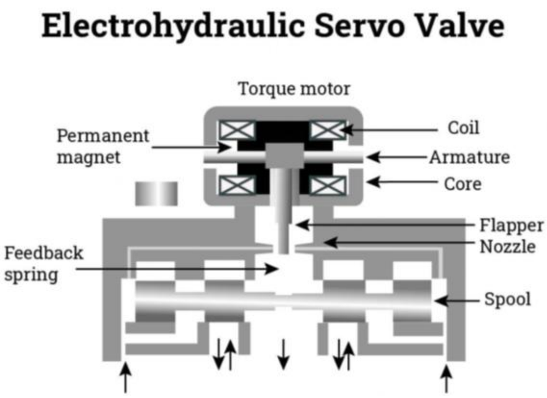

Figure 2. The structure of the electro-hydraulic actuation

Pressurized oil can be generated from a hydraulic pump coupled with an electric motor, gasoline/diesel engines, or even from compressed air. The oil pressure in an electro-hydraulic actuator is typically much higher than compressed air. Since pressurized oil can be 20 to 30 times higher, electro-hydraulic actuators are able to provide greater force (torque/thrust) and cycle at much faster speeds than pneumatic actuators.

Moving to Electric valve actuators, specifically, convert electrical energy to initiate movement and position the valve, as shown in Fig. 3.

Figure 3. Electric valve actuators

The process starts with an input signal, which can either be digital (on/off) or analog (e.g. a range like 4-20mA). This signal tells the actuator how much to open or close the valve

Once the signal is received, an electric motor inside the actuator powers up, generating motion.

Now, this motion is typically fast but not powerful enough to directly move large, heavy industrial valves. The *gear mechanism* absorbs and distributes the mechanical dress generated, slowing down the motor speed and increasing the torque.

Finally, the motion is applied to the valve stem, which either rotates or moves linearly to adjust the valve's position:

Rotary motion: Involves turning the valve stem, usually by 90° or 180°, and is commonly used with ball, butterfly, and plug valves.

Linear motion: Involves moving the valve stem in a straight line, which is the case for gate or globe valves that require up-and-down motion to regulate flow [6].

After introducing various valves and actuators, now combine these two components to form a valves-actuator assembly. This integrated system incorporates automated control mechanisms to maximize efficiency in industrial production and other applications.

2.2. Innovative valve control system

2.2.1 Smart servo-operated ball valve

This innovative approach, presented at the 2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE) in Bangalore, India, is an intelligent servo ball valve system integrating the Internet of Things (IoT) and PID control algorithms to achieve high-precision fluid control, such as water level regulation. The core of the system is a closed-loop PID control algorithm implemented on an ESP32-WROOM microcontroller.

The control loop operates as shown in Fig. 4:

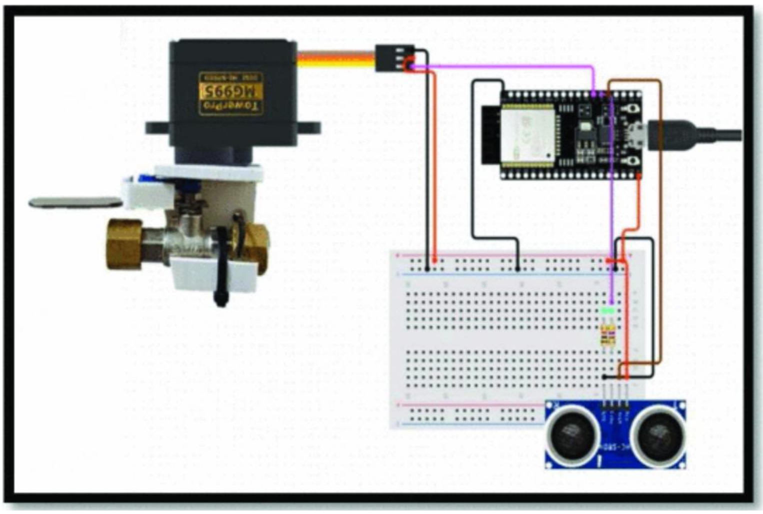

Figure 4. The connection diagram of the system

Sensing: An HC-SR04 ultrasonic sensor measures the current fluid level in the tank.

