Advantages of Real-Time Closed-Loop Simulation

Scott Manson, Abdel Rahman Khatib, Niannian Cai, and Siddharth S. Rajan
Schweitzer Engineering Laboratories, Inc.

This paper was presented at the 68th Annual Petroleum and Chemical Industry Technical Conference, San Antonio, TX, September 13–16, 2021.

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Paper No. PCIC-TBD

Scott Manson
Senior Member, IEEE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163, USA
scott_manson@selinc.com

Abdel Rahman Khatib
Senior Member, IEEE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163, USA
abdel_rahman_khatib@selinc.com

Niannian Cai
Member, IEEE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163, USA
niannian_cai@selinc.com

Siddharth S. Rajan
Member, IEEE
Schweitzer Engineering Laboratories, Inc.
3100 Wilcrest Drive, Suite 350
Houston, TX 77042, USA
siddharth_rajan@selinc.com

Abstract—Protective relays, controllers, and other hardware equipment can be connected to real-time simulation equipment for hardware-in-the-loop (HIL) simulation. These HIL real-time closed-loop simulations have historically been used in the aeronautics, space, defense, and utility industries. In this paper, the authors share their experience and best practices in applying HIL techniques for the petrochemical industry. The paper discusses best practices for constructing and validating models, connecting hardware to simulators, and running an effective HIL factory acceptance test. The authors highlight several in-service petrochemical projects that used HIL simulations and benefited from the resulting cost reduction and risk mitigation.

Index Terms—Hardware-in-the-loop, HIL, simulation, EMTP.

I. INTRODUCTION

Hardware-in-the-loop (HIL) methods are used throughout the aeronautics, space, defense, and power system industries. This paper focuses on the application of HIL simulation for industrial electric power systems.

HIL simulations are the real-time closed-loop modeling of systems. For the electric power industry, the models are created using Electromagnetic Transients Program (EMTP) modeling. These EMTP models run in real time to simulate primary equipment such as engines, generators, inverters, transformers, conductors, cables, and loads. HIL models provide real-time responses to faults, disturbances, load changes, and controller or protection actions. These responses include power, frequency, rotor angle, voltage, and load reactions.

HIL models for the electric power industry are built primarily to test protection and/or control systems. Transmission relaying, industrial power management controls, wide-area special protection systems, and microgrid controls and protection are the most common devices tested on an HIL model. HIL testing is used to model complex phenomena, such as power system instabilities [1], interactions between steam and electric systems [2], complex transmission protection applications [3], and electromechanical phenomena not replicated by other means of modeling [4].

Factory acceptance tests (FATs) are commonly run with an HIL simulator to ensure the user can replicate field behavior. An HIL model operates sufficiently fast to test closed-loop control and protection systems. System owners' intimate knowledge of their power systems is useful in testing complex or unusual scenarios. For example, a system owner can commonly recall unusual phenomena to model in HIL simulations.

Because HIL simulation is in real time, thousands of test cases can be run, providing site personnel with a great amount of confidence that all systems will react as expected under the most adverse scenarios. HIL FATs provide a fast training program for system owners. Because thousands of test cases are run, an operator can gain more experience from a one-week HIL FAT than from a decade of field work.

HIL simulations are divided into two categories: control hardware-in-the-loop (CHIL) and power hardware-in-the-loop (PHIL). CHIL simulation, shown in Fig. 1, involves the protection and control electronics directly connected to the real-time simulator.

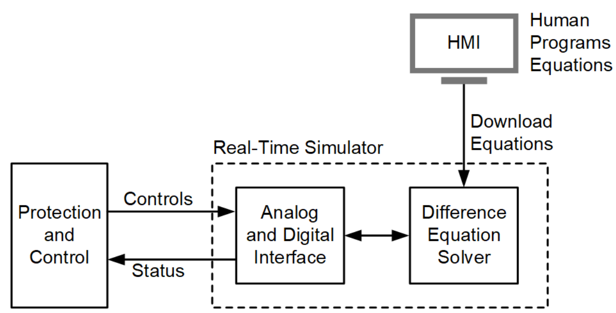

Fig. 1 CHIL Setup

PHIL simulations involve a portion of the actual power system, usually equipment such as tap changers, inverters, and generator sets (see Fig. 2). PHIL simulations commonly use devices called grid simulation inverters to simulate the portion of the grid that is not under live power demonstration. The real-time simulator represents the net system behavior of a much larger power system.

