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Experimental Hardware-in-the-Loop Centrifugal Pump Simulator for Laboratory Purposes

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Abstract: A hardware-in-the-loop (HIL) experimental test-bench is suggested for a rotodynamic pump in this paper. The HIL simulator is composed of two separate modules and two variable-speed drive (VSD) systems that are connected with the help of a programmable logical controller (PLC) and a process field bus unit. One of the fundamental components of the suggested simulation approach is the mathematical representation of a rotodynamic pump system embedded into HIL. A number of tests were conducted in order to study the suggested simulation approach. The experiments demonstrated the developed system's adaptability and precision in replicating the behavior of the rotodynamic pump in various operation modes. A special user interface for the HIL simulation allows for changing the types of preloaded pump characteristics, reading the output data, and controlling operational parameters. The obtained simulation results showed that the proposed approach can be suitable for research purposes.

Keywords: centrifugal pump; hardware-in-the-loop; experimental test-bench; education; variable-speed drives; induction motor; pumping system; PLC

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1. Introduction

Centrifugal pumps are complex electromechanical devices that combine hydraulic, mechanical, and electrical parts. For simplification purposes, a centrifugal pump system can be presented as a centrifugal pump itself connected to an induction motor. Usually, these parts are coupled without using a gearbox thanks to the high rotation speed of the induction motor. Centrifugal pumping systems are a significant part of any modern water production and distribution industry. They also play an important role in sewerage systems. It is impossible to imagine the proper functioning of a huge variety of industrial, household, and commercial applications without pumps in modern society [1,2]. To ensure the stable operation of centrifugal pump systems, it is necessary to apply advanced and sophisticated control algorithms. There are a variety of control techniques available to increase their efficiency and decrease energy use [3,4]. Centrifugal pumps are among the biggest consumers of electrical energy, and thus it is also important to consider issues with regard to rising greenhouse gas emissions and the price of conventional fossil fuels.

A large number of approaches have been put forth to investigate the potential of optimizing pumping systems [5]. As shown in the literature [6], one way to express the objective function J of a centrifugal pump's optimum operation is as follows:

- E—a particular pump of multi-pump system;

$$J = \sum_{e} \int_{t_i}^{t_f} [c_e Q_e(t) + b_e H_e(t) Q_e(t) / \eta(Q_e(t))] dt, \quad (1)$$

- t_i—the initial time of operation;
- t_f—the final time of operation;

- c_e—the unit cost of water production;
- b_e—the unit price of energy;
- $Q_e(t)$—the flow of the pump;
- H_e—the energy head;
- $\eta(Q_e(t))$—the efficiency as a function of flow.

The dependences between the flow and the energy head are expressed by a non-linear function and are shown in Equation (1). A dynamic, non-linear system is described by the equation. There have been numerous attempts to find a generic method to solve the above-mentioned equation. In fact, it is quite hard to come up with a general solution to this equation. Designing flexible and straightforward enhancement solutions is required because finding a generic answer is challenging. By looking at some of the defining qualities and specifications of centrifugal pumps, the task can be solved in a simplified way.

1.1. Prototype and Software-Based Simulation Approaches

It is typical practice to research these systems using prototypes and simulation to investigate complex electro-mechanical systems and to obtain better results through the application of both methods. Both of these methods can effectively forecast how the system would behave in practice and characterize its attributes. The first strategy's key drawback is that it is expensive and requires quite a long preparation period for the development of a physical twin.

However, using merely the capabilities of contemporary simulation hardware and software environments, the second strategy, which involves simulation, can assist in obtaining results. Software tools such as Ansys CFX for turbomachinery, ETAP PS or SIMUL8, products from MathWorks, for power system modeling and validation, or optimizers based on neural network architecture are already available and are targeted to perform a variety of simulations in many engineering domains [7–10]. The ability to save time and money compared to physical prototyping is the key benefit of using computer simulations.

In [11], the authors propose a novel excitation approach of variable-speed pumping storage, utilizing the possibility to implement voltage source techniques instead of the traditional current source approach to simulate the transient processes of a complex pumping system. The electrodynamics parameters of the rotor of an electrical machine for variable-speed pumping storage were taken into account. Then, they were investigated by a classical analytical approach. This approach involved mainly the application of differential equations. For usage in real life, a multistage hybrid simulation approach is suggested in [12]. In the beginning, a just-in-time model (JITM) was built using comparable data gathered from a tested system. The modeling technique was then updated to include the helpful process knowledge of pumping plants. By substituting some field sensors for the suggested data-and-knowledge hybrid simulation approach, process variables could be obtained online, improving the effectiveness of the performance prediction. In [13], the authors carefully simulated the losses within hydraulic machinery, and a theoretical model for the energy performance of the rotodynamic machines in the pump and turbine operation mode was proposed. A flowrate-based iteration strategy was suggested to find the best efficiency point (BEP) in the turbine mode based on the theoretical simulation approach. In addition, a thorough analysis of the pump with respect to the turbine (PAT) performance and losses in the pump and turbine operation modes was conducted.

