Intelligent Digital Controller Design and Experimental Implementation for a Digital Hydraulic Lifting System

Alaa Jasim Abd
Mechatronics Engineering Department, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, Iraq
aalaa.abd2202m@kecbu.uobaghdad.edu.iq (corresponding author)

Maher Yahya Salloom
Mechatronics Engineering Department, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, Iraq
drmahir@kecbu.uobaghdad.edu.iq

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ABSTRACT

This paper examines the enhancement of hydraulic performance through the replacement of a proportional valve with a Digital Valve Unit (DVU) for flow control purposes. The study underscores the significance of proportional hydraulic valves in precise flow regulation, while concurrently acknowledging that efficiencies in flow control may adversely affect the operational efficacy of actuators, particularly in hydraulic lifting systems. The digital valve system uses simple on/off solenoid valves arranged in parallel and integrated with an intelligent controller, designed utilizing a Programmable Logic Controller (PLC) to compete with conventional valves. To this end, both theoretical and experimental evaluations were conducted to compare the performance of the digital and proportional valve systems. The intelligent digital controller operates with discrete flow rates based on geometric sequence, ensuring precise modulation, while the proportional valve uses continuous flow regulation in a closed-loop system. The results revealed that the digital valve system had a 97.8% improvement in energy efficiency, referring to its lower differential pressure. The digital system also exhibited superior linearity and reduced pressure drop at low flow rates; however, its large package size posed a challenge. The proposed configuration was tested through simulations and practical implementation with the PLC, demonstrating its flexibility in adapting to various flow control needs in hydraulic lifting systems. In conclusion, the Digital Hydraulic System (DHS) offers a promising solution for meter-in flow control, providing enhanced performance in hydraulic applications.

Keywords-Digital Valve Unit (DVU); proportional valve; PLC; proximity sensor; meter-in control

I. INTRODUCTION

Digital hydraulic technology has emerged as a significant component of fluid power technology, offering superior energy efficiency, enhanced control, and greater flexibility compared to conventional hydraulic systems [1]. Authors in [2] explain that digital hydraulic systems employ discrete control components, such as on/off solenoid valves and digital switching methodologies, to modulate fluid flow and pressure, thereby enhancing efficiency across a range of applications. Authors in [3] described the systematic evaluation and enhancement of control methodologies, which facilitated the achievement of energy efficiency, accuracy, and dependability within digital systems. Despite these advancements, authors in [4] point out the persistence of significant challenges, impeding digital hydraulics to achieve a widespread adoption, particularly regarding the cost and size of components. A key characteristic of digital hydraulic systems, emphasized in [5], is the enhancement of both system efficiency and precision control. Consequently, digital hydraulic technology applications, as highlighted in [6], offer distinct advantages, particularly in the industrial, biomedical, and aeronautical domains. Authors in [7] presented a DHS that enhances hydraulic system operation by replacing continuous flow control with on/off valves, hence improving energy efficiency and precision. This system offers adaptability to variable demands, facilitating rapid adjustments in flow and pressure, and consequently reducing energy consumption and component wear. The DHS has been shown to reduce maintenance frequency by minimizing shocks, vibrations, and degradation, thereby enhancing system reliability, performance, and sustainability. Authors in [8] demonstrated that parallel-connected on/off valves can function as servo valves within the digital hydraulic method. In this method, the hydraulic system, using water as the fluid, operates with valves arranged in parallel. These valves, which possess different flow rates, are controlled by a binary coding method. The experimental findings revealed that the velocity and position graphs obtained were analogous to those of a servo valve actuated system. However, it was observed that the pressure shocks within the system were substantial. In contrast, the second digital hydraulic valve presented in [9], despite not yet surpassing the performance of previously studied digital hydraulic valves due to the incorporation of a cam and servo motor, demonstrates considerable potential for enhancement. With a more compact design and the integration of additional valves, the system can be optimized, especially considering its demonstrated potential with cost-effective components.

According to [10], a key innovation is the transition from continuous to discrete control of fluid flow by combining on/off valves to regulate flow and pressure. This method simulates continuously variable valves without the associated complexities, achieving high energy efficiency and precise control. Authors in [11] described a conventional variable flow control valve in the digital system that is replaced with an assembly of binary on/off valves that offer several flow rates with similar pressure drops. These valves operate in two distinct states: energized (ON) or de-energized (OFF), resulting in discrete flow steps. At low speeds, a small flow rate is used, while higher speeds require the opening of more valves. It should also be noted that digital valves can function as switching valves, where variable flow is achieved by adjusting the duty cycle. To enhance the dynamic performance of the DVU, authors in [12] proposed a design with three on/off valves. The working principle and mathematical model were established, and an analysis was conducted to assess the impact of control and structural parameters. Authors in [13] presented both experimental and theoretical studies and the results showed an improvement in the performance of the DVU. Mechatronics systems are defined as the integration of hardware and software, forming a unified system. The incorporation of DHS into mechatronics systems has been shown to enhance performance and reduce complexity, therefore facilitating maintenance and operation. Authors in [14] discussed a notable integration approach that has been identified as conducive to achieving the desired system performance is digital control. A digital system, distinguished by its intelligent control, has been shown to outperform simple on/off mechanisms. Parallel digital hydraulic technology employs modulated discrete digital signals to govern component states, enabling precise and energy-efficient control, as highlighted in [15]. In education, researchers developed a digital-twin-enabled virtual hydraulic workstation simulator using Automation Studio, integrating 3D-modeled components and dynamic behavior graphs to enhance theoretical and practical learning, particularly in resource-limited settings [16]. Authors in [17] integrated a performance enhancement into engineering curricula to promote efficiency principles. Authors in [18] found that many challenges, particularly in performance and cost optimization, remain unaddressed. This study highlights how DHS addresses critical issues, offering cost savings and operational improvements. It proposes using the DVU to optimize efficiency and develop an analog lifting model deploying digital hydraulic technology. The study further proposes the integration of a digital hydraulic design to enhance DVU performance, achieving high energy efficiency and precise control. To validate the performance and effectiveness of both the analog and digital systems, practical implementation and testing were conducted.

