A Comparison of the Performance Characteristics of Conventional and Proportional Valves Applied for Synchronizing Hydraulic Cylinders

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ABSTRACT

This study examines the synchronization of hydraulic systems using conventional and proportional valves, evaluating performance details, as well as time responses, energy consumption, and operating efficiency. Synchronizing hydraulic systems through cylinder motion control plays a key role in the accuracy of regular speed operations in applications. The rapid flow changes after using conventional four-way (4/3) directional control valves result in energy loss due to abrupt movements resulting from their precise open/closed positions. The solution provided by the proportional valves emerges from their ability to continuously adjust the fluid flow and pressure, enabling the fluid movement to be synchronized with pressure-sensitive system processes. Programmable Logic Controller (PLC)-controlled amplification cards allow these valves to provide fast operation while reducing energy consumption by directing orifice positions based on input data. Advanced control systems, when coupled with conventional valves, can simulate the performance of proportional valves in control applications. The controller uses specific algorithms to gradually adjust the valve positions, mimicking the output of the proportional valves. Under proper operating conditions, standard valves operate with similar efficiency to that of proportional valves. The latter achieve excellent results in high-precision dynamic control systems, because of their precise operation, speed, and significant energy savings. The hydraulic synchronization systems choose proportional valves over conventional control systems because they offer exceptional performance and maximum efficiency.

Keywords--synchronous system; conventional valves; proportional valves; distance sensor; PLC

I. INTRODUCTION

The accuracy of hydraulic system control depends entirely on matching the hydraulic cylinders properly. The use of conventional valves through traditional methods presents several operational challenges. These approaches often result in uneven load distribution, pressure imbalances, and mechanical wear, ultimately compromising system functionality and reliability. Modern synchronization technologies equipped with proportional valves enable systems to achieve better accuracy, operate more smoothly, and maintain improved control capabilities [1]. Authors in [2] demonstrated that the advances in synchronization technology improve hydraulic system operations, along with providing greater operational efficiency and sustainability. System safety and reliability are enhanced when electro-hydraulic actuators operate with intelligent control algorithms that incorporate real-time monitoring systems for adaptive synchronization operations. According to [3], synchronization processes achieve better performance when they incorporate smart technologies with Industry 4.0 principles, irrespective of conventional or proportional valves. Various challenges inhibit the development of present-day synchronization technology systems. Authors in [4] identified the major obstacle for new technology implementation into conventional valve-based hydraulic systems, as these legacy components do not fulfill the current synchronization requirements. According to [5], the process of integrating electro-hydraulic actuators with enhanced intelligent control systems and real-time monitoring systems requires skilled technicians and large resources due to its complex technical procedures. Authors in [6] highlighted that system synchronization accuracy and stability experience adverse effects from temperature changes as well as load shifts together with pressure imbalances in operational environments. According to [7], proportional valves provide enhanced control but their signals need precise management to stop system instability. The technical requirements for hardware and software need further development because of the challenging circumstances in hydraulic application, synchronization, maintenance, and implementation processes. According to [8], proportional valves provide control over dual-cylinder systems with enhanced system performance affecting accuracy, speed, and energy efficiency. Authors in [9] demonstrated that implementing feed-forward along with feedback control through proportional valves enhances both control accuracy and dynamic response performance. The lack of synchronized control characteristics between the individual on/off states makes conventional valves unable to achieve synchronization efficiency. Authors in [10] discussed how proportional valves enable hybrid electro-hydraulic systems to gain precise control and stability features, supporting system synchronization functions. According to [11], proportional systems offer similar levels of response stability to conventional valve systems, despite their slow and unresponsive operations. Authors in [12] demonstrated that proportional valves controlling dual-cylinder systems achieve precise synchronization while enhancing timing and energy efficiency. Authors in [13] explained how implementing proportional valves with feed-forward and feedback control generates enhanced control accuracy together with higher dynamic response performance. The system introduces enhanced synchronization control by using proportional valves, which operate individually from the standard valve mechanisms. Authors in [14] analyzed how proportional valves improve stability and precision in hybrid electro-hydraulic systems through detailed explanations of the proportional control for hydraulic system synchronization. Authors in [15] showed that the proportional systems demonstrate enhanced performance dynamics, producing stronger response and stability features than the standard slow-acting valve systems. Proportional valves deliver superior synchronization, precise command execution, and energy optimization capabilities that meet the requirements for fast and precise performance.

II. EXPERIMENTAL STUDY OF HYDRAULIC SYSTEM SYNCHRONIZATION

As explained in [16], this experimental study evaluates the synchronization of a hydraulic system using multiple synchronized hydraulic cylinders, tested under various operating conditions. Industries using lifting systems, automated machinery, and heavy mining equipment rely on synchronized cylinder operations to achieve three goals: reduced mechanical stress, improved operational efficiency, and a uniform load distribution. The experimental system requires the design and application of various synchronization methods to measure performance accuracy, response times, and energy efficiency, as well as to evaluate failure resistance. According to [17], instantaneous displacement data are collected from linear position sensors mounted on two hydraulic cylinders that comprise the typical experimental system. The cylinders are actuated by hydraulic control valves consisting of conventional directional valves, as shown in Figure 1, or proportional valves, as depicted in Figure 2. A hydraulic pump and reservoir form the power source maintain stable hydraulic fluid delivery at specified pressures and flow rates. A control unit analyzes the sensor readings to control the valve positions and ensure synchronization. The data collection system enables monitoring vital measurements of cylinder behavior, as well as pressure changes and flow measurements, to conduct a comprehensive system analysis. Various synchronization methods are applied and tested in different operating scenarios. The effectiveness of conventional synchronization methods, designed using conventional directional control valves to maintain constant cylinder motion, has been tested. Authors in [18] stated that these synchronization techniques demonstrate basic effectiveness, but cause flow problems and are limited in their ability to manage variable operating loads. Continuous fluid flow control via proportional valve control systems is evaluated for their instantaneous feedback capabilities, enhancing synchronization accuracy while ensuring a smooth operation. Authors in [19] explained that system robustness is demonstrated through assessing the external load adjustments to disturbances. Multiple external forces affect the cylinders during these tests, enabling controllers to evaluate their response to unbalanced forces. The automatic detection and sensor-based adjustment of inaccurate valve positions determine how to maintain synchronization control in closed-loop feedback control systems. Authors in [20] claimed that system performance analysis combines synchronization accuracy assessment with response time measurements, and applies system dynamics assessments and fault analysis. The synchronization accuracy assessment is based on the relative motion distance between two cylinders over a specified period of time. Performance improves as positional deviations are minimized. The system response time describes how quickly synchronization problems are resolved following disturbances affecting the system. This research evaluates energy efficiency through measurements of conventional and proportional valve control systems. Authors in [21] indicated that the correct use of proportional valves improves fluid distribution, reducing energy losses. The system identifies fault conditions by detecting synchronization errors, enabling it to take appropriate corrective actions to prevent major problems from developing before they occur. Experimental methods yield fundamental results for determining the best synchronization methods and their performance under given conditions. Proportional valve control systems operate with excellent accuracy and tunability, although they require complex control software and regular equipment maintenance due to their sensitivity to environmental factors. Conventional, low-cost valve synchronization systems ensure consistent reliability, but their ability to handle changing operating conditions is limited.