In [14], the authors investigated the feasibility of employing computational fluid dynamics (CFD) to implement them as a major tool for pump designers and engineers to assess pump performance. The possibility of such an approach is examined in this work. An approach for using computational fluid dynamics simulations to confirm pump properties, including energy head, pump unit efficiency, and flowrate of fluid, is presented and positioned as a major tool for conceptual pump design. To examine the fluid dynamics of four distinct pump intake structures, a multiphase simulation employing the volume-of-fluid (VOF) approach is used. In order to circumvent scaling concerns discovered during the lower-scale physical model test, a full-sized computational fluid dynamics model of the pumping plant was employed for the intake structure study. The findings offered a clear picture of the hydraulic phenomenon and the pumping plant system's distinctive curves. Among the different intake component designs, a decline in performance in terms of a reduction in the total dynamic head (TDH) was projected. A comprehensive understanding of the differences in the vortex, flowrate direction, and impact on the pump efficiency between the four situations was given by the computational fluid dynamics modeling of the intake structure. Since the computational fluid dynamics findings for the pump's operational curve had the ability to coincide with the provided performance curve, it was demonstrated that the grid independence research presented in this work, which was conducted with only one flow condition, in this case at 90 percent of the flowrate close to the best efficiency point, was sufficient. The application of a hybrid simulation approach based on both Matlab/Simulink and ABB DriveSize simulation environments is proposed in [15]. The energy head and pressure control for a single-drive pumping plant were calculated using a model that combined the advantages of both pieces of simulation software. The model's capacity to forecast the energy efficiency of a centrifugal pump system at different working points during pressure regulation utilizing either throttling or speed control depending on the desired energy head level and pipework hydraulic resistance is one of the proposed simulation approach advantages. The model exhibited a sufficiently high accuracy in a variety of simulation states that replicated the physical phenomena that occur in a real centrifugal pumping plant system. In [16], the authors checked the viability of the concept of using a pump as a turbine at one of Saudi Arabia's hydrocarbon distribution facilities to partially recover the excess power dissipated from pressure-reducing valves installed on the discharge outlets of oil industry product shipping pumping plants. The possibility of such an approach was examined in this study. To accomplish this, a number of pumps as turbine installation configurations were investigated, with the best layout ultimately chosen to enhance the energy recovery. Based on the manufacturer's pumping plant performance curves, a new technique for forecasting the pumping plant characteristics in reverse mode was created. The proposed simulation results either had the smallest deviation or the second minimum deviation out of all the models when compared to real data obtained from the experiments with experimental setups. In the three different modes of operation, the anticipated variation for the flow ratio prediction was only 3.83 percent, 1.14 percent, and 1.35 percent. According to the economic research carried out by the authors, the capital payback period (CPP) for five of the best pumps used as turbines was approximately five years. In comparison to earlier models, the new technique demonstrated a more accurate performance forecast of multistage pumping plants operating in a turbine state. In [17], the pipework of a pumping plant's complete flow field was numerically simulated in steady-state and transient modes using the open-source program OpenFOAM 5.0 throughout a large operational capacity range of 0.3 to 1.4 from the nominal capacity. In the flow-controlling equations, the standard shear-stress transport vortex models were chosen. The steady-state and transient computations/were performed using the basic Foam and basic DyMFoam solvers, respectively. The obtained flowrate speed, pressure, and streamline distributions were displayed using OpenFOAM's postprocessor ParaView, which was also utilized to examine the connection between the vortex and the pump's hydraulic loss. Taking into account the modelled flowrate fields, the exterior performance characteristics of the pump, including the head, mechanical power on the shaft, and pumping plant's efficiency, were also computed. With the same calculation model, hydraulic characteristics, and boundary conditions, the test results and pump performances predicted by OpenFOAM and Ansys-Fluent were compared in this study. The comparison indicated that OpenFOAM predicted that the pumping plant's characteristics in the current state had a high level of accuracy. The pressure at the suction side of a pumping plant was believed to be high enough in the current study to prevent cavitation. In actuality, cavitation always happens and negatively impacts the efficiency of operation of a pump system.

A novel method taking into account the intrinsic operating characteristics of a centrifugal pump was proposed in [18] to estimate the parameters of a complete pumping plant in order to solve the problem related to the lack of documentation provided by the manufacturer. A mathematical model representing all of the features of a pumping plant was derived using the Euler approach that included the application of equations and the speed triangles at the suction inlet, which was connected through the housing volute to the impeller. Following this, a nonlinear dependency between the values of the characteristic operating points and a given speed was developed using several recorded complete pumping plant parameters. The complete pump characteristics for a particular specific speed were successfully forecasted by combining the mathematical model and the nonlinear dependencies. According to the authors, in a case study, the forecasted complete pump characteristics were essentially in line with the observed data, demonstrating a high level of accuracy.