II. GENERAL DESIGN APPROACH

The components considered in this study have been the subject of experimental validation. The system under consideration includes a supply unit equipped with a DVU consisting of three 4/2-way solenoid-operated direction control valves. The implementation of the intelligent controller was achieved through the use of a PLC, which provided acceptable flow steps, as shown in Figure 1.

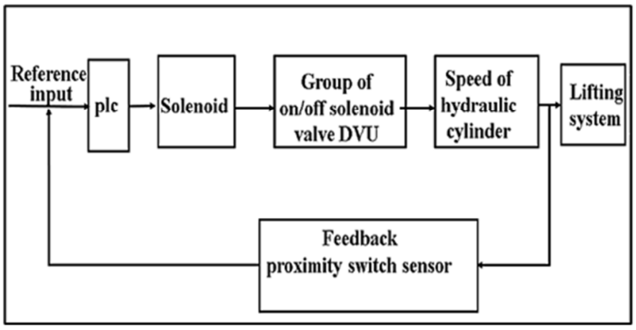

Fig. 1. Closed-loop control of DVU system with PLC.

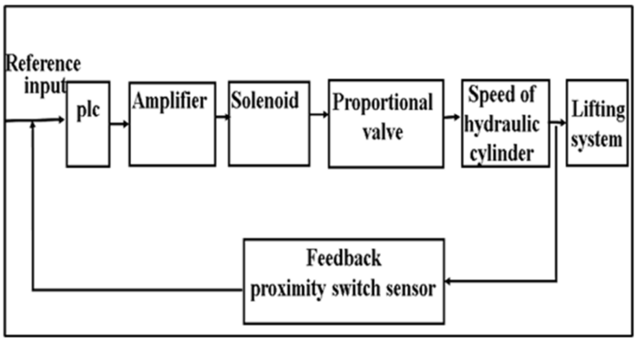

Fig. 2. Closed-loop control of proportional valve system with PLC.

Authors in [19] described the procedure for designing and sizing the hydraulic flow in the Digital Flow Control Unit (DFCU), which is: each 4/2 directional valve is attached to a hydraulic orifice, which is controlled by a flow control valve from the Festo company. Authors in [20-23] outlined the binary method employed to size the hydraulic orifice. This approach enables the DFCU to generate proportional flow rates by utilizing a combination of on/off states of the 4/2 valves. The DFCU is comparable to a quantized adaptation of the 4/3 proportional valve. To control a coil on Passive Displacement Ventilation (PDV), which adds complexity and increases system cost, the input is attached to an amplifier system, as portrayed in Figure 2.

III. COMPONENTS OF THE SYSTEM

The PLC in this system is responsible for the control and automation of hydraulic operations. It manages the flow and pressure regulation, ensuring precise control and real-time adjustments. This integration with the hydraulic system facilitates smooth interaction between the simulation and practical implementation, leading to improved performance and enhanced control accuracy, as presented by the digital hydraulic circuit in Figures 3 and 4 and the detailed description of the system components in Table I.

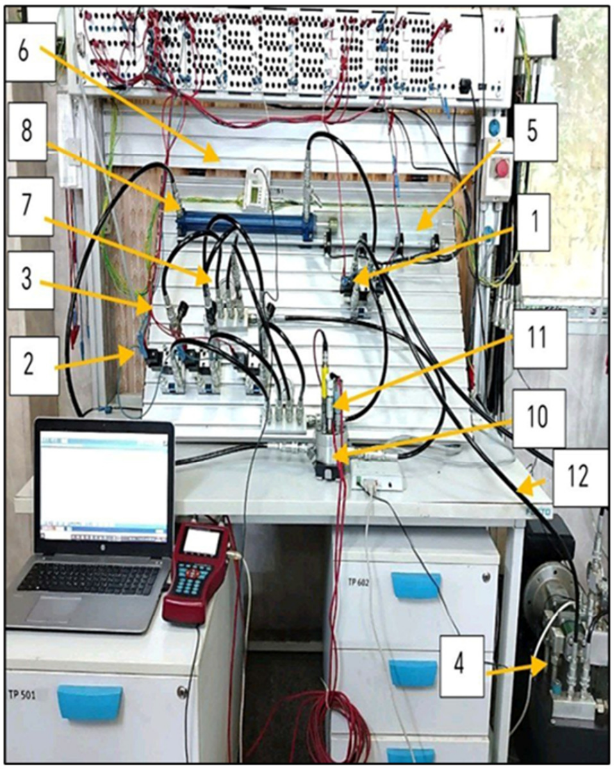

Fig. 3. Closed-loop control of DVU with PLC.

