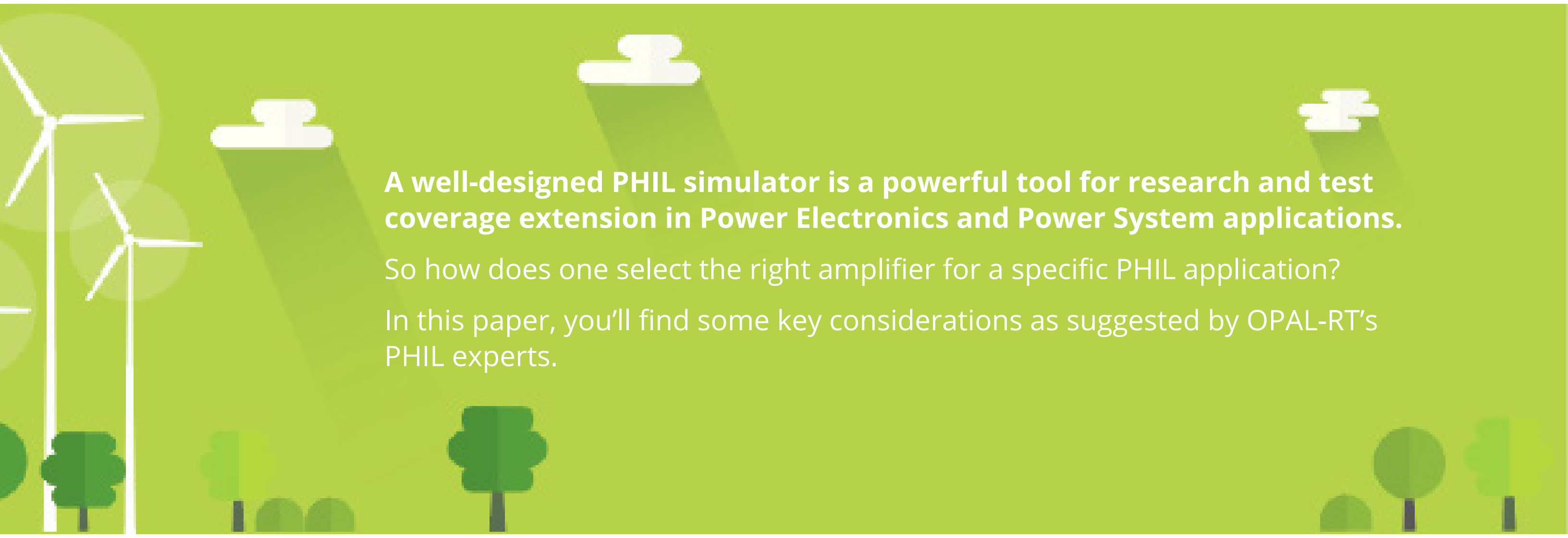
Key Considerations

When Selecting Amplifiers for your
Power Hardware-in-the-Loop (PHIL) Testbed



A well-designed PHIL simulator is a powerful tool for research and test coverage extension in Power Electronics and Power System applications.

So how does one select the right amplifier for a specific PHIL application?

In this paper, you'll find some key considerations as suggested by OPAL-RT's PHIL experts.

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Introduction

PHIL at a Glance

OPAL-RT is at the vanguard of power electronics applications in the areas of industrial development, power distribution, aerospace, military and electric transportation systems. At the forefront, the trend towards increasingly rapid innovation involves application-oriented R&D used in system modularization, analysis, modeling, real-time simulation, design and experimental evaluation. By connecting a simulator to a Device Under Test (DuT) with low power capability I/Os, and by subjecting it to rigorous testing as Controller Hardware-in-the-Loop (CHIL), OPAL-RT can help substantially reduce time to market.

Power Hardware-in-the-Loop (PHIL) simulation is an extension of CHIL, in which the real-time simulation environment exchanges not only low-power analog/digital signals and data through communication protocols with a control DuT, but also offers the capability of emulating a physical plant or power device. Virtual equipment can further be interfaced with a power-DuT, using a power amplifier on signals provided by the real-time simulator. PHIL simulation requires closing of the loop to ensure accurate interactions between the virtual and physical worlds, through adequate sensors connected to the I/O of the real-time simulator.

Power amplifiers are selected, among other things, based on on their closed-loop performance and ability to generate and absorb power.

PHIL enables engineers to test various types of power equipment—including power converters, generators and motors—while benefiting from high-fidelity simulation that provides greater flexibility to apply tests that are not practical in a non-destructive manner on analog testbeds or on a real system.