Error Calculation: ESP32 calculates error (the difference between the measured level and the desired setpoint).

PID Computation: A PID control algorithm, developed using the PID_v1 library in the Arduino IDE, processes this error.

Actuation: The resulting PID output signal adjusts the position of an MG995 servo motor, which precisely rotates a 1/4-inch ball valve to regulate fluid flow.

The PID parameters (K_p=24, K_i=0.4, K_d=2.2) were meticulously tuned using the Ziegler-Nichols method to optimize performance. The results demonstrated a highly effective system with a fast response time (5-7 seconds), minimal steady-state error (±0.1L), and low overshoot (~0.2L).

Furthermore, the ESP32's integrated Wi-Fi facilitates IoT integration with the Thingspeak cloud platform, enabling real-time remote monitoring of the process variables (level, valve position) and allowing for remote setpoint changes [7].

This project presents a cost-effective and well-integrated fluid control system using an ESP32 microcontroller, a servo-operated ball valve, and ultrasonic sensing. The core PID control algorithm demonstrates excellent performance with fast response, minimal steady-state error and low overshoot. The addition of IoT connectivity through ThingSpeak enables real-time remote monitoring and control. This solution successfully combines classic control theory with modern IoT capabilities into a practical, high-value system for automated fluid management. Although this design was developed within the context of agricultural production, it can also perform effectively in chemical manufacturing after undergoing more precise and rigorous calculations.

2.2.2 PLC based flow control system using a motor operated valve

The following will introduce a PLC-based automatic control system for regulating fluid flow using a motor-operated valve. The system employs a 12V PMDC motor, geared down to 3 RPM, to actuate a Teflon-seated valve in a 20mm pipeline. Control is achieved through a closed-loop architecture centered on a Programmable Logic Controller (PLC).