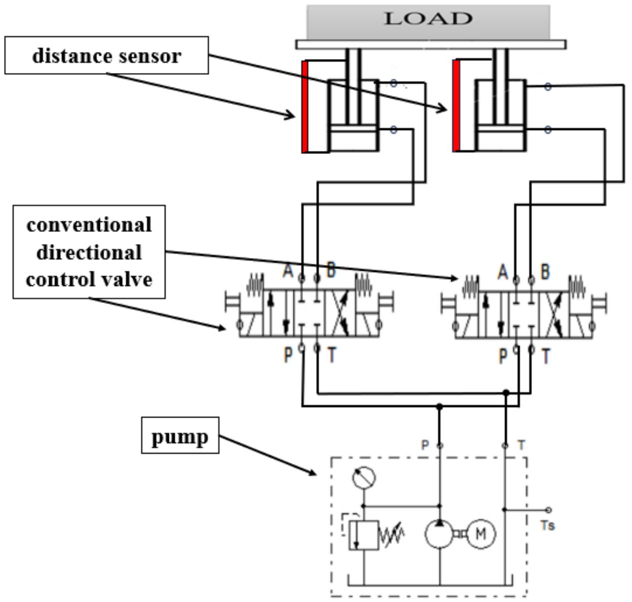

Fig. 1. Synchronous hydraulic system connected to conventional valves.

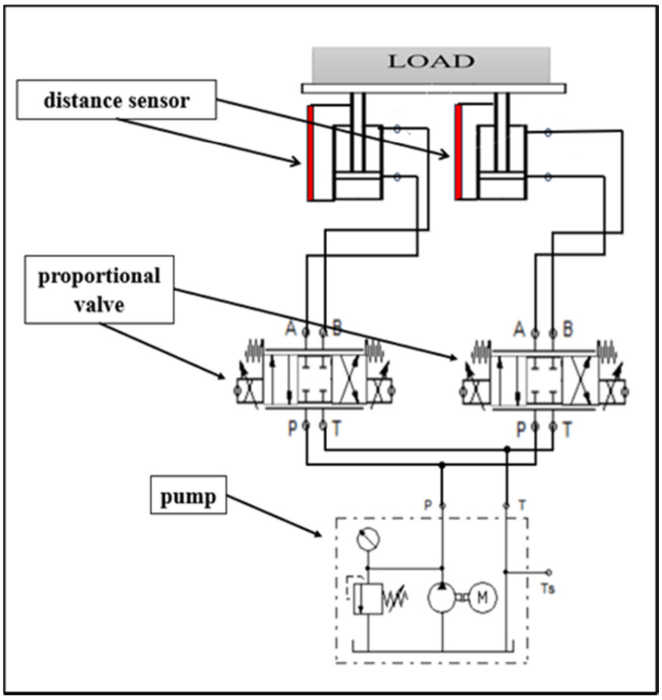

Fig. 2. Synchronous hydraulic system connected with proportional valves.

III. SYSTEM COMPONENTS

Proper flow management along with rapid position monitoring allows the two hydraulic cylinders to work in unison with the hydraulic system. The hydraulic cylinders serve as linear motion actuators by tracking the hydraulic fluid coming from the hydraulic pump system. Each hydraulic cylinder requires either conventional valves (Figure 3) or proportional valves (Figure 4) for fluid distribution control, to achieve synchronized operations.

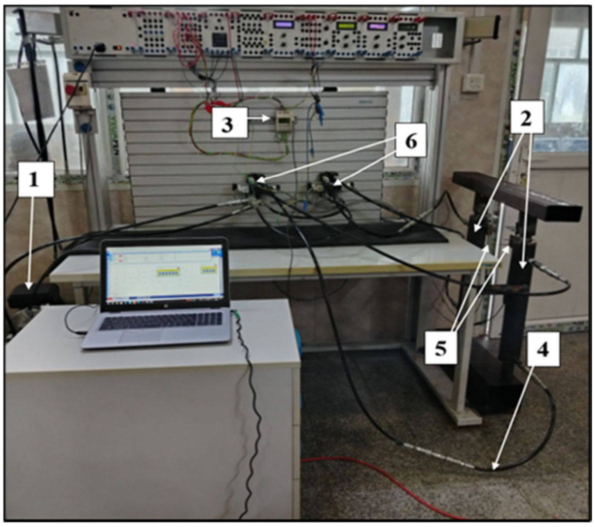

Fig. 3. Conventional valve control in closed loop by PLC systems.

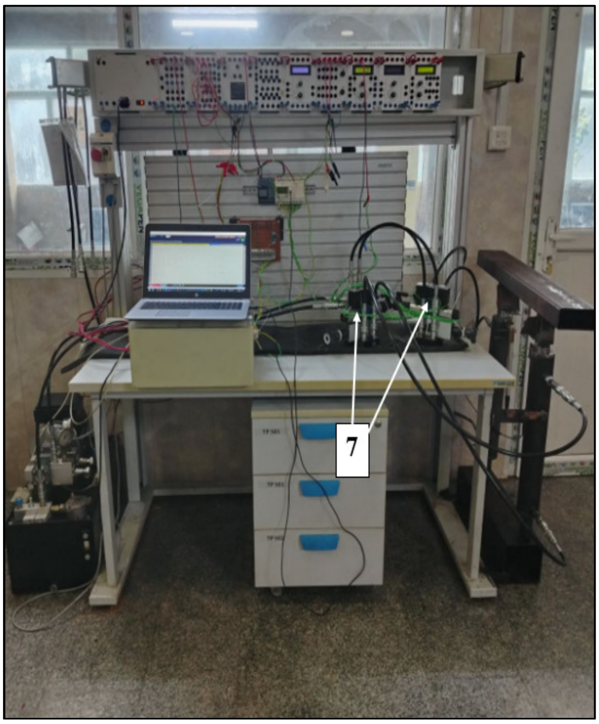

Fig. 4. Proportional valve closed-loop control through PLC systems.

Table I lists the parameters that define the hydraulic system, where distance sensors feed cylinder position data to a real-time control unit for analysis. The control unit conducts comparator processing of the cylinder positions until the valves obtain the adjustment signals needed for synchronized movement. The control system achieves improved performance through closed-loop feedback regulation in terms of accuracy, efficiency, and stability.