The real-time simulator engine is typically an assemblage of hardware comprised of field-programmable gate array (FPGA), application-specific integrated circuit (ASIC), and central processing unit (CPU) modules. This simulator takes significant computational efforts because it solves the difference equations that the user programs at a solve rate faster than the slowest system time constant. For an electric power system, that means updates at 50 microseconds or faster.

Protective relays, controllers, and other hardware equipment can be connected to real-time simulation equipment for PHIL or CHIL simulations [5]. This paper focuses on CHIL simulations built to validate relays and controllers used to provide power management control, microgrid control, generator set dispatch, synchronization, decoupling, and open-circuit and short-circuit protection functions.

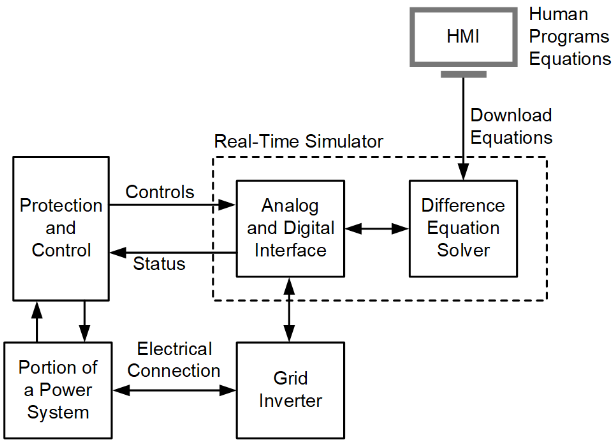

Fig. 2 PHIL Setup

CHIL testing allows the simulation of a physically large and spatially distributed power system in a single room with the actual protection equipment, controllers, and physical devices installed in the field. The testing takes place in live conditions in a lab environment, without any danger to the physical equipment. Performing such live tests on a power system in the field is not feasible and can pose several safety issues.

CHIL testing exposes the equipment under test to an environment that would fully reproduce the dynamic behaviors of the power system under transient conditions. Using CHIL, the simulation can be done in real time as opposed to simulation time. The dynamic simulator in which the power system is modeled typically uses advanced parallel processing techniques, enabling the simulator to solve complex EMTP simulations.

Through CHIL testing, thousands of faults can be simulated on the power system for various system contingencies and load flows, thereby providing high-resolution visibility of the power system. Transient event data files generated from the CHIL testing can be used for field testing to verify the actual field wiring, relay settings, and physical operation of breaker operating sequences. CHIL testing can thus save a significant amount of time and capital that would otherwise be spent troubleshooting problems in the field.

II. DIFFERENCE EQUATIONS

There are significant differences between the modeling techniques used in the electric power industry. HIL and, hence, EMTP use a specific method of simultaneous difference equation solution. Difference equations are the time-sampled version of mathematically derived differential equations. Differential equations are continuous time, whereas difference equations assume an iterative time interval between samples.

As shown in Fig. 1 and Fig. 2, the user must program a set of difference equations into the real-time simulator. These difference equations are a digital representation of time-domain differential equations. The real-time simulator solves difference equations in a process called numerical integration. In cases where it is applied to solve electromagnetic phenomena, the process is called real-time EMTP.

To explain the underlying technology and to lay out the lexicon, this section provides a simple example of differential equations.

Fig. 3 depicts a fuel delivery system for an engine. The position of the actuator is a function of the force from the solenoid. The current from an amplifier is proportional to the current sent to the actuator solenoid, hence the force. A fuel valve return spring pushes back on the solenoid to ensure fuel shut-off if the solenoid is unpowered. Mechanical dampening controls provide a dashpot style of dampening to quell oscillations.

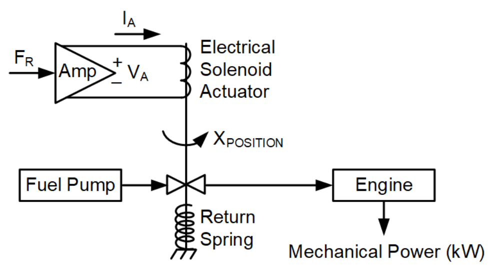

Fig. 3 Engine Fuel Actuator Example

Equation (1) describes the relationship between the solenoid current and the amplifier voltage. The left side of the equation includes a derivative of current and a proportional current term. This is a single-order differential equation, as it has one derivative.

$$\frac{d}{dt}I_A(t)+\frac{R}{L}I_A(t)=\frac{1}{L}V_A(t) \qquad (1)$$

where:

(t) represents that this equation is in the time domain.

$I_A(t)$ is the time-domain current.

d/dt is the time-domain derivative.

