Power Hardware–in–the–Loop Testing of Pump–Inverter Drives in Water Distribution Networks

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ABSTRACT

In this study, a Hardware-in-the-Loop (HIL) framework is presented for the laboratory evaluation of pump-inverter drives in water distribution systems. The platform includes an electric pump, a variable frequency drive, and a stepper valve as a controllable hydraulic load, integrated with the real-time simulation of the remaining water network. To validate the HIL simulation results, a mathematical model was developed and implemented in a Model-in-the-Loop (MIL) configuration. Comparative analyses demonstrate a very close agreement between the two methods. The Root Mean Square Error (RMS) for the output flow rate, discharge pressure, and pressure drop was found to be 0.18 lpm, 0.009 MPa, and 0.011 MPa, respectively, with a maximum relative difference of less than 4.1%, confirming the high accuracy of the proposed system. Static and dynamic tests were conducted to identify system behavior. In static tests, the relationship between valve opening, flow rate, and pressure at various motor speeds was examined, while dynamic tests demonstrated the framework's capability to reproduce transient responses and capture nonlinear effects such as hysteresis. Furthermore, a variable frequency drive equipped with a Proportional-Integral-Derivative (PID) controller was utilized for pressure regulation, exhibiting stable and robust performance under varying initial conditions. The results indicate that the developed HIL simulation approach is effective for studying the performance and control of pump-inverter systems, providing a suitable balance between laboratory realism and modeling flexibility. This framework offers a reliable tool for system validation and can support future developments in energy-efficient control, fault analysis, and intelligent water management.

KEYWORDS

Power Hardware–in–the–Loop (PHIL), Pump–Inverter Drive, Water Distribution System

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1. Introduction

Pumping systems are vital for fluid transmission, yet conventional regulation methods cause significant energy losses [1], which variable-speed drives (VSDs) successfully mitigate by matching pump speeds to actual demand across various applications [2, 3]. However, managing complex multivariable dynamics requires advanced dynamic evaluation beyond static curves [4], prompting the use of Power Hardware-in-the-Loop (PHIL) simulation to enable real-time, bi-directional interaction between numerical models and physical hardware [5]. Building upon these foundations, this study implements a comprehensive real-time PHIL testbed integrating network simulations with physical pumps and inverters, with three primary contributions: designing a fully coupled PHIL testbed for transient dynamic testing; establishing a rigorous quantitative cross-validation framework between Model-in-the-Loop (MIL) and HIL environments using statistical error metrics; and optimizing closed-loop stability via a dedicated UDP-based communication protocol and digital filtering to mitigate network delays and sensor noise.

2. PHIL Experimental Setup

The developed Power Hardware-in-the-Loop (PHIL) testbed integrates real-world hardware—comprising an electro-pump, an inverter, and a stepper-motor-actuated control valve—with a real-time simulated water distribution network. The architecture consists of three core layers:

a) Real-Time Simulation Core: Modeled in MATLAB/Simulink with a fixed time step (100 Hz / 10 ms sampling rate), this layer simulates the hydraulic network dynamics (pipes, storage elements, and demand patterns) and establishes system boundary conditions.

b) Physical Hardware Layer: Features a real electric pump and inverter to capture complex non-linear electrical and mechanical dynamics, alongside an adjustable stepping valve that acts as a controllable hydraulic load to emulate varying consumer demands without needing large-scale physical test rigs.

c) Communication and Interface Layer: Bidirectional data exchange between the simulated and physical domains is executed in real time via a UDP networking protocol, achieving an average communication delay of under 2 ms.

To ensure closed-loop system stability and mitigate phase shifts caused by network latency or sensor noise, first-order low-pass filters are applied to pressure and flow feedback signals, supplemented by a packet-loss handling protocol that retains the last valid data point when necessary. Physical instrumentation includes 24V pressure transmitters (yielding 4–20 mA analog signals) and a 5V turbine flowmeter (calibrated via a rotameter), with data acquisition managed centrally through a Programmable Logic Controller (PLC) linked to the real-time target environment.

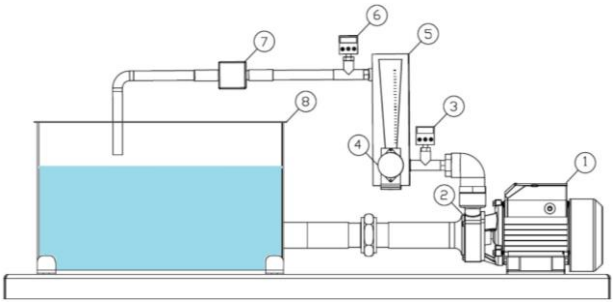


Figure 1. Schematic of the PHIL Experimental Setup

3. Model-in-the-Loop Simulation

To validate the accuracy of the hardware-in-the-loop (PHIL) framework, a comprehensive mathematical model of the pumping and water distribution system was developed to serve as a reliable reference benchmark. This hybrid model incorporates both electrical and hydraulic domains:

a) Electric Motor Modeling: The induction motor is modeled using a rotating reference frame to capture stator and rotor fluxes, electromagnetic torque generation, and mechanical shaft rotation. The variable-frequency drive (VFD) and inverter are represented through averaged pulse-width modulation (PWM) dynamics to preserve primary voltage and current behaviors while reducing computational load. The motor's acceleration is governed by the torque balance between electromagnetic torque, mechanical friction, and the resistive torque exerted by the pump and fluid.