TABLE I. COMPONENTS OF A SYNCHRONOUS HYDRAULIC SYSTEM

Equipment	**Parameters**	**Value**	**Unit**	**Product number**
Power pact with AC motor	Nominal voltage	230	V	Festo 572128
	Rated output power	1.1	Kw	
	Delivery rate	2 ×3.7	L/min	
Double acting cylinder	Rod diameter	45	mm	No brand
	Borediametr	63	mm	
	Max Stroke	460	mm	
PLC	Discrete input voltage	24	VDC	Schneider Electric SR3B261BD
	Cycle time	6–9	ms	
Hose line with quick release couplings	DN	6	mm	Festo 159386
4/3 solenoid-operated directional control valve	Power supply	24	VDC	Bosch Rexroth R900561278
	Operated pressure	6	MPa	
4/3-proportional directional valve	Power supply	24	VDC	Bosch Rexroth 124359961
	Operated pressure	6	MPa	

IV. OPTIMIZATION AND EXECUTION OF SYNCHRONOUS HYDRAULIC CONTROL SYSTEMS

Pressurized fluid is transferred to conventional directional or proportional valves through the controlled operation of a hydraulic pump system. When the system activates the valves, it receives hydraulic fluid that directs flow directions to control the movement of the hydraulic cylinders. As explained in [22], hydraulic directional control valves operate in specific positions—fully open, partially open, or fully closed—which facilitates fluid flow regulation. Proportional valves offer expanded operational capabilities due to their ability to control the movement of hydraulic cylinders by adjusting flow rates and pressure levels based on electrical signals. According to [23], system developments require a PLC to track position sensor data that monitors both cylinders, as illustrated in Figure 5. The hydraulic fluid enters or exits the cylinders via valves that control their expansion or contraction, whether conventional or proportional. Flow rates in proportional valves change instantaneously, allowing the cylinders to operate at varying speeds and forces unattainable in conventional valve systems.

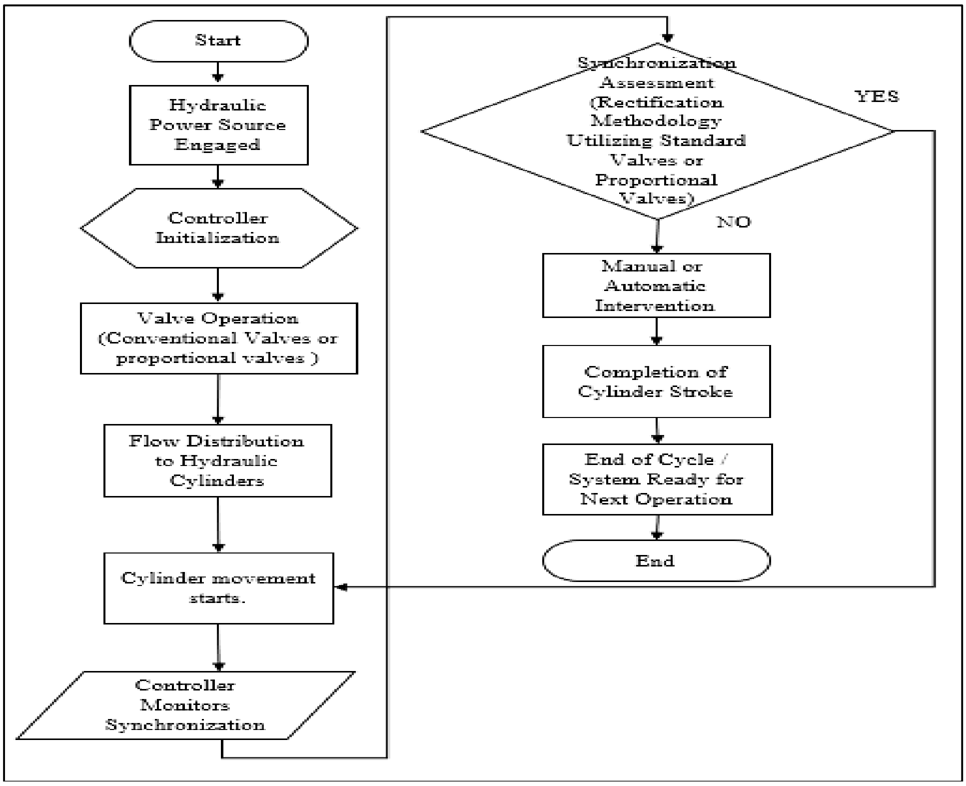

Fig. 5. Relative flowchart showing the correction mechanism of a synchronous hydraulic system.

A continuous comparison of the instantaneous sensor outputs from both cylinders allows the controller to examine the position and velocity characteristics. As described in [24], this method detects synchronization problems by analyzing position differences that exceed the tolerance limits. The system operates at acceptable levels when both cylinders are in parallel in terms of velocity and displacement measurements. This system enters a correction phase during which steady changes in cylinder positions occur for alignment purposes. The system's operating condition stabilizes again after appropriate adjustments are made. Operational synchronization requires manual correction by the operator when automatic methods fail to resolve discrepancies. Directional and proportional valves stop the hydraulic flow to the cylinders after reaching the target positions, allowing either mechanical maintenance of the desired endpoints, or a return to neutral positions. The hydraulic system either switches to standby mode or begins preparing for subsequent operations by restarting the process in Step 2. Energy consumption is significantly reduced when the hydraulic pump is shut down during the shutdown period. The main difference between conventional valves and proportional valves is their precise controllability and operating speed. Conventional valves maintain only two operating states, which limits the cylinder motion control and leads to poor performance when applying synchronization adjustments. As noted in [25], the continuous flow control capability of the proportional valves improves motion accuracy, which in turn improves cylinder motion control. The improved control provided by proportional valves offers significant benefits for synchronization applications, given the importance of precise and stable positioning requirements. Proportional valves improve system efficiency because they manage energy consumption by automatically adjusting the flow rates according to the current operating needs, beyond fixed valve operations. The performance capability, operational flexibility, and energy-saving aspects of the proportional valves provide benefits for complex and high-precision hydraulic systems.

V. OPERATIONAL FRAMEWORKS AND SYNCHRONIZATION APPROACHES IN HYDRAULIC SYSTEMS

A synchronization system consists of basic components, such as two hydraulic cylinders, two conventional or proportional valves, two distance sensors, and a control unit that operates through feedback control. The control unit maintains continuous system operation by obtaining position data from the corresponding distance sensors on each cylinder. Furthermore, these sensors transmit real-time cylinder position measurement data to the control unit. As analyzed in [26], the control unit continuously monitors the relative positions of the two cylinders by processing the position data. The monitoring system uses the real-time cylinder positions to verify synchronization between them. The control unit adjusts the hydraulic flow rates through the valves using the feedback information that exceeds a specified threshold. Through systematic processes, the control unit makes evaluation position adjustments based on the calculations to correct any synchronization errors.