R is the solenoid resistance.

L is the solenoid inductance.

V_A is the amplifier output voltage

Equation (2) describes the relationship between the solenoid current and the fuel valve position. The left side of the equation includes two derivatives and a proportional term of position. This is a second-order differential equation, as it has a double derivative.

$$\frac{d^2}{dt}X(t)+\frac{K_{DAMP}}{J}\frac{d}{dt}X(t)+\frac{K_{SPR}}{J}X(t)=\frac{K_{SOL}}{J}I_A(t) \quad (2)$$

where:

X is the solenoid shuttle position.

K_{DAMP} is the damping coefficient.

J is the solenoid shuttle inertia.

K_{SPR} is the return spring constant.

K_{SOL} is the current-to-actuator force constant.

The fuel solenoid current and position are the state variables in (1) and (2), as they are assumed to not change instantaneously.

In a recent modeling event, 21 differential equations were required to approximate a single engine and generator set driving a resistive load. Simulating large power systems of interconnected generators, engines, transformers, transmission lines, loads, and more can take tens of thousands of differential equations for a small power system. Thankfully, the programming environment of these HIL simulators abstracts the user programming from the actual equations and simplifies the modeler's work.

III. REAL-TIME SOLUTIONS

Since these differential equations are solved by digital representations, the effect of numerically integrating the solutions must be understood. Many first-time HIL modelers experience what is called numerical instability. Fig. 4 shows an example of the phantom effect of improperly configured difference equations, also known as numerical instability. Difference equations are a computer representation of differential equations.

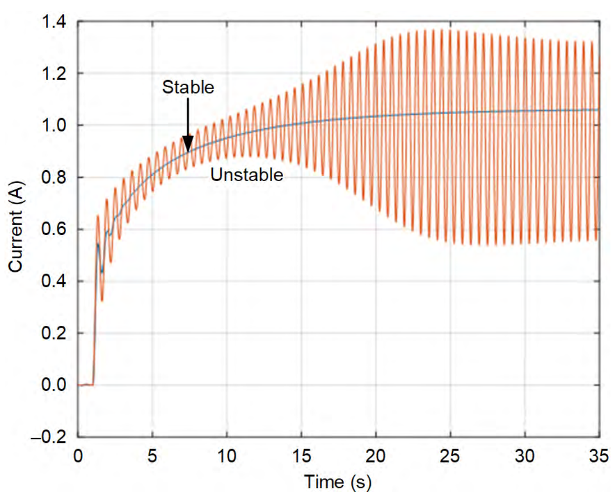

Fig. 4 Numerical Integration Instability

To avoid numerical instability and to ensure accurate results, the real-time nature of HIL must be discussed. Fig. 5 shows the actual path of solenoid current for a step change in amplifier voltage. The L/R time constant (shown in Fig. 5) must be understood by the modeling engineer. Notice the smooth and continuous advance of current.

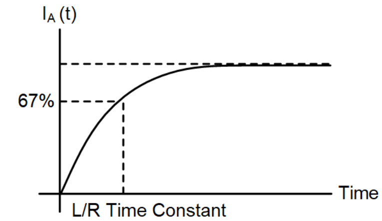

Fig. 5 Actuator Current in Time Domain

Fig. 6 shows the (numerically stable) estimated digital representation of the simulated current in a real-time simulator. The time interval between the steps is the update interval of the simulation. This step-time interval must be less than 1/10 the time interval of the fastest time constant being simulated. For example, an L/R circuit of 1 second could be adequately simulated by an update interval of 0.1 seconds. Every modeling engineer must choose numerical integration time-step intervals based on the time constant of the system being modeled; this requires experience.

Numerical instability commonly occurs when the step-time interval is not sufficiently small, causing mathematical assumptions to break down.

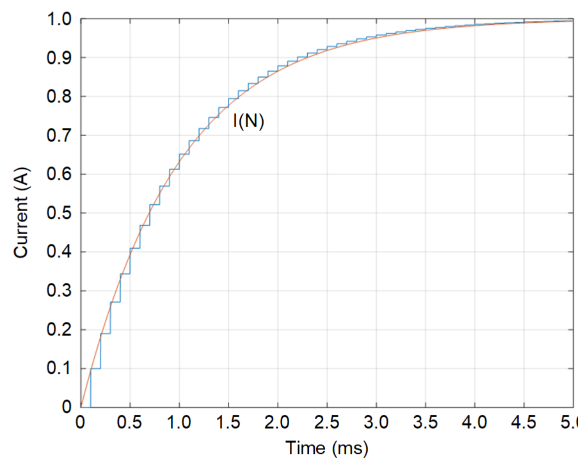

Fig. 6 Digital Representation of Actuator Current

IV. WHAT IS NOT HIL

To qualify as HIL, a solution must provide realistic conditions to the relay and/or controller. This means that many types of simulations are not appropriate or used for HIL work in the electric power industry.