1.2. HIL-Based Simulation Approaches

The aforementioned simulation approaches have numerous shortcomings, constraints, and simplifications. The following details are the most important among these approaches. The same stator coils and rotor bars are taken into account in the motor models. It is assumed that the air gap distance between the armature and the stator is steady and unaffected by the rotor allocation. The fluctuation of these parameters in rotodynamic machines for pumping plants exceeds several percent. The majority of variable-speed drive manufacturers guarantee that their equipment includes semiconductors with precise resistance recalculations caused by conduction, switching, reverse leakage, and component heating to reduce temperature instability, which improves the accuracy of control signal counting. The models do not have this capability. Another issue is that the simulated power electronic converters are frequently regarded as ideal voltage source inverters. The simulated process distortion and control errors are caused by the absence of consideration of the DC link voltage fluctuation whilst at the same time ignoring asymmetric phase currents. Models for voltage and current sensors are also idealized. For high-level references, it is common to have highly saturated and non-linear characteristics that are typically neglected, resulting in erroneous simulation results. The simulation of direct torque control units, which includes electrical machine models, Clarke and Park transforms, voltage-switching blocks, and regulators, calls for special focus. Every variable-speed drive producer actually offers their own specific hardware topologies, algorithms, and software packages for their execution. Unproved instruments cannot correctly and accurately represent this implementation. At the same time, the use of affinity rules, which can only be applied efficiently within an established narrow speed range, is what causes problems in the majority of pump models. Their accuracy decreases when the rotodynamic machine has a large friction head compared to the static head, under-speeding, overloading, and other conditions. In this regard, the primary issue is due to fluid transient mitigation, which leads to considerable differences between the expected and real flow rates in the application of affinity laws. The proposed research focused on another simulation strategy that is appropriate from the perspective of a full-scale variable-speed drive-fed pump analysis in light of the aforementioned disadvantages.

The hardware-in-the-loop (HIL) methodology is presented in this paper to enhance the overall productivity of centrifugal pump system modeling and testing by combining the benefits of both approaches [19,20]. This study offers such a strategy of hardware-in-the-loop implementation that has not been developed much in the field of pumping systems. HIL simulation presumes system analysis utilizing a mathematical representation of a centrifugal pumping system for software specifically developed for that purpose. In this simulation environment, the real-world equipment components are incorporated using an experimental test bench made of two electric drives connected to each other.

The hardware-in-the loop technique combines two types of models, namely software and hardware models, to analyze the hydraulic and mechanical properties of the centrifugal pump system and estimate the system's energy consumption. This hardware-in-the-loop methodology is a helpful approach for handling the challenging simulation work involved when the hardware system used for the simulation communicates with the mathematical representation of the pumping system.

In the following sections, how to capture motor-driven pump parameters utilizing a hardware-in-the-loop simulation methodology is discussed. Models of actual pumping system equipment with integrated hardware devices and software solutions were created. The electrical motors of the centrifugal pump were applied using their inherent control systems, but the pumping capacity was replaced with specially created emulators, whose initial description was ambiguous. A double-motor arrangement was built and used as a generic pump prototype in order to explain the model topology and characteristics. Hence, the benefits of mathematical representation and physical modeling were coupled with the best possible relationship between the two methodologies.

2. Main Principles of Pumping Plant Operation

Many separate parts make up a typical pumping plant system, including a pump, an electrical machine, couplings, bearings, seals, and tubes or pipes connected to the discharge outlet. The pump is the primary mechanism in charge of transferring the liquid. An electrical machine supplies the energy to run the pump. The connection joins the electrical machine and pump together. The rotating components of the pump are held in place by bearings. Pump leaks are avoided by using special seals. The fluid is transferred from one location to another through the pipework.

The primary features of the pumping units are usually included in the technical specifications provided by pump manufacturers. Among these specifications are so-called head (H)–flow (Q) dependencies, efficiency (η) characteristics, and power (P)–flow (Q) dependences. As was noted, it is challenging to express these dependences using analytical equations because of the complex and non-linear nature of the characteristics of primary hydraulic and mechanical pumps. Hence, the empirical dependences provided by manufacturer aid in examining the features of pumping plant systems and forecasting the system's behavior during control operation.

In order to investigate the pumping plant system using a simulation approach, look-up tables can be introduced using the dependences between the key properties described above. Figure 1 depicts the relationships between the primary pump properties during regulation.

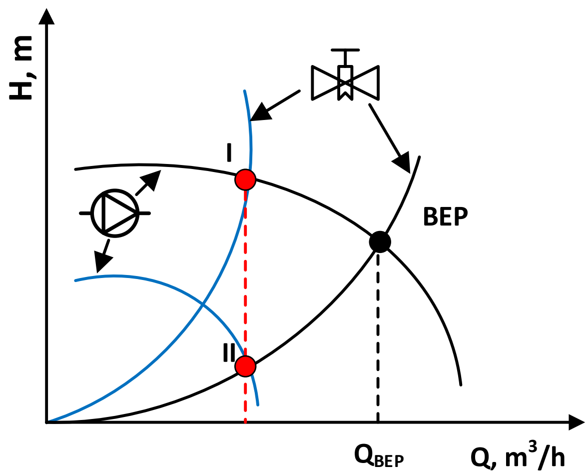

Figure 1. Operation points and hydraulic curve dependences.

The position of the operation point, which defines the primary system parameters such as flow, energy head, pressure, efficiency, and others, is marked by the dots at the intersection of the pumping plant performance curve and system curve. Manufacturers often graphically present information that contains the characteristics of primary pumping plants. Obtaining the values of the primary pump characteristics at any working point is important in order to compute the system's total input power.