VI. SYNCHRONIZED CONTROL AND CORRECTION MECHANISM OF HYDRAULIC CYLINDERS DURING THE ASCENTING PHASE

The hydraulic cylinders operate seamlessly and independently throughout the ascent phase, without the need for human assistance or corrective adjustments. The controller automatically intervenes to restore synchronization whenever a cylinder experiences a failure or misalignment during its movement. Corrective actions are triggered by the system when it detects a delay or deviation in the movement of the first cylinder, and the distance sensor (I_c) performs monitoring. The system maintains a synchronous movement by using the controller to match the speed of the first cylinder to the speed of the second cylinder, according to the distance sensor (I_d) detection, as presented in Table II. The feedback control system continuously evaluates the displacement and speed of both cylinders to implement real-time corrections.

TABLE II. CORRECTION CASES IN THE LIFTING STATE OF HYDRAULIC CYLINDERS

Symbol on ladder diagram in PLC	Cases	Reason
A1	$I_c = I_d$	The system operates error-free because its cylinder operations are executed synchronously in an uncorrected manner.
A2	$I_c < I_d$	When the first cylinder, related to the distance sensor(I_c), faces a problem or delay, the control unit increases its speed to achieve a match with the second cylinder, which is linked to the distance sensor (I_d).
A3	$I_c > I_d$	Here, the situation is reversed. The control unit increases the speed of the second cylinder connected to the distance sensor (I_d) whenever an error, or malfunction, or delay occurs to keep its operation synchronized with the first cylinder(I_c).

Distance sensors I_c (monitoring the first cylinder) and I_d (monitoring the second cylinder) transmit continuous position and speed data, enabling the controller to detect movement inconsistencies. The control system uses predetermined operating points as a reference to determine the extent of misalignment between the systems. The hydraulic fluid flow controls are adjusted by a conventional control valve by the controller to compensate for any acceleration or deceleration in the movement of the first cylinder. The instantaneous adjustment of the hydraulic flow through dynamic control synchronizes the speed of the first cylinder with the second, maintaining consistent movement patterns.

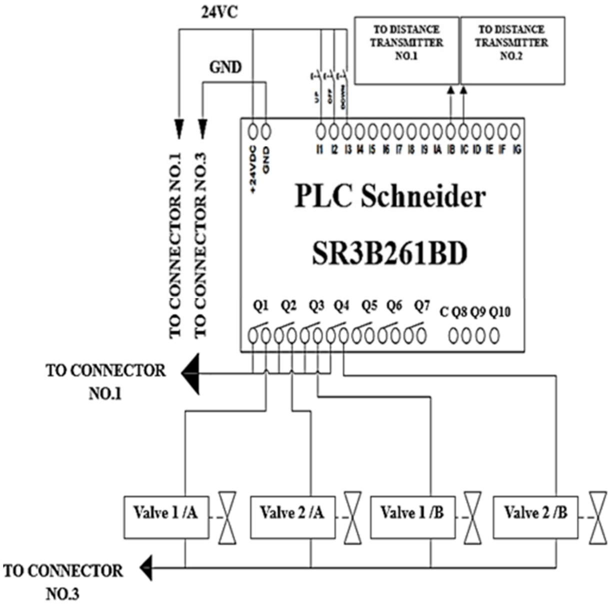

Fig. 6. Control unit with conventional valves and distance sensors.

In [27], the ladder diagram helps explain the control process by showing the sequential control logic that governs the synchronization processes. The deviation actuator operates within a closed-loop control system to achieve dynamic hydraulic synchronization by properly adjusting the flow. The structural design of the ladder logic creates an instantaneous monitoring and control system, improving the accuracy of the hydraulic cylinder, as shown in Figure 6. According to [28], through continuous feedback analysis, the system makes additional changes to the flow rate to address any detected deviations, ensuring stability between the various system components. The feedback control system maintains synchronization by acting as a basic mechanism that operates independently of the hydraulic pressure changes and internal and external disturbances. Any delays or speed problems detected in the second cylinder prompt the controller to adjust the valve flow rate to control the synchronization between the two cylinders. The real-time adaptive control system used by this system enables the hydraulic system to achieve precise, stable, and efficient synchronization, improving performance in industrial and mechanical applications.

Synchronous hydraulic systems operate by integrating proportional valves with amplification cards and controller devices, achieving a precise flow control over multiple hydraulic cylinders. As noted in [29], proportional valves provide adjustable control of pressure and flow, distinguishing them from conventional valves that operate in fixed open and closed states, producing smooth and adaptable outputs. The controller typically operates as a PLC, monitoring both the displacement and speed of each cylinder by processing real-time data from position sensors mounted on the cylinders. When the PLC receives feedback, it uses analog voltage signals, such as 0–10 V, to send them to an amplification card, which generates corresponding proportional electrical current outputs. The proportional valve's solenoid coils control their position through these electrical currents, which determine the position of the valve spool and control the flow of hydraulic fluid to the cylinders. The control system maintains valve opening adjustments to achieve synchronous cylinder expansion and contraction, preventing unwanted movements, mechanical shocks, and speed changes. The control unit automatically corrects when synchronization errors are detected to maintain normal motion. The system maintains its efficiency because both cylinders require identical performance in terms of speed and motion. The system requires immediate action in the event of any deviations, including when one cylinder moves at a slower speed than the other. The control unit ensures flow rate adjustments through relative valve position adjustments to ensure the misaligned cylinder reaches the speed and position of the second cylinder.

According to [30], the hydraulic cylinders operate independently to perform their work during the ascent phase. Any alignment problems or system failures trigger the control system to detect the problems, which triggers synchronization restoration. The correction process increases the speed of the slower cylinder by 25% to synchronize with the faster cylinder, and thus maintain a constant displacement, as portrayed in Table II. A continuous monitoring of the motion feedback of both cylinders ensures that the control system makes effective adjustments to the speed and displacement. The two distance sensors track the position and speed of each cylinder; the I_c sensor provides monitoring data for the first cylinder, while the I_d sensor performs the same function for the second cylinder. By detecting real-time feedback, the system instantly adapts to compensate for variations, ensuring a smooth and precise movement. Successful synchronization requires that the PLC programming follow a ladder diagram control scheme. The logic program detects deviation signals, making automatic corrections to maintain constant stability across system cycles. Position data from the two cylinders are transmitted to the PLC, which changes the proportional valve settings via the flow control amplifier card. The correct operation of the voltage regulation, as well as the protection of the proportional valve performance, depend on the internal 10 kΩ, 0.25 W resistors embedded in the amplifier card, as shown in Figure 7.

VII. SYNCHRONOUS CONTROL AND CORRECTION MECHANISM OF HYDRAULIC CYLINDERS DURING THE DESCENT PHASE

The primary operational objective during the descent phase of a synchronous hydraulic system is to coordinate the motion between two the hydraulic cylinders. The descent correction mechanism is the exact opposite of the ascent mechanism. The system applies a correction mechanism to achieve synchronization when the descent of the first cylinder is delayed, as detected by the distance sensor Ic. The controller continuously monitors the distance sensors I_c and I_d, which collect data from both cylinders regarding their position and speed information. The controller performs real-time calculations when descent delays occur to determine the speed adjustments necessary to align the first cylinder with the second cylinder connected to the sensor I_d, as illustrated in Table III.