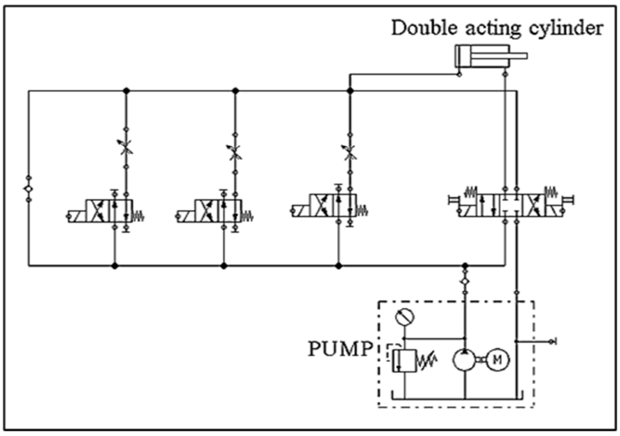

Fig. 4. Configuration of the experimental DVU system.

TABLE I. DHS PARAMETERS

No	Equipment	Parameters	Value	Unit	Product number
1	4/3-way solenoid valve	Power supply	24	V DC	Festo 167083
		Operated pressure	6	MPa	
2	4/2-way solenoid valve	Power supply	24	V DC	Festo 544346
		Operated pressure	6	MPa	
3	Flow control valve	Maximum pressure	12	MPa	Festo 152843
		Setting pressure	2	MPa	
4	Power pact with AC motor	Nominal voltage	230	V	Festo 572128
		Rated output power	1.1	Kw	
		Delivery rate	2×3.7	L/min	
5	Proximity Pensors (PSs)	Detection range	8	mm	Bosch Rexroth R961003106
		Operating voltage	24	V DC	
6	PLC	Discrete input voltage	24	V DC	Schneider Electric SR3B261BD
		Cycle time	69	ms	
7	Check valve	Maximum pressure	12	MPa	Festo
8	Double acting cylinder	Bore diameter D	25	mm	Bosch Rexroth R961009526
		Max Stroke	40	cm	
9	4-way distributor with pressure gauge	Maximum pressure	10	MPa	Festo 159395
10	Gear flow meters	Measuring range	0.05 - 5	L/min	HySense® QG 100
11	Pressure sensors	Measuring range	0 - 250	bar	Hydrotechnik PR 400
12	Hose line with quick release couplings	DN	6	mm	Festo 159386

IV. CONTROL AND OPERATION METHODOLOGY

The present study examines the regulation of fluid flow through the implementation of a digitalized valve mechanism, wherein the primary function of the valve is to facilitate the retraction of the actuator, which is commonly referred to as metering-in. To achieve this, a systematic approach is implemented to regulate flow dynamics, ensuring optimal actuator performance. In the metering-in circuit under consideration, the cylinder's speed is managed through the modulation of the fluid flow entering the cylinder. The hydraulic block is affixed to the piston side. A notable benefit of regulating the feeding in the extension axis is that it facilitates meticulous management of the cylinder velocity. This is due to the fact that a greater volume of fluid enters the piston side compared to the amount that exits the rod side. The model proposed here is predicated on the metering in flow control paradigm. However, rather than employing a traditional analog flow control valve, as shown in Figures 5 and 6, a DVU is used. As outlined in Table I, the components of both systems are identical, with the exception of the valve configuration, wherein the DVU is replaced by a 4/3 proportional directional valve. The valve specifications include a maximum current consumption of less than 2 A, an operating pressure of 315 bar, and an operating voltage range of (-10 to +10) V. This configuration ensures that any observed differences in performance are solely attributable to the type of the utilized valve.

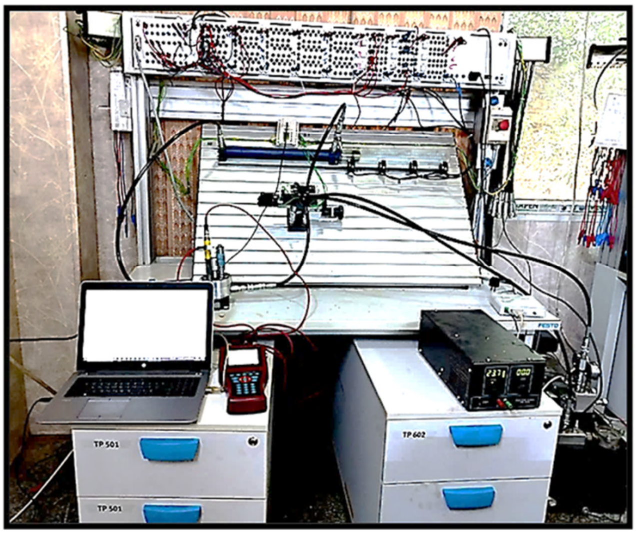

Fig. 5. Closed-loop control of proportional valve with PLC.

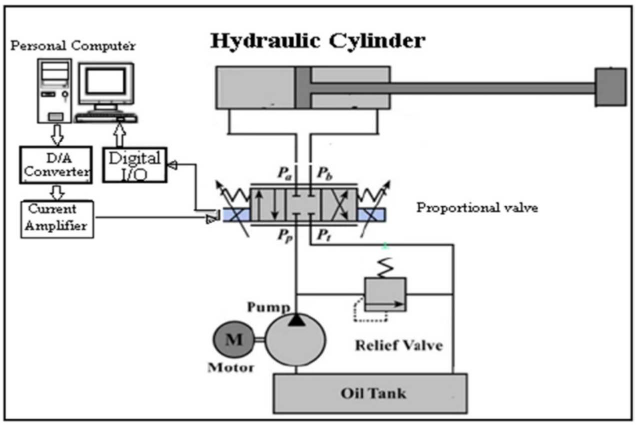

Fig. 6. Configuration of the experimental system.