For example, Fig. 7 shows a static calculation of the final current value for the same step in amplifier voltage. This does not show any of the first- or second-order response behavior. This static simulation is therefore not acceptable for transient or dynamic HIL simulation. It is not useful for studying relay protection behaviors or engine governor and automatic voltage regulator (AVR) controls. However, the static simulations can be used for some type of slower control system testing. For example, load tap changers, supervisory control and data acquisition (SCADA) systems, and some slow dispatch controls can use a static calculation for HIL simulation. The advantage of the static simulation is that difference equations are not required to be solved, thus the computational and engineering efforts are much smaller.

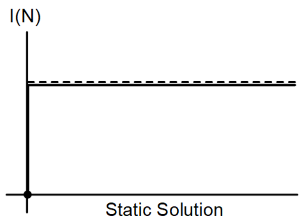

Fig. 7 Static Solution of Actuator Current

This type of static calculation is common and must be discriminated from HIL simulation because it has no iterative solution, no difference equations, and uses simplified mathematical models.

Power flow simulations, fault analysis, relay coordination modeling, and many other simulation types are static calculations. Iterative techniques such as the Newton-Raphson method are used to find solutions to power flow. Neither of these simulation types solves iterative difference equations and neither replicates transient behaviors. It is not cost-efficient to use a transient difference equation solver for simple power flow or fault analysis. Simpler tools such as Newton-Raphson and symmetrical component solvers are, however, used to cross-check and validate HIL model accuracy.

V. WHICH COMPONENTS TO MODEL

Following are the most common devices modeled with difference equations in an HIL simulation, sorted in order of importance for accurate simulation of protection and control systems:

1. Engine control systems including mechanical, hydraulic, steam, and associated fuel and air delivery systems
2. Generator systems including exciters and voltage regulators
3. Inverters for batteries and intermittent renewable energy sources
4. Direct-connected motors and associated mechanical loads
5. Constant power loads such as variable-speed drives and UPS-type equipment
6. Resistive-, inductive-, and capacitive-type loads
7. Transformers and load tap changers
8. Transmission lines, series compensation capacitors, and shunt reactors
9. Circuit breakers, switchers, and motor-operated switches

A. Source Modeling

HIL simulation for frequency and voltage resiliency analysis requires the modeling of power-providing devices in a power system. This includes generators driven by gas turbines, steam turbines, or reciprocating engines, and inverters powered by batteries or photovoltaic sources. The models for these devices must replicate the actual voltage and current behaviors.

Generators driven by reciprocating engines or turbines must have detailed mechanical, electrical, and control systems modeled. The accuracy of these models is especially important for low-inertia islanded microgrids, oil and gas facilities, and offshore platforms where voltage and frequency stability are important. These models must accurately depict generator and prime mover inertia, engine fuel and air flow and associated controls, and generator excitation and voltage controls. A skilled HIL engineer can build accurate generator set models with pictures of the equipment and step test data from live machinery (manufacturer-supplied models are not required).

Inverters can be the most complicated devices to model in an HIL modeling event. A skilled engineer will take weeks or months to replicate inverter models that behave within 1 percent of the actual inverters' current, voltage, and frequency response. Inverters are used to connect batteries, photovoltaic (PV) sources, wind turbines, and other power-producing devices to the electric power system. For most microgrid and industrial projects, these models must accurately behave during faulted-circuit conditions, transient conditions, and interactions with generators, generator excitation systems, generator AVRs, load tap changers, and more.

The requirements for modeling sources are sometimes less complex if only electrical protection behavior requires testing because relays operate much faster than most engine fuel response times, thus sometimes allowing for simplified engine models. AVR and excitation must be full fidelity for protection-only studies because their response times are subsecond.

B. Load Modeling

HIL simulations for the frequency and voltage resilience control systems associated with microgrids and islanded petrochemical facilities must have accurately modeled loads. Loads contribute to the inertia of a power system and affect the transient performance of engines, inverters, and other power producers [6].

HIL simulation for pure protection systems rarely requires detailed load models. Loads rarely contribute significantly to the fault-producing capacity of a power system.