TABLE III. CORRECTION CASES IN THE EVENT OF HYDRAULIC CYLINDERS GOING DOWN

Symbol on ladder diagram in PLC	Case	Reason
A1	$I_c = I_d$	The system operates error-free because its cylinder operations are executed synchronously in an uncorrected manner.
A2	$I_c < I_d$	The second fast cylinder attached to the distance sensor (I_d) automatically decelerates to match the speed of the first cylinder linked to the distance sensor (Ic).
A3	$I_c > I_d$	Here, the opposite happens: the speed of the first cylinder connected to the distance sensor (Ic) decreases to be in line and synchronized with the second cylinder connected to the distance sensor (I_d).

As described in [31], conventional valve correction requires immediate adjustment of the fluid velocities supplied to the faster cylinder. Four-way/three-way directional control valves enable users to achieve precise management and directional control of the hydraulic fluid flow. The controller uses the control valve to reduce the fluid flow to the second, faster cylinder, slowing it down to match the speed of the first cylinder to correct errors. The controller maintains corrections until both cylinders reach positions within acceptable error limits. The feedback loop actively evaluates the cylinder speeds and positions and continuously assesses the success of the correction. The system continues to use the adjusted flow rate until the end of the descent phase, when the speed detection results match. The system alerts operators with an error signal when the correction fails or exceeds the specified limits. The programming sequence within the PLC is defined through a step-by-step flowchart to manage operations effectively [32]. These flowcharts clearly depict the signal path and control instructions of the system. The flowchart illustrates the logical steps to track the continuous signal inputs from the distance sensors I_c and I_d. The PLC compares the position and speed data from both sensors. When a delay in descent occurs, the control logic determines and activates the appropriate output, which sends a signal to reduce the flow of the conventional valve to help delay the accelerated cylinder movement. A "ladder logic" system performs safety checks to prevent the valve from exceeding the safety limits and implements rapid and accurate corrective responses. The same correction mechanism applies if the first cylinder is faster, adjusting and correcting it.

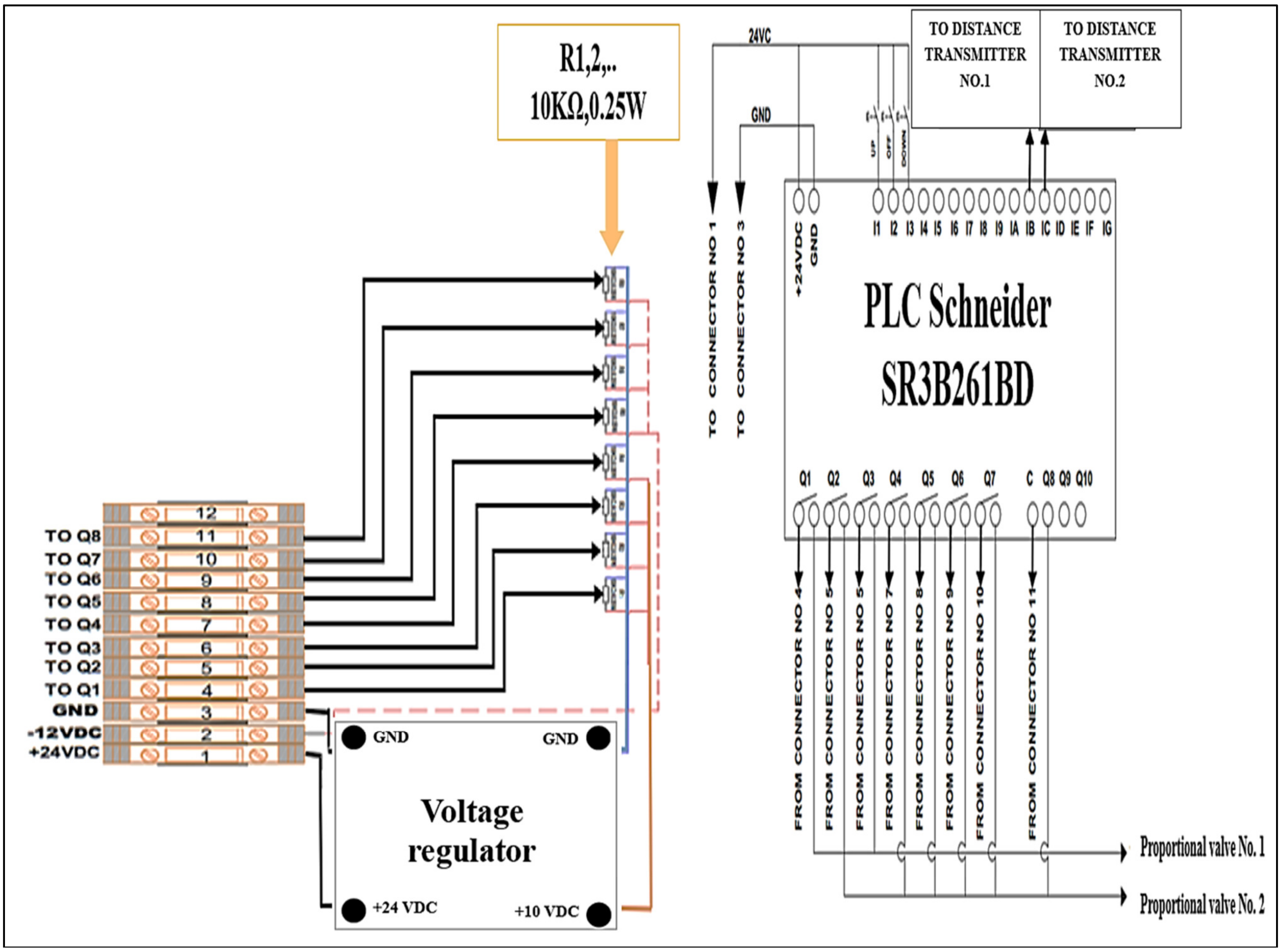

Fig. 7. Control unit with proportional valves and distance sensors.

The descent correction process in a hydraulic synchronization system uses proportional valves to control the flow rates, just as it maintains proper positional alignment between the various cylinders. The corrective action operates identically regardless of misalignment or synchronization issues in the first or second cylinder. The system continuously tracks information about the positions of the two cylinders via position sensors. Real-time data transmissions from the sensors to the control unit enable calculations to determine the gap between the desired cylinder positions and their current actual positions. As mentioned in [33], if any discrepancy is detected—i.e. one cylinder is lagging behind the other during the descent procedure—the control unit generates an error signal proportional to the degree of misalignment. An amplification card processes this error signal, raising the control signal to a level suitable for proportional valve operation. The amplification card also ensures signal stability and responsiveness. The control unit then sends the amplified signal to the proportional valve that controls the faster cylinder, i.e., the cylinder lagging behind in the descent process.