V. CONTROLLING DESIGN

The hydraulic system's control framework is meticulously engineered to optimize the regulation of flow rates while concurrently maximizing energy efficiency. A closed-loop controller has been employed for the regulation of speed. Thus, there is an absence of any Proximity Sensor (PS) noise complications. The closed-loop controller signifies a critical selection in this instance, as the principal objective of this manuscript is to focus on the methodology pertaining to speed control using DVU. As presented in Figure 7, a hydraulic lifting system is shown to include a DVU executing a sequence manufacturing operation. The speed hydraulic cylinder (actuator speed) is controlled by one 4/3-direction flow control valve metering out return flow (VR) from the hydraulic cylinder, which manages the return flow from cylinder. The selection of an appropriate flow control valve is performed by directional valves that are activated by a control unit, ensuring the forward motion (VF) as required.

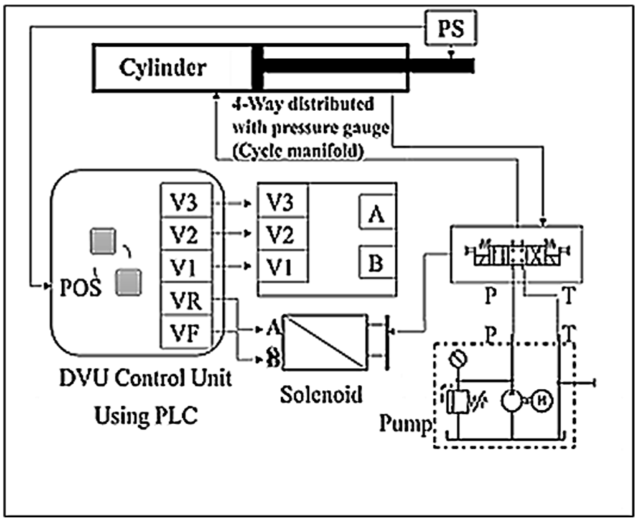

Fig. 7. Control of actuator speed in a hydraulic lifting system using PLC controller.

The intelligent controller for the DVU was constructed using the Zelio Logic SR2 SR3, a smart relay programmed with the Ladder Diagram (LAD). The circuit was developed within the LAD environment using ZelioSoft2 to create, simulate, and monitor the program, ensuring efficient and precise operation in industrial applications. The inputs indicate the position as determined by the PS. The hydraulic cylinder, measuring 40 cm in total length, is divided into three equal sections. The first proximity switch is positioned at 0 cm, the second at approximately 13.33 cm, the third at 26.66 cm, and the last at 40 cm. These fixed sensor locations enable precise position detection and facilitate the efficient control of the digital hydraulic system. Figure 8 depicts the input and output assignments of the PLC controlling the digital hydraulic lifting machine.

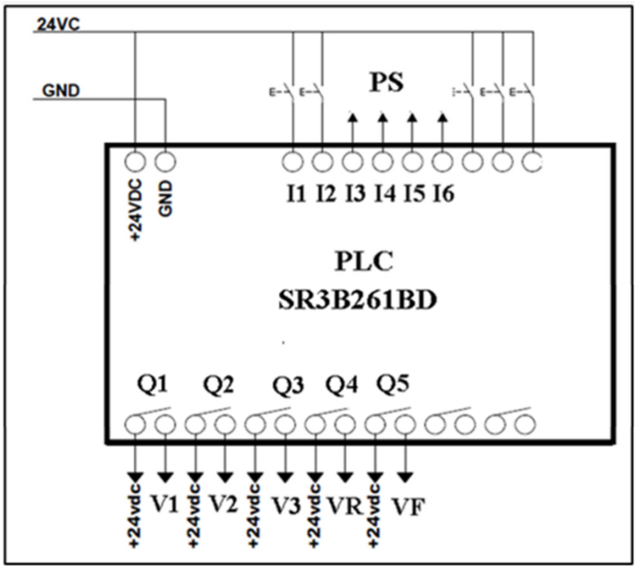

Fig. 8. PLC speed controller.

VI. OPERATIONAL PRACTICES

As illustrated in Figure 9, the flowchart delineates the procedural steps pertinent to the ideal scenario. For the sake of clarity, a selection of merely three valves has been employed for explanatory purposes.

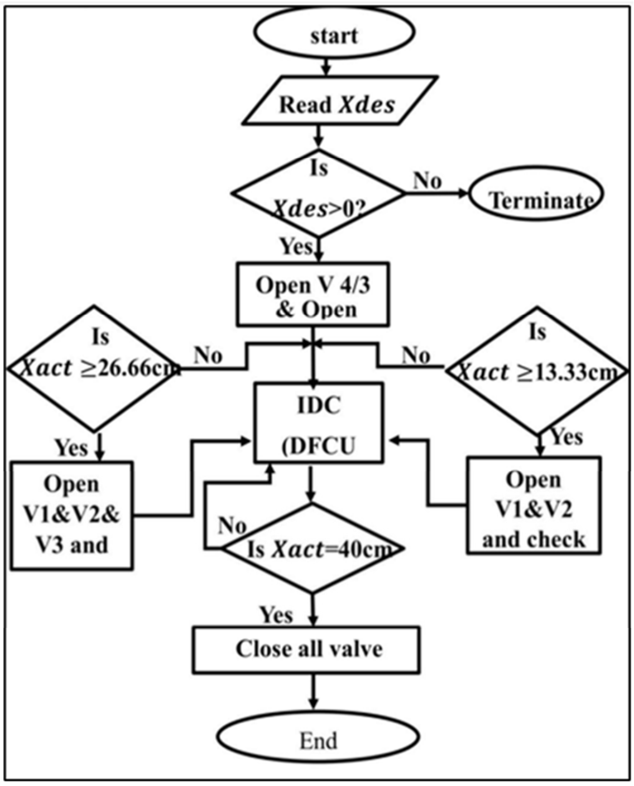

Fig. 9. Controller flowchart.