There are three types of load models the HIL modeler must consider: –R, R, and motor-type. These three loads have significantly different behaviors during off-nominal voltage and frequency conditions and dramatically affect such analysis. For example, the variations of a net system load from a motor load-dominated system to a –R-based system are known to destabilize conventional generator set control systems [1].

R loads are resistive loads that consist of conventionally acting R, L, and C components. As voltage increases, current increases.

–R loads are synonymous with P/Q, or constant power loads. These loads are power electronic loads like variable-frequency drives (VFDs), power supplies, etc. As voltage increases, current decreases.

Motor loads are direct-driven loads, typically induction motors, feed pumps, or compressors. These loads increase their power consumption as frequency increases. The modeling of the mechanical load attached to the motor is critical for this type of load.

The percentage of each type of load is called the load composition. Due to limited computational ability in HIL equipment, it is necessary to aggregate loads by type and location in a method called lumping [6].

C. Modeling Power Transport

Modeling the equipment that transports electric power includes the modeling of transmission and distribution lines, series and shunt capacitors, transformers, and other associated equipment.

For most industrial facilities, the accuracy of cables is not essential for frequency or voltage stability studies. Time is better spent on source and load modeling. Industrial facilities with large geographic dispersion of loads and sources require this modeling.

Modeling this equipment is essential for detailed fault and/or protection studies and voltage collapse or rotor angle stability studies in large power systems. It is critical for angle stability studies for large power systems or systems with a large impedance [7].

VI. SIMPLIFYING MODELS

Critical in the success of any HIL modeling endeavor is modeling what is needed and no more. For example, weeks can be spent modeling a single transformer to perfection, but time is better spent in modeling other devices that have a larger impact on voltage and current transient behavior. It is typical to build detailed models of steam, hydraulic, and fuel delivery systems, turbines (all sorts), wind turbine blade controls, inverter systems, and more. With all of this potential complexity, an engineer must have a strategy to meet accuracy requirements that considers labor, time, and budget requirements.

Perfect modeling of all transients is rarely required. Some items can be simplified to reduce costs. For example, the impedances of a power system are critical for accurate fault determination, CT sizing, circuit breaker sizing, transformer selection, and protection coordination studies. These phenomena primarily impact protection systems and not control systems. These phenomena are inexpensively modeled using simple static fault models, which are less costly than HIL methods. Thus, impedance details are commonly lower priority in an industrial HIL model focused on testing microgrid controls, stability, or system resiliency.

HIL model development and validation for an industrial power system depends on the complexity of the power system and accuracy requirements. Engineers should therefore build the simplest models possible.

The most successful HIL models contain mechanical, electrical, and magnetic models derived from first-principle physics. Validation reports must be accompanied with the mathematical derivation of model components. HIL modeling engineers have built and validated first-principle models for systems such as flywheel storage, wind generation, turbine and reciprocating generation, governors, AVRs, excitation systems, PV controls, and battery storage, as well as all forms of load [8].

Once a first-principle model has been validated with field results, it is common to find simplifications for these modeling blocks that expedite overall model development and have no impact on model accuracy. These simplifications take decades of modeling experience and significant field testing to validate [8].

The time constants of the protection or control system being tested affect the HIL model accuracy required. For example, a regional dispatch control may take 30 seconds to return the frequency to nominal after an event. This type of control scheme is much slower than rotating machinery transient and subtransient electrical time constants; thus, a less-detailed generator and motor electromechanical model will suffice [8]. For example, Fig. 8 is a simplified but accurate model of an islanded microgrid that was sufficiently accurate to replicate frequency instabilities caused by a steam governor low-load instability [8]. Although fit for purposes in replicating frequency stability, Fig. 8 would not be an adequate model for replicating transient rotor angle stability.

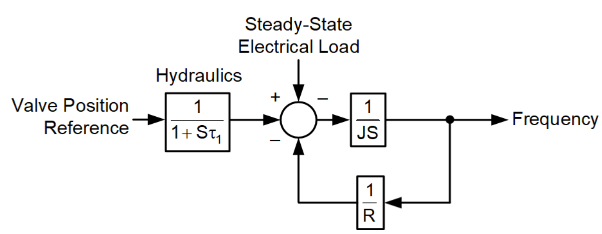

Fig. 8 Simplified Power System Model [8]

VII. WHEN IS HIL A FIT?

Table I shows a simplified set of typical risks that drive users toward specifying HIL techniques. These are questions to ask at the evaluation stage of any project.

Note that every project is unique and must be evaluated by experts in the field based on experience and a comprehensive objective understanding of the user situation. The questions in Table I can help steer a user toward an appropriate level of modeling. An answer of yes to each question corresponds to how strongly a user should consider HIL simulation.