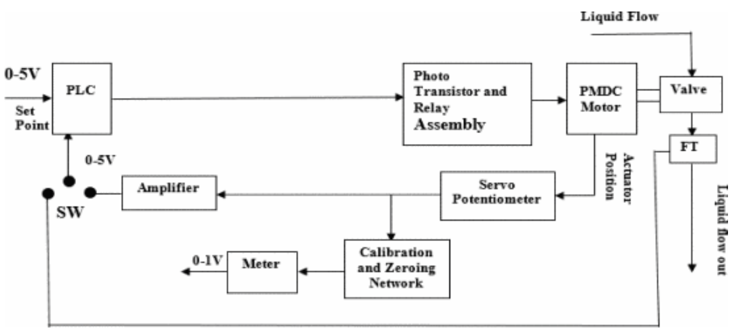

Figure 5. Block diagram of the system

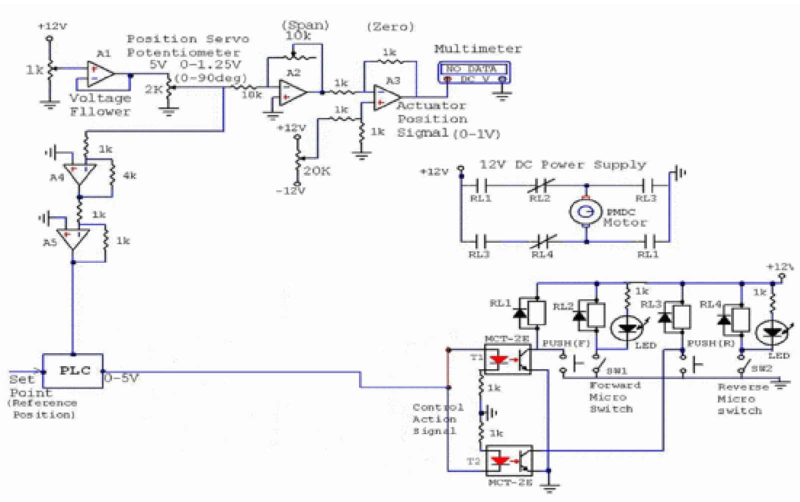

Figure 6. Detailed circuit diagram

As shown in Fig. 5 and Fig. 6, the PLC generates an analog output signal ranging from 0 to ±5V DC. However, as this voltage is insufficient to directly drive the 12V valve motor, a custom driver circuit is implemented. This circuit utilizes opto-isolated phototransistors and a relay assembly. The polarity of the PLC's output signal determines the switching of the relays, which in turn controls the direction of current flow through the motor, enabling both opening and closing actions.

For feedback, the system primarily uses a servo potentiometer attached to the motor shaft to provide a voltage signal corresponding to the actual valve position. This signal is fed back to an analog input on the PLC. The PLC's built-in PID control algorithm (programmed using ladder logic software) continuously compares this feedback value to the desired setpoint. The resulting PID output adjusts the analog signal sent to the driver circuit, creating a precise position control loop for the valve. This entire setup allows for accurate and automated regulation of the valve's opening based on the process requirements [8].

This method presents a robust and practical industrial solution. Using a PLC as the core controller leverages its inherent advantages in reliability, ease of integration with analog I/O, and suitability for harsh environments. The custom driver circuit is a cost-effective alternative to commercial drives. The system demonstrates high accuracy, with linearity errors within ±0.4%, proving the effectiveness of the PID control implementation. However, the reliance on a potentiometer for feedback, instead of a more modern encoder, could be a limitation for applications requiring higher resolution or long-term mechanical durability. Overall, it is a well-validated and highly applicable approach for process control.

2.2.3 Pneumatic valve position control of third-order LADRC based on RBF neural network

The two methods described above both utilize motor-driven valve automation systems. Next will introduce the control of pneumatic valves.

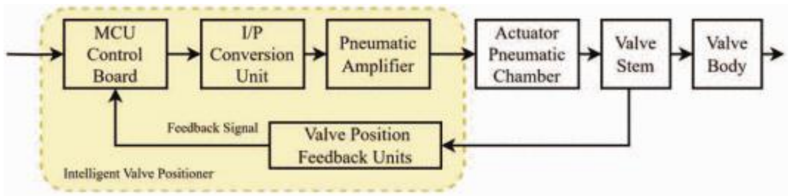

Figure 7. Pneumatic valve position control system [10]

As shown in Fig. 7, this is an intelligent control strategy that combines a third-order Linear Active Disturbance Rejection Controller (LADRC) with a Radial Basis Function (RBF) neural network to enhance the precision and robustness of pneumatic valve position control. Pneumatic control valves are widely used in industrial processes but exhibit strong nonlinearity and are susceptible to time-varying disturbances, making conventional PID control inadequate for high-performance applications.

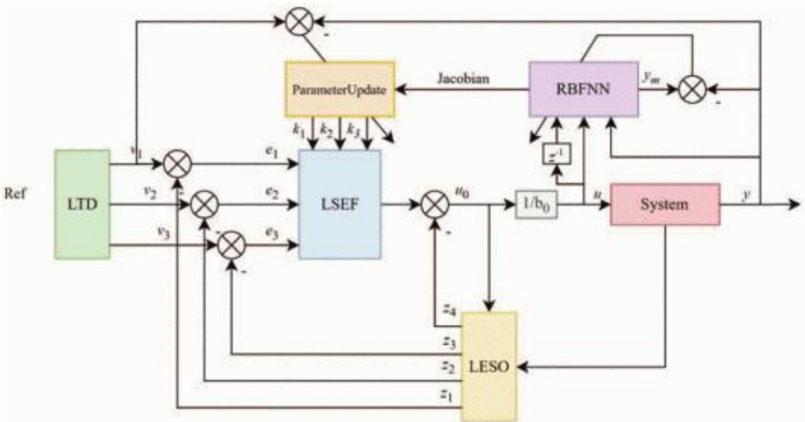

Figure 8. Structure of RBF-LADRC [10]

As shown in Fig. 8, the researchers first established a third-order transfer function model for the pneumatic valve, incorporating both electro-pneumatic and pneumatic-position conversion processes.