The system's functionality is delineated by three distinct states, depicted in the flowchart: V1 is open, V2 is open, and both V1 and V2 are open concurrently. The third state, signified by the synchronous activation of V1, V2, and V3, is also denoted in the flowchart. The symbol representing the intended output position is used, while another symbol denotes the feedback position as measured by the sensor. The quantification of the actual output flow was performed using a gear flow meter, with the measurements obtained through the use of a Hydro Technique apparatus integrated with HYDROcom6 software on a personal computer. Authors in [24] demonstrated that this configuration enabled real-time observation of flow and pressure, with data acquisition having occured at an expedited sampling frequency of approximately 1 ms. This ascertained a detailed analysis of system performance across temporal dimensions.

VII. 4/3-WAY ELECTRO-PROPORTIONAL VALVE: MODELING AND CONTROL

To ensure a comprehensive comparison, a 4/3 proportional valve was selected for analysis alongside the DVU, as both systems exhibit equivalent maximum flow rates. The proportional valve attains a maximum flow rate of 4 lt/min at a 40-bar pressure drop, whereas the proposed DVU operates efficiently with a mere 4.1-bar pressure drop. Proportional valves function by adjusting the output flow rate in response to the commanded input signal. The circuits for the proportional valve system were designed and built by researchers, who used simple electronic components and amplifier cards to control the proportional valves. Authors in [25, 26] explain that proportional route control valves with analog commands regulate oil flow as a percentage of the maximum flow rate. This mechanism introduces a restriction within the valve, which modulates the flow rate. In proportional valves, the flow rate is directly controlled by the voltage, which is controlled by the amplifier card connected to the valve. The voltage signal determines the valve opening, allowing for precise control of the flow rate:

$$Q_{PDV} = k\,u\,\sqrt{\Delta p} \qquad (1)$$

where Q_{PDV} is the flow rate through the PDV, u is a coefficient dependent on the applied voltage, k is a constant related to the valve's design and Δp is the pressure differential across the valve. The command voltage for the amplifier card is adjusted using internal potentiometers built into the card. These potentiometers allow for precise selection of the required voltage to control the card's command value. The amount of fluid flow is directly dependent on this voltage. For the given setup, the selected command voltages are 2.91V, 5V, 7.33V, and 9.5V, as can be seen in Table II and Figure 10.

TABLE II. PROPORTIONAL DIRECTIONAL CONTROL VALVE BEHAVIOURS OF HYDRAULIC SYSTEM

Voltage (V)	Flow (L/min)
2.91	1.3
3.94	1.5
4	2.1
5	2.9
7.33	3.2
9.5	3.7

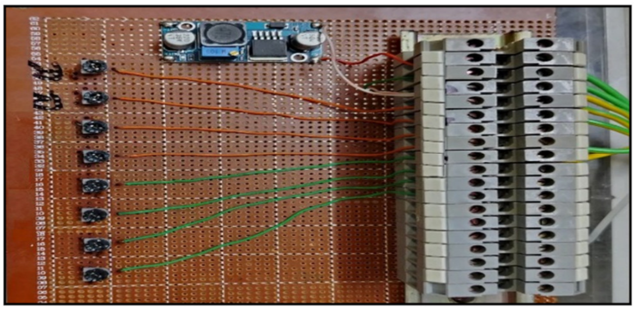

Fig. 10. Electronic Card.

The closed-loop proportional valve system (PS) connected to the hydraulic cylinder is regarded as the standard for comparison with the DVU system. Authors in [27] showed that all other parameters of the PDV circuit model were equivalent to those of the DVU system. Figure 11 presents the configuration, demonstrating the integration between the PLC, the PS, and the electronic card, and highlighting the necessary interactions for proper system functionality. Digital hydraulic technology uses digital signals for direct valve control, thus eliminating the need for digital to analog conversion (A/D). This approach simplifies the control process and reduces noise sensitivity typically associated with conventional systems. According to [28], the proportional valve demonstrates performance metrics with hysteresis under 4%, linearity deviation below 8%, and repeatability within 2%, alongside a total dead band of 25%. This setup provides a clear framework for evaluating the performance of the DVU system in comparison to the conventional proportional valve system.

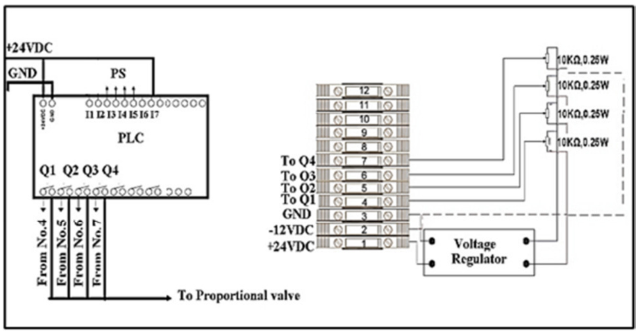

Fig. 11. Connection diagram of PLC, PS, and electronic card.

VIII. RESULTS AND DISCUSSION

A detailed PLC simulation was conducted to evaluate the effectiveness of the engineered systems, namely the DCV and the PDV system. Hydraulic systems require precise and consistent fluid control to ensure efficiency, minimize energy expenditure, and facilitate the seamless operation of the system.