The proportional valve reduces the flow rate to the faster cylinder by 25%, making it descend more slowly than the master cylinder. The proportional valve achieves flow regulation, resulting in smooth acceleration by eliminating the sudden mechanical stress while maintaining system operation. The flow rate returns to normal upon synchronization, ensuring a constant movement between the cylinders.

According to [34], real-time position data flow through closed-loop control systems, enabling the controller to continuously update the data until the desired dynamic changes are made. This control system follows a ladder diagram structure, corresponding to input modules that collect sensor data, processing blocks that calculate errors during the execution of control algorithms, and output modules that actuate the valve. In real time, a feedback loop corrects position errors to achieve and maintain a precise synchronization during the descent process.

VIII. RESULTS AND DISCUSSION

Both conventional valves and proportional valves use 10.5 bar pressure settings but show diverging performance in the flow rate control and system speed for the hydraulic system. The conventional valve used a 3.7 L/min flow rate because it presented fixed flow characteristics that were less adaptable. Conventional valves work in an on-off fashion along with stepwise operations, yet these mechanisms produce sharp flow and pressure fluctuations that might cause synchronization-related mechanical stress and oscillations. Varying loads and cylinder positioning differences become obstacles for the system because of this operational design. The proportional valves boosted flow rate to reach 4.3 L/min when attached to the hydraulic system. The proportional valve controls fluid flow with precision because it produces increased flow rates in response to input signals. The proportional valve system enables smooth fluid control instead of abrupt changes through its operation, which improves synchronization accuracy and reduces the hydraulic component stress. The proportional control works to quickly identify misalignments because these occur primarily during descent, where gravitational forces affect the cylinder movements. The proportional valves ensure a rapid cylinder movement and swift reaction speeds that excel in motion coordination and delay reduction. The system kept its stability and safety even though higher flows occurred because proportional valves consistently maintained their 10.5 bar operating pressure. The transition from the conventional to proportional valves leads to improved precision along with reduced machine vibrations and accelerated dynamic responses, which results in a sturdy synchronized machine that operates stably under conditions with changing parameters.

A. Case Study 1

The precise coordination between the primary and secondary hydraulic cylinders enables the hydraulic system to operate optimally when there is no force acting on the system, as depicted in Figure 8. Figure 9 shows the response of the hydraulic system when connected to a conventional valve and when connected to a proportional valve, comparing it with the system's reference value.

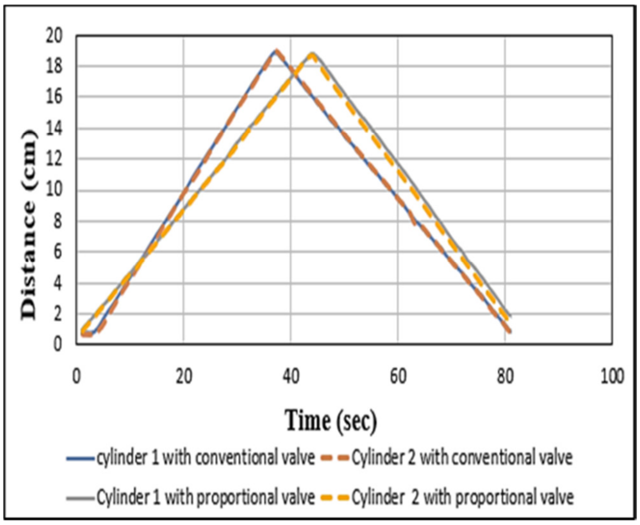

Fig. 8. Response of dual hydraulic cylinders under no load.

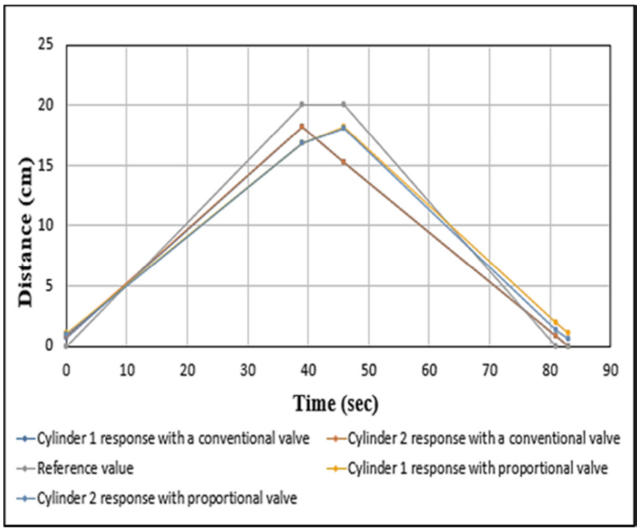

Fig. 9. Evaluation of the effect of valve type on the hydraulic system response to the reference inputs under no applied force.

B. Case Study 2

A weight of 10 kg was applied to both the first and second cylinders, as illustrated in Figure 10. Figure 11 displays the response of the hydraulic system when connected to a conventional valve and when connected to a proportional valve, comparing it with the system's reference value.

C. Case Study 3

The alignment of the first hydraulic cylinder remains parallel to the second, regardless of whether the system uses conventional or proportional valves. A weight of 40 kg acts on the first cylinder, while the second remains empty, as shown in Figure 12. Figure 13 demonstrates the response of the hydraulic system when connected to a conventional valve and when connected to a proportional valve, comparing it with the system's reference value.

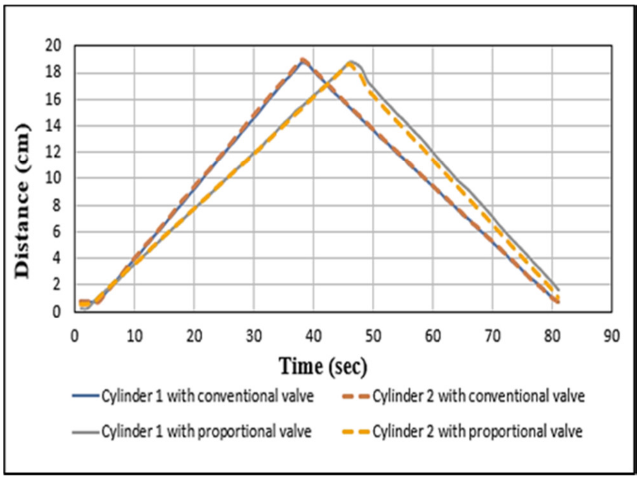

Fig. 10. Response of dual hydraulic cylinders under symmetrical loading conditions.