Based on this model, a third-order LADRC is designed, consisting of a linear tracking differentiator, a linear extended state observer (LESO), and a linear state error feedback controller. To further improve adaptability, an RBF neural network is integrated to identify the Jacobian information of the system online. This allows real-time adjustment of the LADRC control parameters using gradient descent optimization.

As shown in Fig. 9, simulations and experimental validations demonstrate that the proposed RBF-LADRC method outperforms both standard PID and conventional LADRC in terms of tracking accuracy, disturbance rejection, and robustness. It achieves nearly zero overshoots, shorter settling time, and lower ITAE performance indices under various operating conditions. The results confirm that the integration of RBF neural network with LADRC effectively enhances control performance, making it suitable for demanding industrial valve control applications [9].

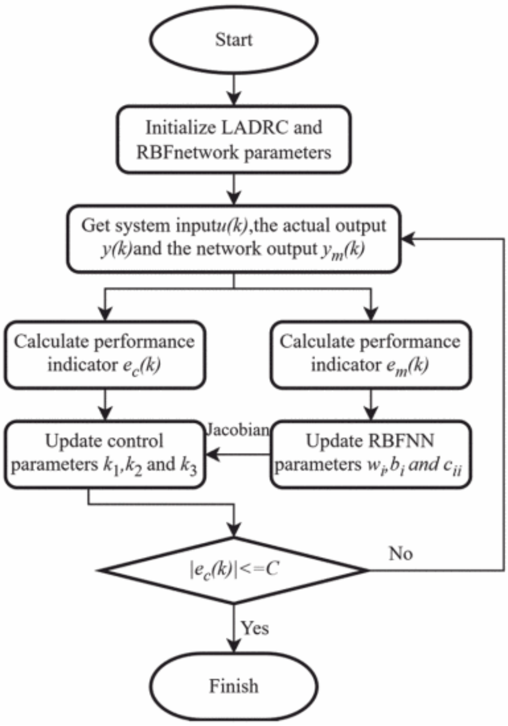

Figure 9. Control flow chart of RBF-LADRC [10]

3. Conclusion

This study conducted a comprehensive analysis of the mainstream valve types and their integration schemes with pneumatic, electric, and electro-hydraulic drive systems, and evaluated advanced control strategies such as PID control based on the Internet of Things, PLC automation, and linear active disturbance rejection control (LADRC) based on RBF neural networks. By establishing a comprehensive evaluation framework based on key indicators such as control accuracy, response speed, torque output, and environmental adaptability, this study provided a systematic decision-making basis for selecting the optimal valve-executor configuration for specific industrial needs.

The research results clearly indicate that there is no universal optimal combination of valves and actuators. The best choice highly depends on the specific application scenario. Gate valves and globe valves, with their linear motion control characteristics, perform exceptionally well in situations requiring precise throttling; while ball valves and butterfly valves, combined with rotary actuators, have the advantage of quick opening and closing and are more suitable for on-off control and general regulation conditions. Pneumatic systems have the advantages of low cost and high speed in clean environments. Electric actuators have high precision and are easy to connect to digital control networks, while electro-hydraulic drives dominate in high-load and high-cycle frequency conditions. The introduction of intelligent control strategies further enhances system performance, making adaptive control, high-precision regulation, and remote operation possible, meeting the core requirements of modern industrial automation development.

This study fills the gap between theoretical research and engineering selection, providing engineers and decision-makers with empirical-based guidance for system design and optimization. This helps to enhance the reliability, operational efficiency, and sustainability of fluid control systems. Future research could focus on the performance of these systems under extreme conditions, the development of predictive maintenance functions integrated with artificial intelligence, and the establishment of standardized test benchmarks for next-generation intelligent fluid control systems.

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