The manufacturer's head (H)–flow (Q) performance curve typically solely relates to the pumping plant's rated rotational speed. The performance curve in Figure 1 for a given pumping application's unique system curve, which depicts the pump hydraulic characteristics brought on by a particular design, can be used to describe said application according to the general expression [21,22]:

$$H(Q) = H_0 + C_K Q^2, \tag{2}$$

where H_0 is the so-called static head, and C_K is the head friction coefficient.

Most of the additional features are likewise provided for the nominal velocity. The affinity rules allow for the discovery of similar properties for different speeds [23]:

$$\frac{q_{is}}{q_{rs}} = \frac{n_i}{n_r}, \frac{h_{is}}{h_{rs}} = \left(\frac{n_i}{n_r}\right)^2, \frac{P_{is}}{P_{rs}} = \left(\frac{n_i}{n_r}\right)^3, \tag{3}$$

where q is the flowrate, n is the rotational speed, h is the energy head, and P is the power on the shaft. The index r links the coordinates of specific working points of an s-th operation characteristic, and at the same time the index s links the points of an operation characteristic curve for the s-th rotational speed, and the index i links the points on the rated operation characteristic curve. These equations are used to recalculate pump characteristics for various rotational speeds. When a centrifugal pump operates with an excessively viscous fluid, the standard Equation (3) is not entirely applicable for performance estimation [24].

There are two major ways to modify a centrifugal pump's flow rate:

- The method of throttling that employs a regulating valve;
- The variable-speed-drive-based speed control technique.

The pumping unit's operating point moves horizontally to the right or left along the operational curve when the throttling control is applied depending on where the regulating valve is positioned. Throttling thus has an impact on the position of the system curve. On the other hand, when speed variation causes the position of the performance curve to vary, the operation point moves along the line that represents the characteristics of a pipeline.

3. HIL Simulator

The main layout of the developed hardware-in-the-loop system for pumping plant simulation utilizing speed and torque adjustment and based on variable-speed drives is shown in Figure 2. The developed HIL platform was custom-designed and supplied with the equipment provided by the ABB company.

The HIL imitator is based on a combination of hardware and software parts. The main duty of the simulator is to couple the central processing unit (CPU) operating two types of variable-speed drives. The first one imitates the pumping unit while the second one imitates the network connected to the discharge side of the pumping plant. In the case of primary hardware-in-the-loop, the block equally incorporates the physical equipment and the control part of the fully functional pumping unit's variable-speed drive with an identical topology to an actual variable-speed drive [25]. Another block, also based on a hardware-in-the-loop simulator, was built to imitate the network connected to the discharge side of a pumping plant. The third block was built with the help of a programmable logic controller (PLC) connected to the aforementioned variable-speed drive. It contains an originally developed toolkit designed to simulate a pumping unit with specific modules. The ABB DriveWindow software and the specifically designed user interface were incorporated in the last block. The details of the electrical machines and variable-speed drives of the hardware-in-the-loop test bench can be found in [26,27].

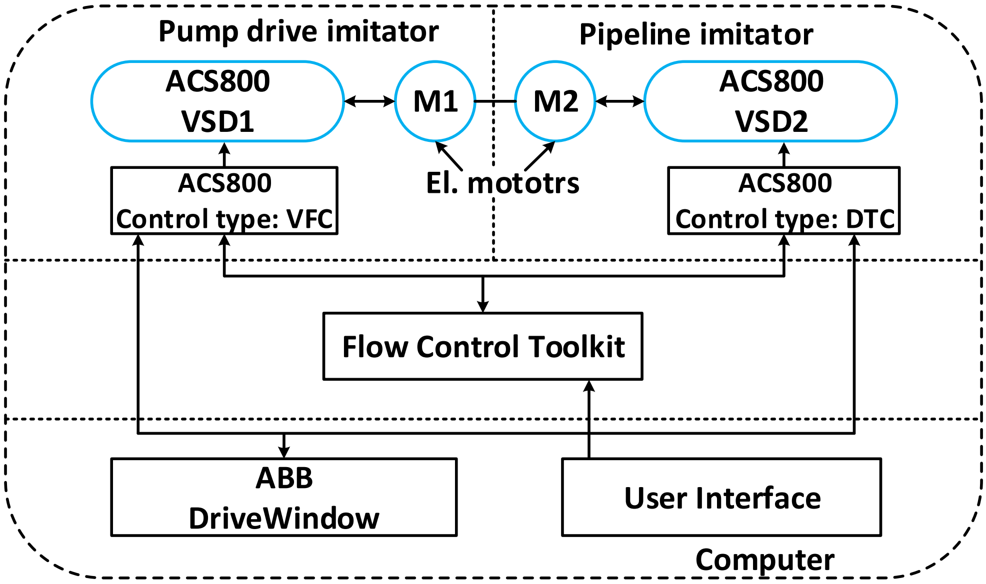

Figure 2. HIL centrifugal pump and pipeline imitators.

The ABB DriveWindow software was applied to regulate the various parameters of the hardware-in-the-loop test bench and measure the current data as well as to carry out data collection. It can also be helpful for representing the real-time information from the sensors in the form of graphs [28,29]. Variable-frequency control (VFC) and direct-torque control (DTC) were also applied. For the control purposes of the first block, variable-frequency control was applied since the major goal of the variable-speed-drive pumping unit is the regulation of the rotor's angular velocity. In order to imitate the discharge network of the pumping unit, direct-torque control was chosen due to the fact that the primary goal of the second module is to manage the torque.