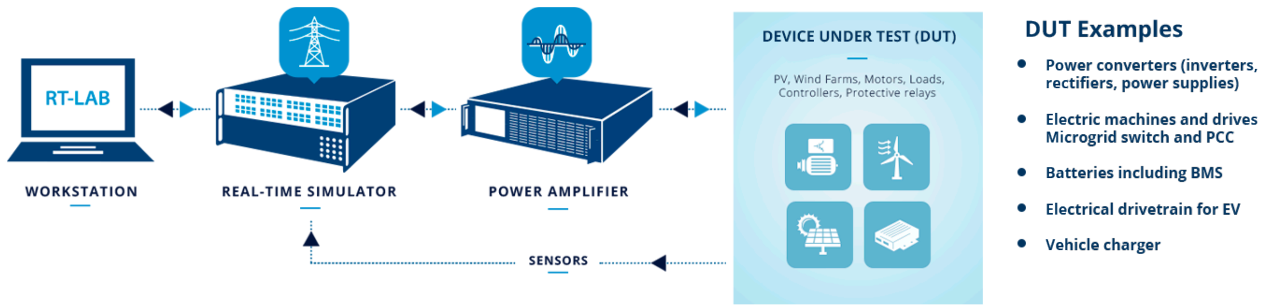

Fig. 1: PHIL configuration with DuT examples

Introduction

PHIL at a Glance

There are many power amplifier suppliers and each of them has their own range of products, many specializing in specific market segments. The figure below shows some suppliers, sorted into three such segments:

Amplifier manufacturers		
< 10 kVA	10 kVA to 150 kVA	> 150 kVA
OPAL-RT TECHNOLOGIES	NATIONAL INSTRUMENTS	
AETECHRON	SPHEREA PUISSANCE PLUS	
AN ISO 9001 COMPANY KEPCO THE POWER SUPPLIER™	REGATRON programmable power supplies	
	cinergia	
	Chroma	EGSTON POWER
	AMETEK	
	SPITZENBERGER SPIES	
	PONOVO	

Fig. 2 : Amplifier manufacturers sorted by typical unit power

1 | First Consideration

The Amplifier's Operating Range (Voltage, Current & Power)

The first consideration in designing a PHIL testbed is to evaluate the operating range of the devices that will interface with it. One common error is to select an amplifier based solely on its generating power capabilities without considering its capability to absorb power, or its bandwidth. Further, design must be done to test requirements, which can exceed the device's nominal quantities during transient tests forcing overcurrent, overvoltage or temporary overload.
The following aspects need consideration in the selection of the amplifier:

• Nominal/steady-state specifications:

- Number of phases
- Nominal Power at nominal frequency (kVA for AC, kW for DC)
- Power factor and rating in sourcing and sinking modes for each quadrant (if four-quadrant operation is required)
- Nominal AC and DC voltage
- Nominal operating frequency
- Frequency bandwith
- Power and current rating as function of voltage and frequency

• Transient and temporary operating characteristics:

In addition to these characteristics, some manufacturers specify the degree of (and even offer) configurability for overvoltage and overcurrent protections. Users may want to consider this in the testbed's operating range and design. Most amplifier suppliers will provide you characteristic graphics of the amplifier's dynamics. The following graphic represents the frequency response of OPAL-RT's OP8110 Amplifier as gain.