b) Centrifugal Pump Modeling: The pump is characterized by non-linear affinity laws linking head, flow rate, and torque to rotational speed. Quadratic head-flow relationships account for kinetic energy generation and hydraulic losses across different operating points.

c) Control Valve and Network Modeling: The adjustable stepping valve is modeled as a variable hydraulic resistance where discharge depends on valve opening degree and pressure differentials, simulating consumer demand variations and transient disturbances. Pipeline and storage dynamics are integrated using continuity and momentum principles, with head losses calculated via standard friction formulas.

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Finally, the Simulink-based modular architecture allows seamless integration between Model-in-the-Loop (MIL) and Hardware-in-the-Loop (HIL) environments, facilitating real-time data exchange via UDP protocols to evaluate steady-state and transient responses under controlled conditions.

4. Results

Figures 2–4 compare the experimental HIL results with the mathematical MIL model under periodic demand variations over 120 seconds. Figures 2 and 3 show that the model closely reproduces the cyclic changes in flow rate and discharge pressure. Figure 4 presents the flow-rate–valve-opening relationship, including the hysteresis between the valve's opening and closing paths. Overall, the results demonstrate good agreement between MIL and HIL and confirm that the model captures the system's key dynamic behavior.

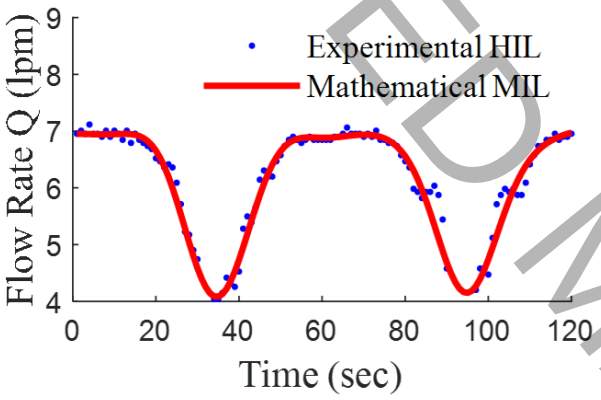


Figure 2. Flow-rate comparison between HIL and MIL

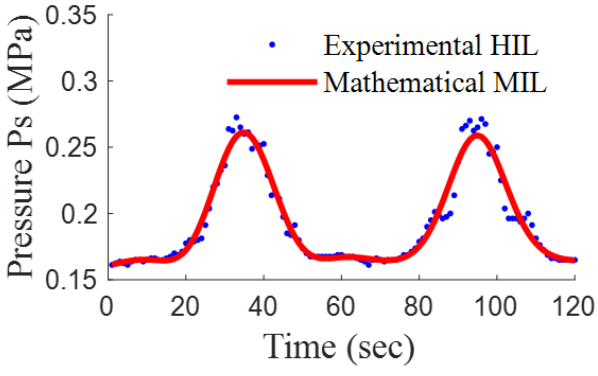


Figure 3. Supply pressure comparison between HIL and MIL

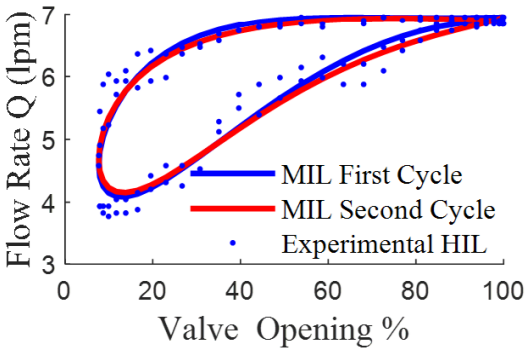


Figure 4. Flow rate versus valve opening, showing hysteresis

5. Conclusions

This study successfully developed and experimentally validated a Power Hardware-in-the-Loop (PHIL) and Model-in-the-Loop (MIL) framework to evaluate variable-speed pump systems in water networks. By combining real hardware (pumps, VFDs, valves) with real-time simulations, the platform accurately replicates complex transient behaviors, valve hysteresis, and harmonic demands under robust PID control, offering a safe, cost-effective tool for optimizing smart water infrastructure.

6. References

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