A. Case Study 1

A detailed comparative analysis was carried out to assess the performance of the DVU system in contrast to the conventional hydraulic PDV system, with particular attention paid to response speed and control efficacy. In both systems, valves are actuated by digital input signals transmitted to 24V DC solenoids. A signal of "1" engages the valve, while a signal of "0" disengages it. The hydraulic fluid flow rates were systematically adjusted to regulate the speed of the cylinder, resulting in outcomes that align with those observed in the DVU system. The voltages applied to the proportional valve were documented as V1 = 2.75V, V2 = 3.94V, and V3 = 7.61V, as evidenced in Figure 9. The velocity of the hydraulic cylinder demonstrated a proportional increase in conjunction with elevated flow rates. As depicted in Figure 12, the command value of the directional proportional control valve, the flow rate, and the system pressure collectively influence cylinder speed. It is noteworthy that enhanced command values are associated with augmented fluid flow, resulting in increased cylinder velocities. It is evident that as the quantity of valves within the DVU system increases, the output resolution undergoes a substantial enhancement, thereby facilitating more precise and accurate flow management. To support this claim, the measured flow rates were determined to be Q1 = 1.3 L/min, Q2 = 2.4 L/min, and Q3 = 3.1 L/min. This finding demonstrates the DVU system's ability to achieve superior control resolution in comparison to the PDV system, as the quantity of valves directly influences the precision of the system's output.

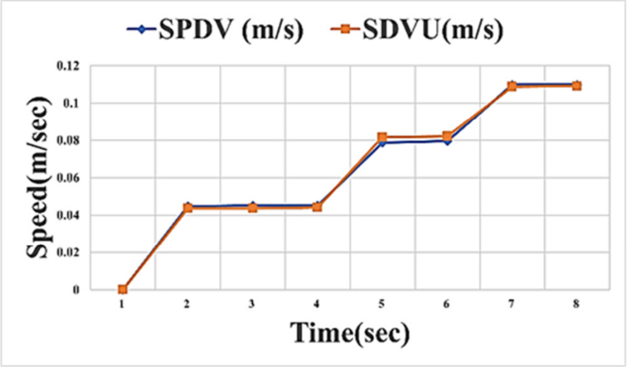

Fig. 12. Comparison of cylinder speed between digital valves and proportional valve Systems.

As the quantity of valves is increased by a single unit, the potential configurations of valve states concurrently expand:

$$N\_States = 2^{(n-1)} \tag{2}$$

where N_States is the total number of states the DVU can have, and n is the number of valves in the DVU. This results in a higher output resolution for the DVU as the number of valves increases. In 3-bit DFCU, 2^{3-1}, i.e., 7 distinct flow rates (Q1,..., Q8) can be achieved. A thorough examination reveals that at t = 0 s, the fluid speed is low for both the DVU and PDV systems. Subsequent to this initial period, the fluid speed steadily rises, reaching a maximum of 0.1091 m/s at t = 8s, a finding that applies to both systems. Thereafter, the speed undergoes fluctuations, though it remains elevated, suggesting variations in flow rate or system dynamics. According to [29, 30], a comparison of the two systems reveals that, while both exhibit similar speed responses, the DVU system displays superior resolution and control as the valve count increases. The calculated efficiency of 97.8% enhances energy management and flow smoothness, while reducing energy loss:

$$\eta = 1 - \left|\frac{Q_{PDV}}{Q_{DVU}}\right| \tag{3}$$

where Q_{PDV} is the measured flow rate from the proportional valve and Q_{DVU} is the measured flow rate from the DVU system.

B. Case Study 2

A comparison of the speed response in DVU and conventional PDV systems with activation of the first valve of DVU (SV1) is provided in Figure 13. The data present the speed hydraulic cylinder over time for both the DVU (SV1) and conventional PDV (SPDV) systems. When a voltage of 2.75 V was applied to the proportional valve, the DVU system attained a flow rate of 1.3 L/min when only the first valve was active. A gradual increase in speed from 0.0000327 m/s at t = 1 s to approximately 0.04626 m/s at t = 8 s was observed in both systems. The results demonstrate a similar trend in speed response between the two systems, indicating that the DVU system effectively regulates flow and speed, achieving the desired performance with controlled valve activation.

C. Case Study 3

Figure 14 presents a comparison of the speed response in DVU and conventional PDV systems with the activation of the second valve (SV2) in DVU, where the data provide a measurement of the hydraulic cylinder speed over time for both the DVU (SV2) and conventional PDV systems. Applying a voltage of 2.91 V to the proportional valve resulted in a flow rate of 1.3 L/min, with only the first valve having been active in the DVU system.

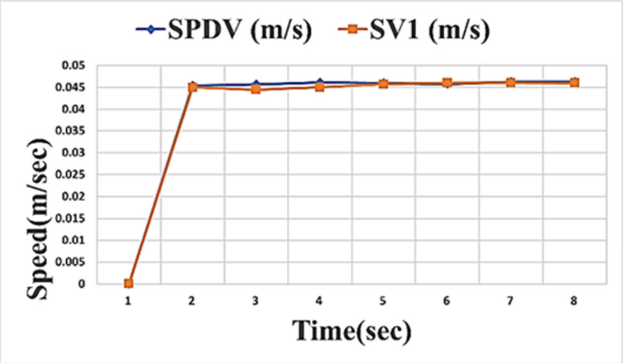

Fig. 13. Cylinder operation demonstrating initial speed performance.