An AC500 programmable logic controller allows for general control and communication between both parts of the simulator. During the control process, the pump drive simulator provides the reference pumping speed. On the other hand, the pipeline simulator applies the necessary torque to the rotor of the second electrical machine, enabling the system to maintain all operational parameters. The torque value is considered by the system as a variable that depends on the angular velocity of the matching shaft. The integrated electrical machine's mathematical model and the electrical data measured by the sensors are used in the direct torque control system to calculate the torque value. A diagram of the AC500 programmable logic controller for the first module of a hardware-in-the-loop test-bench is displayed in Figure 3.

There are several main parts of the PLC, including the CPU PM573, which is a main central processing unit capable of storing and computing the data received from the electrical drives, and a personal computer connected to the PLC. CM572 DP is a Profibus communication block that helps to establish communication between the CPU and the Profibus DP adapter module RPBA-01. The Profibus adapter device RPBA-01 connects the electrical drives to the PLC and plays the role of an interface by sending and receiving data based on the drive parameters. DA501 is a digital–analog in/out block that can be used to apply external control signals and to read data by using additional measuring equipment [30].

Electrical three-phase motors, electronic power converters, remote panels, a cabinet with electrical equipment, housing, measuring tools, and communication equipment were all included in the experimental setup consisting of two motor drives from ABB's ACS800 series. These two electrical drives were mechanically connected to each other. Two units with six IGBTs in each and with bidirectional switches were included in the electronic power equipment. The ACS800 device also had model-based monitoring tools based on the developed software that enabled the displaying and tracing of real-time signals. The

HIL setup had integrated logical processors for the programming of the inverter's outputs and inputs in order to handle the main operations related to control options and data processing. A series of optical wires connected each drive to the central processor. The HIL experimental setup can help in the load- and speed-dependent analysis to find the best equipment configurations.

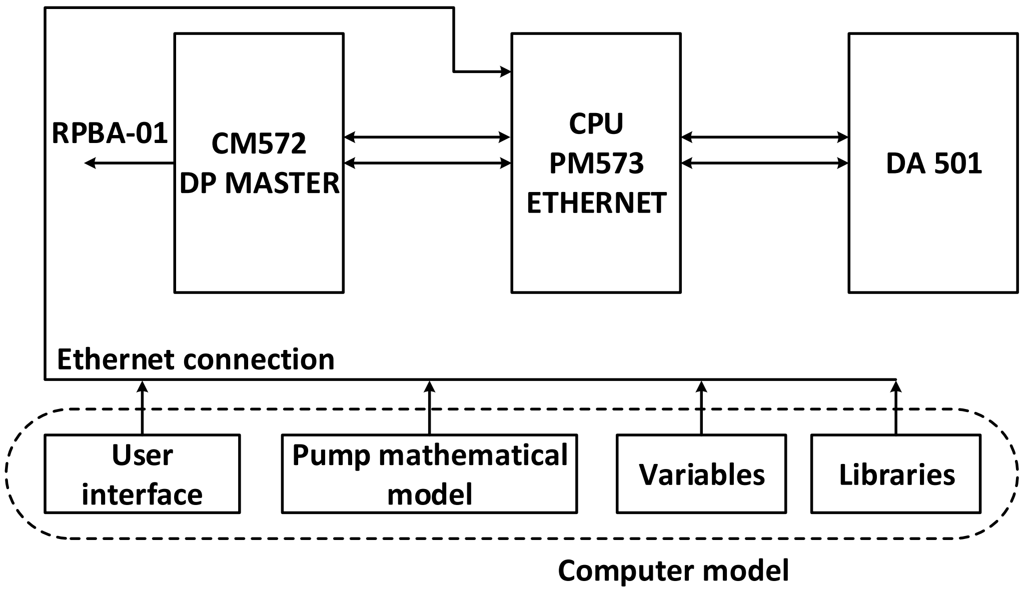

Figure 3. AC500 PLC structure.

The three primary hydraulic parameters that defined the pumping system were Q, p, and H. The main attributes that defined the system operation were the flo—energy head in Equation (2) and the flow–pressure curves that are available and provided by pumping system manufacturers. The dependences of the pumping system shaft's torque and mechanical power were expressed in the following form:

$$T = T_0 + k_T n^2, \quad (4)$$

$$P = P_0 + k_p n^3, \quad (5)$$

where T_0 and P_0 represent the no-load torque and mechanical power, the rotational speed is n, and k_T and k_P are the coefficients. The torque and power on the shaft were connected according to the following equation:

$$P = \omega T = T \frac{2\pi n}{60}, \quad (6)$$

Based on Equations (3) and (6), it was possible to find dependences between the various torques corresponding to different rotational speeds:

$$\frac{T_2}{T_1} = \left(\frac{n_2}{n_1}\right)^2, \quad (7)$$

The special software used in this study was developed in a System CoDeSys environment [31]. The layout of the user interface is shown in Figure 4. The software was coded with the help of structured text language (STL) [32]. It had buttons to select the system variables, a control bar, the start/stop buttons for VSD1 and VSD2, and numerical indicators for the motor parameters. The indicators could be used to track the system characteristics.