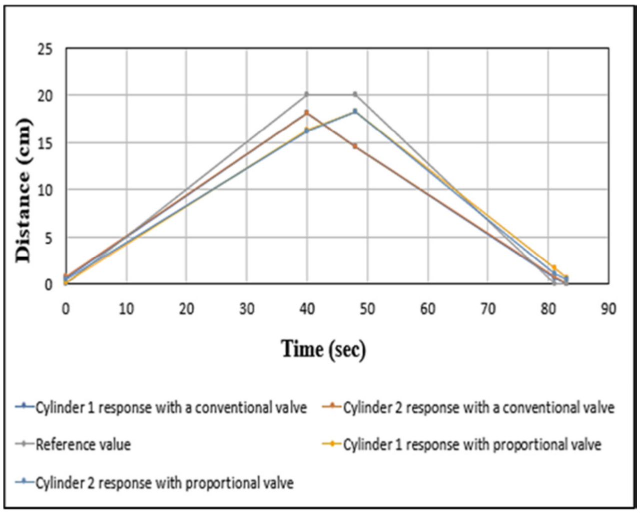

Fig. 11. Evaluation of the effect of valve type on the response of the hydraulic system for the reference inputs under the condition of applying a similar load of 10 kg.

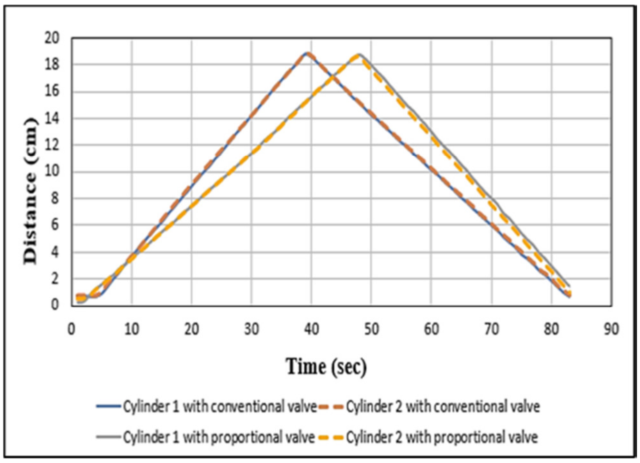

Fig. 12. Response of dual hydraulic cylinders when a load of 40 kg is applied to the first hydraulic cylinder only.

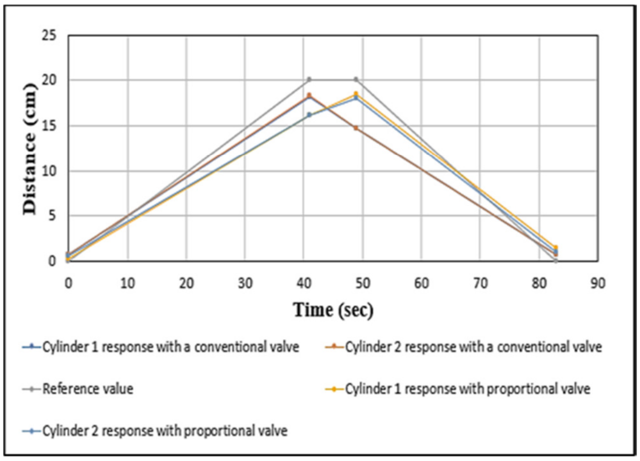

Fig. 13. Evaluation of the effect of the valve type on the response of the hydraulic system to the reference inputs when a load of 40 kg is applied to the first hydraulic cylinder only.

D. Case Study 4

The two hydraulic cylinders operate sequentially, using either conventional valves or proportional technology. A 40-kg load rests on the second cylinder, while the first operates unloaded, as presented in Figure 14. Figure 15 depicts the response of the hydraulic system when connected to a conventional valve and when connected to a proportional valve, comparing it with the system's reference value.

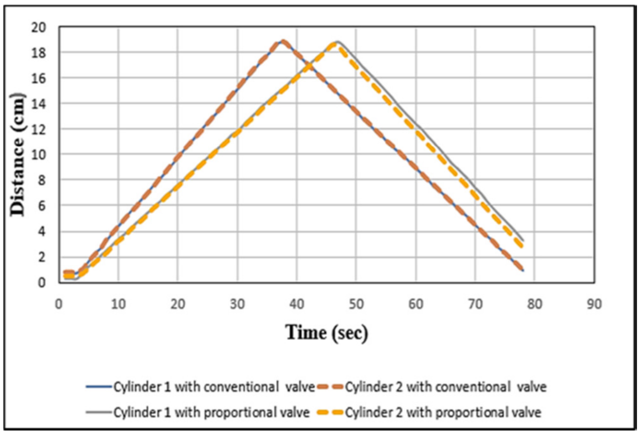

Fig. 14. Response of dual hydraulic cylinders when a load of 40 kg is applied to the second hydraulic cylinder only.

E. Case Study 5

The synchronization of the first hydraulic cylinder with the second hydraulic cylinder occurs. The investigators applied 2.7 kg weight to the first cylinder and similarly weighted the second cylinder. The two cylinders received an additional weight of 35 kg positioned between them, as illustrated in Figure 16. Figure 17 depicts the response of the hydraulic system when connected to a conventional valve and when connected to a proportional valve, comparing it with the system's reference value.

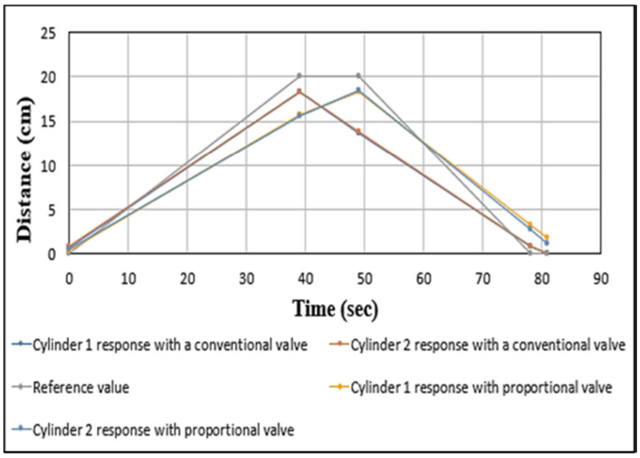

Fig. 15. Evaluation of the effect of the valve type on the hydraulic system response to the reference inputs when a load of 40 kg is applied to the second hydraulic cylinder only.

Under equivalent operating conditions, the synchronization effectiveness showed similar results between the conventional and proportional valves, according to the experimental evaluations. The hydraulic system operated at steady-state conditions when conventional valves were used to regulate the flow, despite the valve's prerequisites for flow control. Changes in the load parameters or the occurrence of nonlinear system behavior affected the synchronization accuracy in terms of deviations from the setpoint. Deviations from the expected values were associated with a slow return to steady-state conditions after these events. In [35], it was demonstrated that using proportional valves as real-time position controllers enhanced the system response and positioning accuracy under dynamic and variable load conditions.