TABLE I
HIL EVALUATION

Question	HIL Consideration
Is your power system islanded regularly?	High
Is there an aggressor nation-state nearby?	High
Is there a physical cyber attack concern?	High
Is your load composition varying?	High
Is the protection or control system new, complex, or nonstandard?	High
Do you have variable fault currents that depend on islanding or which generator sets are in service?	High
Do you have a variety of power sources such as batteries, turbines, and/or renewable energy?	High
Do you have turbine prime power?	High
Is your power system topology complex?	High
Do you have mission-critical loads?	High
Is resiliency your top priority?	High
Do you take regular line outages?	High
Do you have frequency or voltage oscillations?	High
Do you have a history of blackouts?	High
Is the cost of failure high?	High
Is there a weak utility connection?	Moderate
Do you have large variable-speed drives that are >30% of load base?	Moderate
Are you above 50 MW generation on site?	Moderate
Do your inertias change?	Moderate
Are you struggling to keep commissioning and testing on budget?	Moderate
Do you have no generation on site?	Low
Do you only have diesel standby generator sets?	Low
Have you completed an identical system before?	Low
Is the utility intertie reliable?	Low

VIII. BEST PRACTICES

Following a strict procedure for model development is essential to the long-term success of any HIL program. The basic steps the authors use are as follows:

1. Collect data.
2. Built and test small unit models.
3. Compare modeling data to field step test data.
4. Validate the entire model to ensure it is accurate.
5. Perform FATs.

Many HIL modeling programs are plagued with the problem of garbage in, garbage out. Compounding this is that many manufacturers will not share their models of prime movers, generators, or other proprietary equipment. The best alternative is to build first-principle models supervised by principal-level engineers with decades of power system experience. Although simple, second-order models of a device are commonly sufficient to accurately describe very complex multistate system models. Also, it is best to have field step test data rather than rely on manufacturer data.

After building the models, it is critical to validate that the models accurately reflect what happens in the field. Based on the fidelity of the information a user provides, model validation can be divided into three levels of descending certainty:

1. The most confident level of validation is to compare simulation results with the results tested in the field. These results can be obtained from any prior events recorded from the field or the results recorded during site acceptance tests. By replicating the same events or the same tests in the simulation, the accuracy of the model can be evaluated by comparing the simulation responses with the field responses.
2. If the field responses are not available, whether it is a greenfield project or the responses were not recorded, another less certain way to validate the model is to compare the simulation results with the results from a third-party study report. Normally, different manufacturers use different simulation software and have different insights for modeling and studies. Cross-checking with a study report from a different manufacturer helps validate the model.
3. If field responses or study reports are not available, the model can still be validated, although at the least certain level, by reviewing the simulation results with experienced engineers. Those engineers who are eligible to review the simulation results are either the manufacturers or the owners of system operations. For example, a senior engineer from a generator set manufacturer can provide valuable insight on the load acceptance or load rejection tests of a generator set. The power system engineer from operation can review the system response of an event.

IX. MODEL VALIDATION

Model validation is the process of proving that an HIL model accurately depicts pertinent dynamic electrical, magnetic, and mechanical characteristics. Fig. 9 shows a comparison of frequency responses for a complete model versus data captured from a live field event. This model was deemed accurate enough because the peak and steady-state frequency were sufficiently accurate. The effort to make the model replicate the transients between 5 and 20 seconds was considered unnecessary as it did not affect the control scheme under test [8].

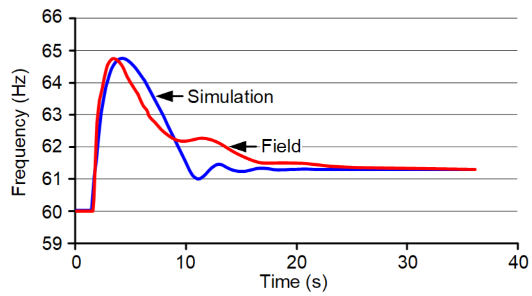

Fig. 9 Simulated and Field Frequency Response [8]

Steady-state electrical conditions are validated by power flow studies performed with the HIL model. Power flow studies show that voltages, frequencies, active and reactive power flows, and generator outputs are within nominal. These results are compared to the known flows of installed equipment. Power flow analysis must be run for several scenarios, including point of common coupling (PCC) open, islanded conditions, and cases with some power production offline. Power flow results validate that the electrical impedances, nominal load levels, distribution of load to feeders, normal operating status of breakers, and isolation switches are correct [8].