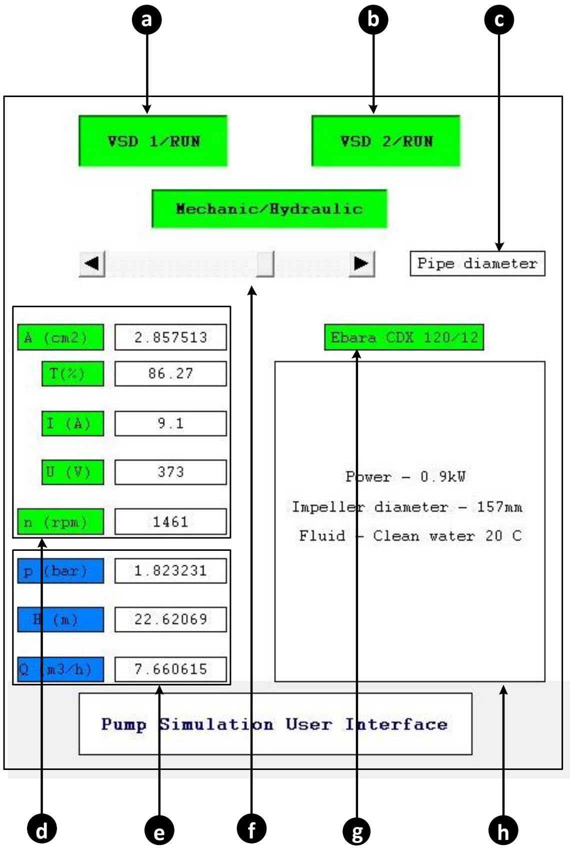

Figure 4. Software developed to control HIL test-bench.

In the above:

- *a*—start/stop button for the loading variable-speed drive;
- *b*—start/stop button for the testing variable-speed drive;
- *c*—an indicator of the second variable-speed drive's velocity in the case when the key "Mechanic/Hydraulic" was switched off or the pipe diameter when the key "Mechanic/Hydraulic" was switched on;
- *d*—an indicator of electromechanical properties;
- *e*—an indicator of hydraulic properties;
- *f*—used to adjust the second variable-speed drive's velocity when the key "Mechanic/Hydraulic" was switched off or the pipe diameter when the key "Mechanic/Hydraulic" was switched on;
- *g*—a drop-down menu for pump selection;
- *h*—showed the main characteristics of the selected pump.

4. Simulation Results

To evaluate the mechanical characteristics, several tests were carried out with the help of the developed HIL simulator, as shown in Figure 5. The HIL simulation results for the torque–speed characteristics and real pump characteristics are shown on the same diagram.

To obtain the torque–speed characteristics, it was necessary to gradually increase the rotation speed of the pump imitator, and at the same time the appropriate values of the torque response were obtained. With the help of the ABB DriveWindow toolkit, it was possible to find the power–speed curve, as shown in Figure 6. The maximum error between the simulation and experimental results was 3.2% for the T–n characteristics and up to 4% for the P–n characteristics.

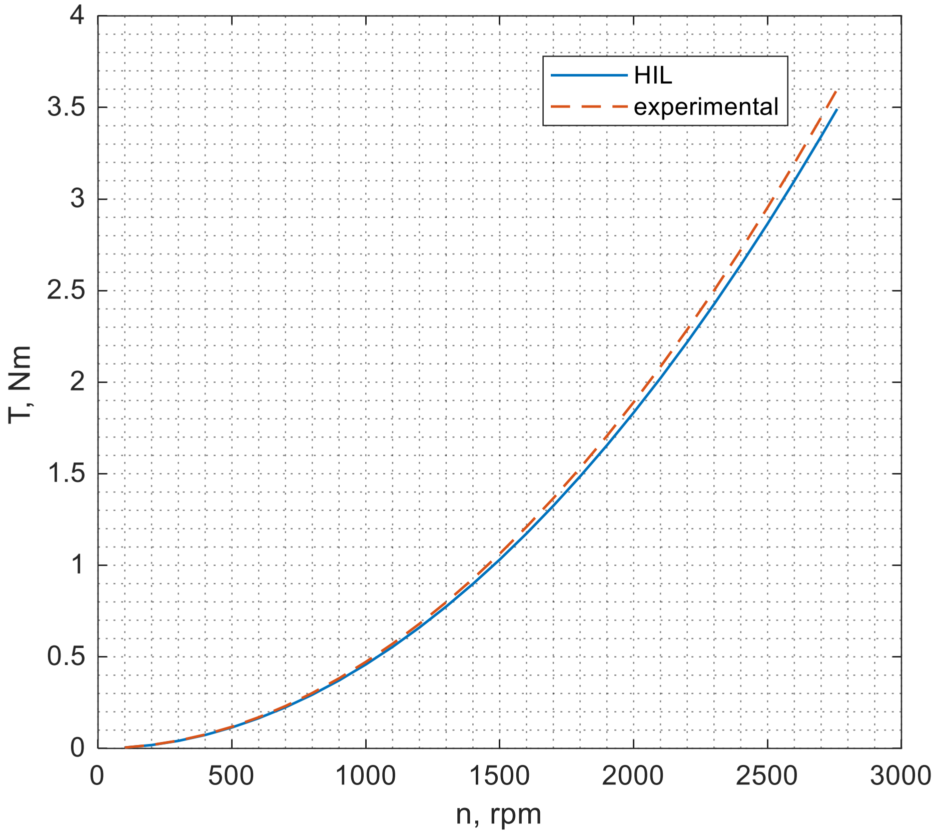

Figure 5. Torque–speed (T–*n*) characteristics of the simulated and real pumps.