The better response time and precise control characteristics of proportional valves outperformed solenoid valves, but their extended synchronization performance showed identical results. The results demonstrated that properly integrated conventional valve systems achieve identical synchronization results to those of the proportional valves under steady-state operating conditions. The complexity of the systems and their operational context, as well as the overall costs determine the valve selection, rather than relying solely on the synchronization capabilities. Table IV presents the synchronization evaluation by comparing reference paths under different valves, providing measurements of the error percentage. Table V displays the permissible synchronization deviation and the observed synchronization accuracy across all test setups. The evaluation used a cylinder travel of 20 cm as the reference, and set a 2% stroke length threshold, equivalent to 0.4 cm, as the synchronization tolerance limit. This limit was selected because it provides satisfactory results for practical use scenarios. Synchronization deviation testing was conducted to measure the displacement difference between the hydraulic cylinders from the 0 to 20 cm expansion phase and the 20 to 0 cm return phase, with no external load applied. Accurate synchronization quality evaluations used high-precision instruments, consisting of dispersion gauges and diffusometers, to detect positional changes. The system was further tested at multiple incremental pressure levels, starting at 2.7 kg and progressing to 10 kg, then 35 kg, and then 40 kg, to observe the mechanical response patterns. When operating under no load or light load, the automatic control system-maintained synchronization deviations of less than 0.4 cm, which meets acceptable operating standards. Synchronization accuracy declined with an increasing applied load, as multiple testing limits were exceeded, especially under heavy load conditions. Advanced intelligent control solutions must be developed to maintain synchronization accuracy in environments with high load fluctuations.

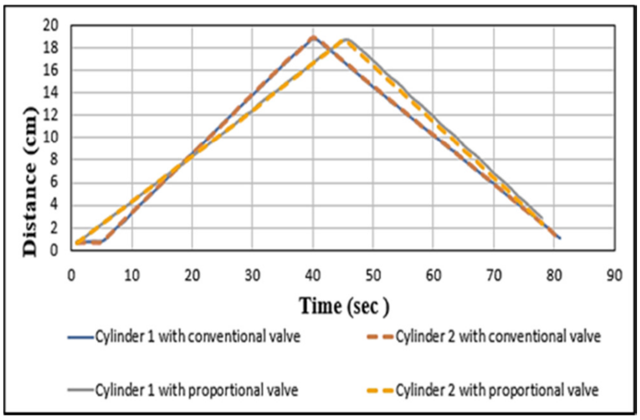

Fig. 16. Response of dual hydraulic cylinders under central and asymmetric loading conditions.

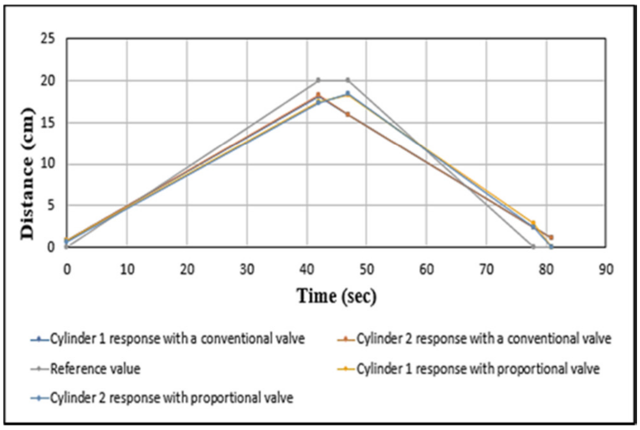

Fig. 17. Evaluation of the effect of valve type on the hydraulic system response to the reference inputs under central and asymmetric loading conditions.

This work advances the scientific knowledge on hydraulic actuator synchronization through a systematic evaluation of the conventional valve control systems and proportional valve control methods. The study confirms the findings of previous research [36], which shows that the conventional valves successfully achieve results comparable to those of the modern proportional valves if properly designed. The synchronization accuracy performance depends on the type of control valve, but additional external variables, such as system nonlinearity and load variations, also affect this result. The research indicates that proportional valves offer superior adaptability and precise control accuracy under dynamic conditions, while conventional valves represent a cost-effective approach for maintaining reliable synchronization in stable systems. The experimental results of [37] demonstrate that intelligent digital control strategies successfully achieve a balanced motion control in hydraulic systems to accomplish a precise synchronization of hydraulic cylinders. This research provides important results through evaluations of the synchronization performance under various operating conditions and load patterns, which reinforces previous theoretical assumptions. The findings enable designers to make better decisions about hydraulic systems by providing performance-based analysis, along with control complexity assessment and economic evaluation. The results of this research serve as an engineering reference tool that helps professionals select appropriate valve systems based on synchronization objectives and application settings.

TABLE IV. ERROR RATE EVALUATION BETWEEN MEASURED SYSTEM RESPONSES AND REFERENCE VALUES UNDER DIFFERENT VALVE TYPES

Case	**System**	**Reference value (cm)**	**First cylinder response (cm)**	**Second cylinder response (cm)**	**Error rate (%)**
1	Conventional valve	20	17.58	17.61	12.02
	Proportional valve	20	17.52	17.51	12.42
2	Conventional valve	20	17.57	17.61	12.05
	Proportional valve	20	17.72	17.61	11.67
3	Conventional valve	20	17.65	17.67	11.70
	Proportional valve	20	17.75	17.46	11.97
4	Conventional valve	20	17.62	17.61	11.92
	Proportional valve	20	17.45	17.64	12.27
5	Conventional valve	20	17.44	17.47	12.72
	Proportional valve	20	17.66	16.83	13.77

TABLE V. SYNCHRONIZATION ACCURACY AND PERMISSIBLE DEVIATION LIMITS IN HYDRAULIC CYLINDER MOTION.

Permissible concurrency limit (%)	**Synchronization accuracy deviation (%)**
2	0.15
2	0.05
2	0.20
2	0.55
2	0.10
2	1.45
2	0.05
2	0.95
2	0.15
2	4.15

IX. CONCLUSION

The present research evaluated the synchronization abilities of hydraulic systems by examining conventional and proportional valve control methods. It is demonstrated that synchronized actuator performance becomes possible with both conventional and proportional valves if their operating parameters match each other. Standard valves maintained acceptably synchronized performance through baseline flow control principles, while their accuracy depended on system load parameters and operating conditions. The fast response characteristics of the proportional valves resulted in better real-time control regarding synchronization accuracy both during brief changes and changing loads. The observed improvements in proportional valves' adaptive performance did not result in major differences when compared to direct-current valve synchronization for both steady-state operations and balanced loads. The selection process between the conventional and proportional valve control requires an analysis of particular system requirements, such as complexity level, cost, and performance specifications. Proportional valves excel in delivering precise responses to dynamic conditions, but well-designed conventional valve setups produce equivalent synchronization results when systems operate with stability. The findings from this study provide essential empirical guidance to the designers of hydraulic systems by establishing a scientific modeling approach for actuator synchronization valve choice.

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