Short-circuit conditions are validated by simulating phase-to-ground and phase-to-phase fault values at several locations in the HIL model. These results are compared to known fault levels of installed equipment. Several cases should be provided, including PCC open, islanded conditions, and cases with some power production offline. These data validate the electrical transient, subtransient, and nontransient impedances, magnetic models, grounding schemes, X/R ratios, and simplified model sections [8].

Load rejection and load pickup tests are used to confirm HIL models of power generation, renewables, and loads. By comparing frequency, power, voltage, and current for an event, the model accuracy is improved. Field data are typically collected from modern microprocessor-based protective relays to validate these results.

X. CASE STUDY PROJECTS

This section highlights several in-service petrochemical projects that used HIL simulations.

A. Remote Upstream Facility

Remote upstream facilities may not have nation-state grid connection. Without strong support from the grid, remote facilities can be vulnerable to system disturbances. It can be expensive if an outage occurs in an upstream facility because it can result in production loss, equipment damage, or even injury. A remote upstream facility needs robust and reliable controllers and protection equipment to maintain sustainable power system operation. HIL simulation provides an affordable way to conduct extensive testing for these controllers and protection equipment.

In this case study, an oil company intended to upgrade gas turbines to include a heat recovery steam generator (HRSG) and a steam turbine, thus making it a combined-cycle system. The upgrade required that the controllers all be upgraded, including the load-shedding system, generation-shedding system, and generation control system.

All upgrades, testing, and commissioning on this remote facility must happen with the plant online. To fully validate the system, the team attached the upgraded control panels to the CHIL platform and performed a CHIL FAT.

Fig. 10 shows the frequency responses of HIL testing when a bus fault caused two gas turbine generators to trip offline (150 MW generation loss). The test shows that the load-shedding system can shed load in a timely manner, and the frequency drops to 59.52 Hz and recovers. This bus fault testing could never be tested on the live system. The extensive testing conducted with HIL simulation gave system owners enough confidence to deploy the controllers in the field.

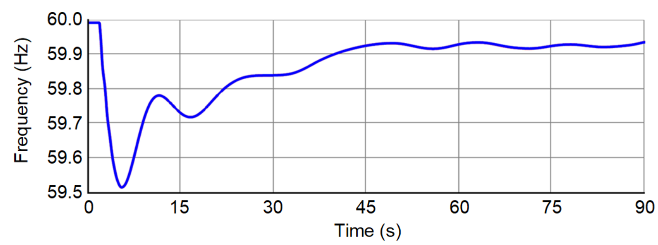

Fig. 10 Load Shedding Helps Upstream Plant Survive Multiple Turbine Trips

B. Large, Complex Refining Facility

Outages in the large refining facility in this case study are usually very expensive, so system owners chose HIL simulation to reduce financial risk. The HIL simulation helped system owners test the complex refining facility controllers; study their decoupling, protection, and underfrequency settings; and develop a commissioning plan.

HIL simulation is normally conducted in the FAT, where the manufacturer explains and displays the functionality of the control or protection system. HIL simulation in this case was used to test that the control and protection system operates correctly for rare or destructive events.

The refinery had five steam turbines, each generating around 800 MW, for a total of 4 GW. It had experienced several blackouts after a sudden loss of load caused power export to the utility to exceed 2 GW, the protective relays to trip the PCC, and a total plant outage.

The engineering team used CHIL techniques to test the generation-shedding control system designed to prevent these outages. Fig. 11 shows the HIL-simulated frequency response to losing the utility as the generation-shedding system successfully tripped two turbines offline and ran back three high-pressure steam valves on the remaining turbines. This shows that the control system successfully prevented a cascading blackout.

These kinds of tests, if conducted in the field, introduce huge and undesirable disturbances to both the utility and refinery. However, if this scenario is not tested, and the generation-shedding system does not make the right decision when this event happens, it can result in a refining system and even a utility system blackout. HIL simulation in this case provided an affordable way to extensively test the controllers before they were deployed in the field.

HIL simulation was also used to train operators. The HIL FAT event allowed the operators to test the controller settings, learn system responses, and develop a maintenance plan. If an event happens in the field, HIL simulation is used to re-create the event using the event records collected from the field. The re-creation of the event can be used for root-cause analysis.