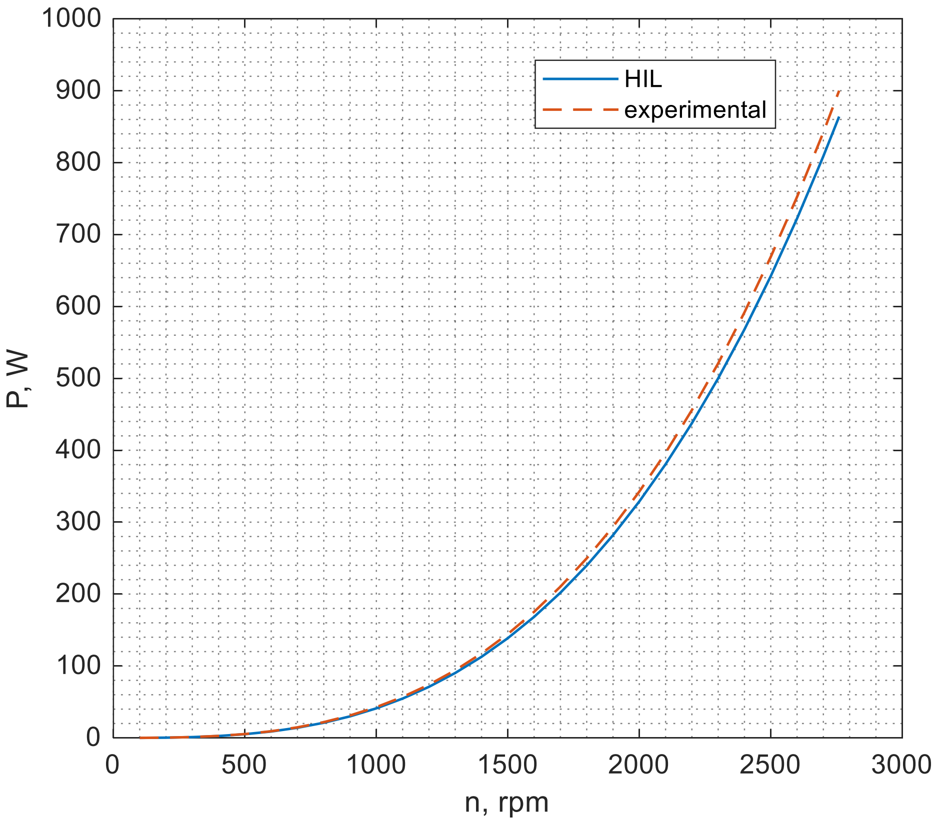

Figure 6. Power–speed (P–*n*) characteristics of the simulated and real pumps.

To derive the performance curve of the simulated pump, the flow–pressure curve, which is described by Equation (2) in a general form, was obtained with the help of gradually varying the pipe diameter at a constant nominal rotation speed corresponding to 2670 rpm, as shown in Figure 7. At the nominal rotational speed, the nonlinear function *H*(Q) could be easily approximated from the data table provided by the pump's producer. In most cases, the characteristics between the power on the pump shaft and the flowrate P(Q) are also available in the datasheets. Taking into account the fact that the dependences between the torque and the power on the shaft are described by Equation (6), it was possible to recalculate the P(Q) curve into the T(Q) curve. The P(Q) curve is normally given for a nominal rotational speed. For various rotational speeds, the torque–flowrate characteristics can be obtained with the help of Equation (7).

The characteristics were simulated for the EBARA CDX120/12 centrifugal pump with the following characteristics [33–35], as shown in Table 1. The two pairs of curves correspond to different rotational speeds. The upper pair corresponds to the nominal speed and the lower one corresponds to a speed of 1800 rpm, which was approximately 65% of the rated speed. The maximum obtained error in comparison with the real pump was up to 2.7% at the nominal rotational speed. At the same time, the maximum error corresponding to 65% of the rated speed was 3.1%. Both results showed accuracy during the simulation process.

Table 1. Characteristics of EBARA CDX120/12 centrifugal pump.

	kW	m^3/h	RPM	Nm
Power	0.9	-	-	-
Flow (max)	-	9.6	-	-
Speed	-	-	2760	-
Torque	-	-	-	3.6