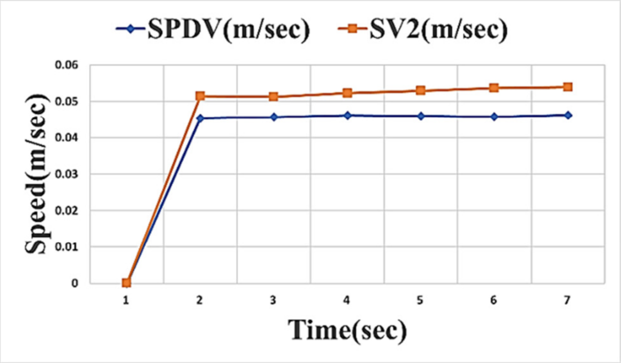

Fig. 14. Cylinder operation demonstrated at second speed only.

D. Case Study 4

This analysis compares the speed response of DVU (SV3) and conventional PDV systems. At 2.75 V, the DVU achieved a flow rate of 1.4 L/min, with the first valve having been active, as shown in Figure 15.

E. Case Study 5

As illustrated in Figure 16, a comparison of the speed response of DVU (SV1, SV2) and PDV systems reveals that at 7.33 V, the DVU reached a flow rate of 3.2 L/min, with the initial valve having been in active mode. However, the activation of both valves (SV1 and SV2) resulted in a substantial improvement in system performance.

F. Case Study 6

As shown in Figure 17, a comparison of the response between the DVU and PDV reaches, at 2.8 V, a flow rate of 2.7 L/min, with both valves (SV1 and SV3) having been activated.

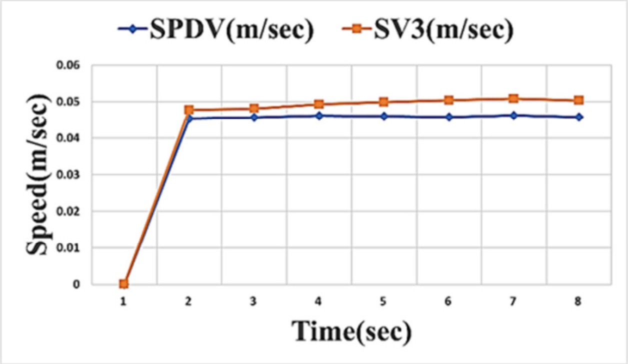

Fig. 15. Cylinder operation demonstrated at third speed only.

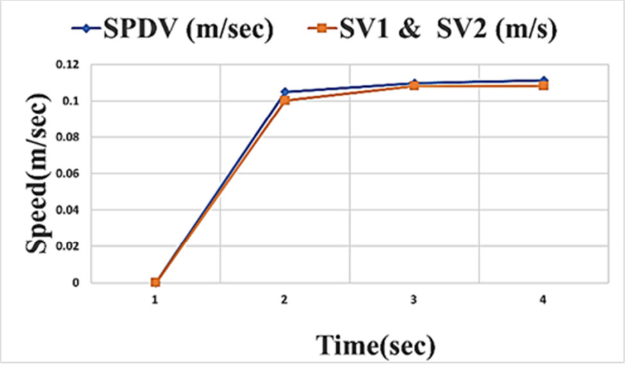

Fig. 16. Speed response analysis in digital valves (SV1, SV2) and proportional systems.

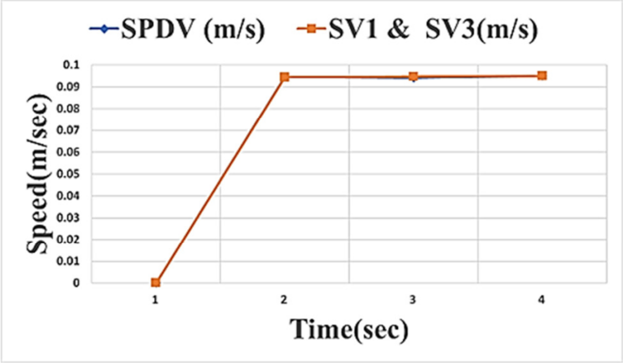

Fig. 17. Speed response analysis in digital valves (SV1, SV3) and proportional systems.

G. Case Study 7

As outlined in Figure 18, a comparative analysis of the speed response between the DVU (SV2, SV3) and PDV systems is presented, where at 5 V, the DVU achieved a flow rate of 3.4 L/min, with both valves (SV2 and SV3) having been activated.

H. Case Study 8

A comparison of the velocity response between the DVU (SV1, SV2, SV3) and PDV systems is depicted in Figure 19, where at 9.5 volts, the DVU achieved a flow rate of 3.7 L/min, with all three valves (SV1, SV2, and SV3) having been activated.

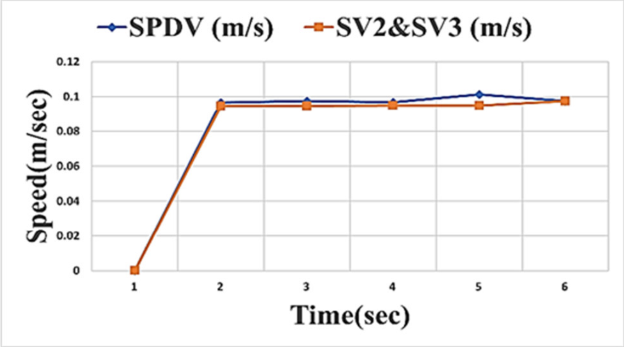

Fig. 18. Speed response analysis in digital valves (SV2, SV3) and proportional systems.