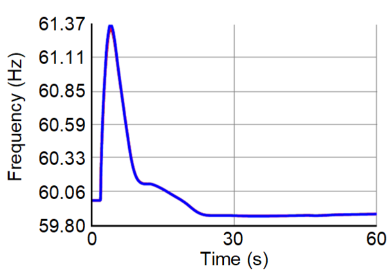

Fig. 11 Generator Runback Keeps Refinery Online After Utility Outage

C. High Value Downstream

A load-shedding system developed for a chemical refinery was designed to protect power system stability during the transition from grid to islanded mode operation. Upon opening the utility interconnect, the turbine governor is automatically changed from droop to isochronous mode [9]. This transition has historically caused the site turbine or generator set to trip offline. The generator set was tripping offline after island transition for several reasons, including overload, underfrequency, and overfrequency conditions. One generator set trip led to a total facility blackout. Recovery to normal operations is labor-intensive, costly, and time-consuming.

Previous attempts to implement a load-shedding system at this site were too rudimentary to support a reliable separation from the power grid. Prior systems did not provide automated load selection or optimized load shedding. A new load-shedding system was needed for this facility to prevent blackouts after a loss of utility [9].

The engineering team used HIL methods to validate the operation of the replacement load-shedding system. Data obtained from the field were used to validate the HIL model. Various power system operating scenarios were modeled and tested. HIL testing exposed the load-shedding system to numerous transient system conditions that would have been nearly impossible to replicate in the field or by using a static simulation program.

HIL testing was critical in creating the decoupling settings to quickly detect the loss of the electric grid, thereby ensuring a smooth transition to island mode. HIL testing also helped optimize the load selection process for various contingencies and ensured the stability of the power system after the actions taken by the load-shedding system. Moreover, HIL testing aided in developing a reliable, adaptive, and user-configurable frequency-based load-shedding solution.

HIL testing played a critical part in developing a state-of-the-art load-shedding solution, improving the reliability of the facility, minimizing operating costs, minimizing production losses during unplanned events, and improving the safe operation of the electric power system and process.

XI. CONCLUSIONS

The key takeaways from the authors' experience with HIL simulation are as follows:

1. CHIL-based FATs are a standard solution to ensure reduced cost, increased reliability, time-savings, improved quality, and increased safety of complex protection and control systems.
2. HIL models based on first-principle physics and validated against field-captured data are superior.
3. HIL simulation must solve the difference equations with numerical integration; other techniques are not adequate to simulate frequency and voltage stability.
4. Labor should be focused on accurate models of key components to ensure accurate simulation of the required behavior.
5. Engineers should avoid building detailed models of equipment that have little impact on the results.
6. Following a strict procedure for model development and validation is essential to the long-term success of any HIL program.
7. All models must be validated and reviewed by senior engineers with decades of experience.

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XIII. VITAE

Scott Manson, P.E. (S 1991, M 1993, SM 2012), received his MSEE from the University of Wisconsin–Madison and his BSEE from Washington State University. Scott is presently the engineering services technology director at Schweitzer Engineering Laboratories, Inc. (SEL). SEL’s mission is to make electric power safer, more reliable, and more economical. As technology director, Scott provides consulting services on control and protection systems worldwide. Scott is a registered professional engineer in 5 states and holds 11 patents.

Abdel Rahman Khatib, PE. (SM 2016), received his BS and MS in electrical power engineering from Military Technical College, Cairo, Egypt. He received his PhD in electrical engineering from Virginia Tech in 2002. Abdel is a senior power system engineer at Schweitzer Engineering Laboratories, Inc. He has 10 years of industrial experience in power management system design, testing, and commissioning for the petrochemical and oil industries. His research interests are power system modeling, load flow and dynamic stability, and protection. Abdel has 12 years of university teaching experience and is a registered professional engineer in Washington, California, Texas, and Indiana.

Niannian Cai (M 2018) received his BS in electrical engineering from Huazhong University of Science and Technology, Wuhan, Hubei, China, in 2009, and his PhD in electrical engineering from Michigan State University in 2014. He is a project engineer at Schweitzer Engineering Laboratories, Inc. His research interests include power system modeling, power system dynamics and control, power system optimization, and microgrids.

Siddharth S. Rajan received his BS in 2010 from Anna University, his MS in power systems in 2012 from Arizona State University, and his MBA in 2017 from the University of Houston. He is an electrical engineer with eight years of experience in power system protection, modeling, fault analysis, relay testing, power flow, and system stability studies. Siddharth is knowledgeable in industry standards and technologies related to the application of protective relay schemes for industrial and utility systems. He is a registered professional engineer in Texas.

Previously presented at the 68th Annual Petroleum and Chemical Industry Technical Conference, San Antonio, Texas, September 2021.

20210929 • TP6960