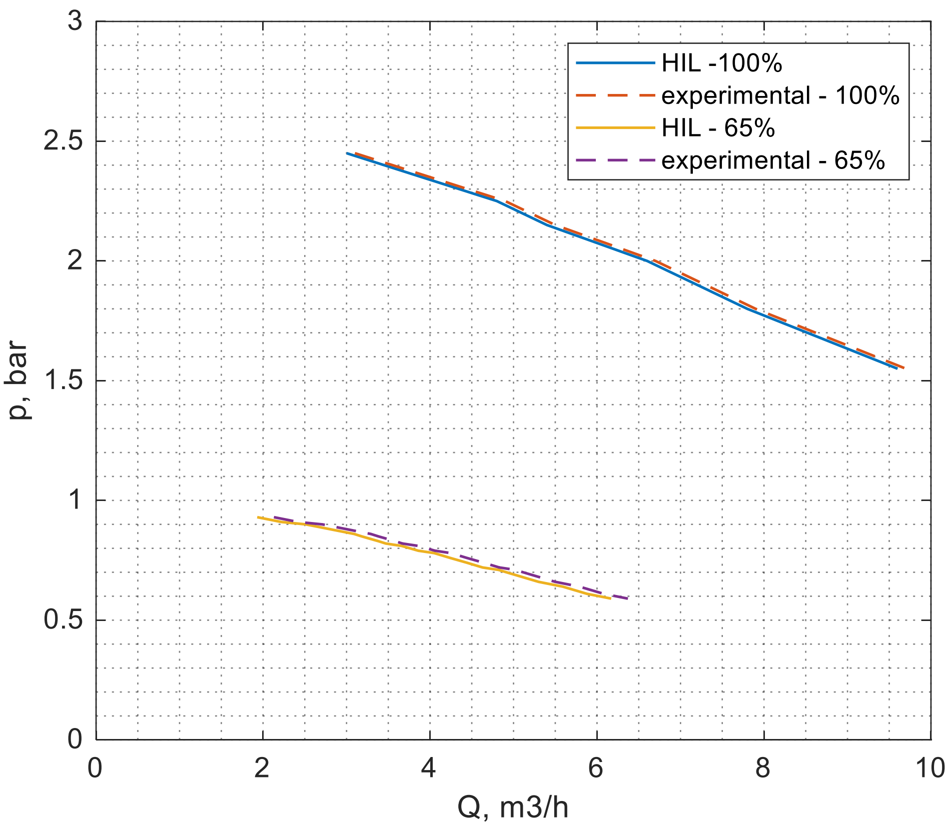

Figure 7. Flow–pressure (p–Q) characteristic of the simulated and real pumps at rated and 65% of the rated speed.

It was shown that it is possible to explore the mechanical characteristics of centrifugal pumps with the help of the HIL approach based on the proposed platform. Thanks to the developed setup and software, it was feasible to obtain all the necessary T–n, P–n, and p–Q curves related to the particular pumping unit for further simulation in the HIL environment. To simulate the mechanical characteristics of the centrifugal pump, a specific load corresponding to a flowrate in a real centrifugal pump system was applied to the pipeline imitator. The proposed HIL platform could be used later for investigating the different aspects of pumps. For instance, it could be helpful for the development of physical prototypes and experiments with various mechanical characteristics of pumps or for the examination of drive systems to obtain the optimal and suitable configuration based on the required load and speed.

In addition, the test results showing the T–n, P–n, and p–Q responses of the proposed original HIL platform for the centrifugal pump simulation proved the appropriateness and accuracy of the HIL system. The HIL platform could serve as a suitable simulation approach. The system was able to accurately simulate both the mechanical and hydraulic responses corresponding to a real centrifugal pump system. Another advantage of the proposed simulation system is its scalability, which allows for simulating different centrifugal pump systems with technical characteristics different from the technical characteristics of the HIL platform. The original software developed for the simulator, in addition to the software tools available on the market and those provided by the manufacturers, helped to create functional tool for the proposed HIL platform. One of the advantages of the HIL system is that the real electronic power components were integrated into the platform, allowing for the use of the proposed platform for energy management simulation, thus taking into consideration the losses in the VSD system of the centrifugal pump.

5. Conclusions

A novel HIL simulation platform for a centrifugal pump was presented in this paper, and the developed simulation approach was described. The designed experimental setup consisted of two main parts, namely a pump and pipeline imitators. The first one was responsible for the speed control of the simulated pump, which was achieved by utilizing the VSD for the speed control. The second imitator was applied to simulate the behavior of the torque response caused by the outgoing flow through the pipeline connected to the outlet of the centrifugal pump. The obtained performance characteristics were accurate in a broad range of operations.

This research offers the utilization of the original HIL system, while the investigated pumps were substituted with specially built replicas. In contrast to many industrial fields where hardware-in-the-loop simulations are becoming popular, there have not been many studies related to the application of similar HIL approaches for the exploration of pumping systems. The novel method enables the taking into account of diverse motor driving characteristics for pumping operations at various load torques and speed ranges. Reducing prior ambiguity and exploring processes with uncertain characterizations are made possible by the inclusion of real equipment in the simulation cycle.

The hardware-in-the-loop simulation test-bench shows flexibility, and the examinations carried out demonstrated that the proposed system is appropriate for the investigation of pumping plants. The results of the simulations were accurate compared to the real pump investigated. They showed flexibility, including the scalability of the proposed HIL platform. A hardware-in-the-loop model can be used for different purposes including teaching, especially for courses concerning electrical drives, hydraulics, and automation, and research activities in the field of pumping systems. At the same time, in accordance with the simulation tasks, the proposed approach can give developers and customers information about the system performance during operation when the pumping system is running in a regular mode. The HIL platform can be used in future research as a tool for testing different energy management strategies for centrifugal pump systems.

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