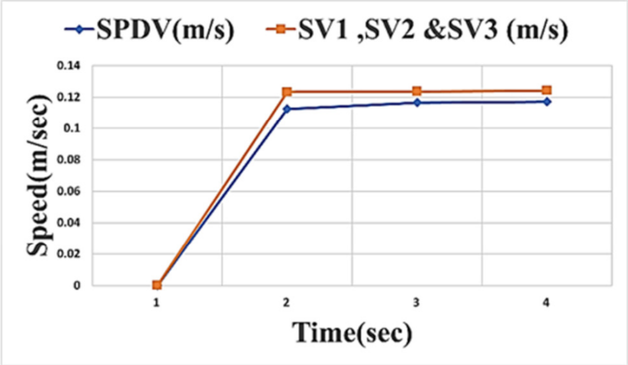

Fig. 19. Comparison of speed response under varying valve configurations.

I. Case Study 9

As shown in Figure 20, a comparison of the pressures used in both the DVU and PDV systems during the experiment reveals that the DVU requires lower pressure to achieve equivalent performance, thereby leading to a substantial reduction in energy consumption when compared to the PDV, which demands higher pressure to attain similar outcomes.

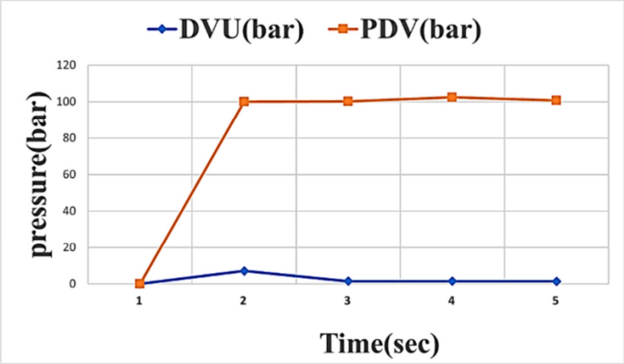

Fig. 20. Comparison of pressure response under varying valve configurations.

The findings suggest that the DVU effectively copies the flow control and efficiency traits of a PDV. The DVU configuration attains proportional-like control by employing coordinated valve actuation methods, yielding comparable or even improved performance in specific metrics. Figure 21 shows a comparison between the conventional proportional directional valve system and the DVU, emphasizing the respective strengths of each. The PDV ensured smooth flow and stable efficiency, while the DVU provided flexible and precise adjustments that closely replicated these performance characteristics. The DVU's modularity and dynamic flow control make it a versatile alternative, especially for applications requiring fine-tuned adjustments across varied conditions. A more comprehensive analysis of the observed speed peaks reveals that the initial desired output is quantified at 0.1 sec, which necessitates a state (V1: on, V2: on, V3: on). However, due to the latency associated with the actuation of the valves, a transient state is induced, wherein all valves are activated concurrently for a variable duration. Authors in [31] demonstrated that this complication can be rectified by using valves that exhibit an expedited response time. The primary challenge posed by the delay can be mitigated by optimizing the valve closure timing based on empirically measured characteristics of the valve's intrinsic switching duration and the inherent unpredictability in valve operation. Authors in [32, 33] explained that this may result in pressure surges, which can be effectively mitigated through the integration of relief valves, accumulators, and suitably designed control systems. This paper introduces a significant advancement towards Industry 4.0, emphasizing cost reduction through the standardization of components. The system enables the operation of valve groups by modifying a few commands within the valve software, thus eliminating the need for valve replacements when different tasks are required, which subsequently reduces resource waste. The DVU enhances hydraulic control by providing precise flow regulation and high linearity. Its programmability affords operational flexibility, while the standardization of components streamlines maintenance processes. In summary, the DVU provides a cost-effective alternative to proportional valves, certifying the reliability and efficiency of hydraulic system design [34].

IX. CONCLUSIONS

This study delineates a proposed Digital Valve Unit (DVU), which is designed to modulate flow dynamics within hydraulic systems, hence presenting a viable alternative to conventional proportional valves. A comparative analysis reveals that the DVU system reduces energy consumption when compared to the 4/3 proportional valve. The results underscore the enhanced efficiency and more uniform flow regulation achievable with DVU, thereby emphasizing their potential applications within hydraulic systems. Empirical evidence has demonstrated that DVUs can lead to a reduction in energy losses and enable more uniform flow modulation, ensuring reliable control under varying conditions, an imperative requirement for high-efficiency applications. The validation of mathematical modeling has also been successfully executed, revealing the relationship between flow rates and operational efficiency. Furthermore, the analysis has underscored the capability of DVUs to replicate the functionalities of Digital Hydraulic

Systems (DHS) at a reduced economic cost, while also enhancing versatility. The research confirmed the ability of DVU to simulate the functions of digital systems at a reduced financial cost, along with improved adaptability. Future research may focus on optimizing DVU to enhance accuracy and expand its application scope. Moreover, a comparative analysis of the DVU system and the Passive Displacement Ventilation (PDV) system elucidated the benefits of the DVU, including elevated linearity, programmable functionality for diverse operations, and diminished pressure losses at lower flow rates. The discourse also considered the standardization of substituting a variety of valves with programmable units. However, significant challenges persist, such as substantial package dimensions, uncertainty regarding valve states, and the occurrence of pressure peaks. This study constitutes a foundational step towards the integration of digital hydraulic systems, positing that DVU can markedly improve flow control, particularly concerning energy efficiency.

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