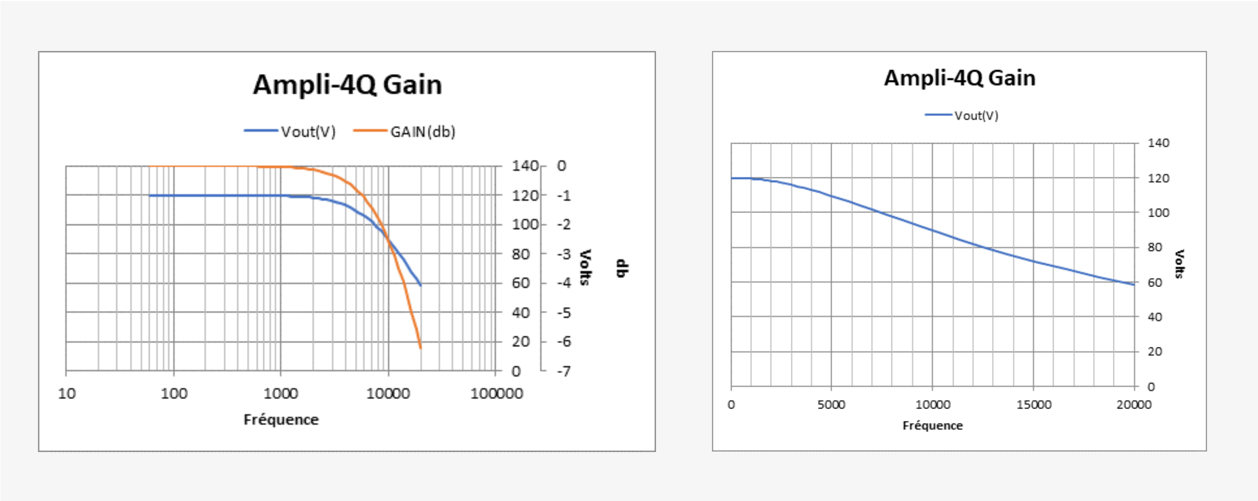

Fig. 3: Gain curve of OPAL-RT's OP8110 amplifier

1 | First Consideration, Cont'd

The Amplifier's Operating Range (Voltage, Current & Power)

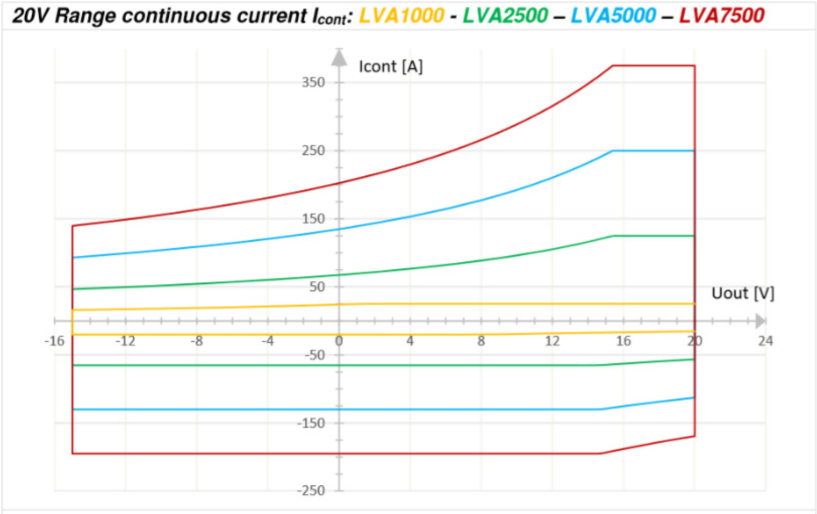

Fig. 4: Unsymmetrical amplifier characteristics, output current capability

Also, many amplifiers can hold a higher current and power than their advertised limit for a short period of time. Additional information may be provided by the manufacturer for special applications where corner conditions must be met.

For certain applications it may be necessary to use a step-up transformer to meet the nominal or maximum voltage rating of the DuT, and users should select the transformer power rating and capability according to the overload capability of the power amplifier, with a 10% to 20% margin. Note that adding a transformer can alter the frequency response of the testbed interface, and this requires specific attention regarding DC response simulation.

Additionally, transformers may easily saturate depending on their saturation characteristics and operating conditions. High transformer-saturation induced by DC voltages or transient conditions such as a fault clearing may be seen by the amplifier as a quasi short-circuit, which may trip the amplifier. Therefore, it is very important to understand the application's needs before designing a PHIL setup. Some transformer designs allow a larger range of linear operation, but they require core oversizing, and the cost and weight can increase considerably.

In the end, the design of a PHIL testbed always involves compromise with regards to cost and operating conditions.

2| Second Consideration

Economic (Rule of Thumb)

The second consideration is related to the amplifier price versus the available budget. The amplifier power rating, voltage range and frequency bandwidth can greatly influence its price, and this factor must always be part of the selection process. As given in *Fig. 5: Ballpark estimates of amplifier cost sorted by power rating,* prices range from 1k$/kW to 2k$/kW for 4Q—low bandwidth—amplifiers and can exceed 12k$/kW for high-frequency linear 4Q amplifiers. These ranges are rough estimations of the current market prices, and other factors may influence these further. These are: the chosen bandwidth of the amplifier, the source and sink options, and the type of instrumentation and control used in the final system.

Selecting the right operating range can be a daunting task since so much depends on the intended purpose, as well as interactions between the many variables at play in the final system. Also, not all amplifiers have internal measurement feedback fast enough for a PHIL closed loop. In this case, additional external sensors for high voltage and high current measurement should be added to the integration cost of your amplifier.

For some applications, it will be necessary to consider additional costs and design aspects on top of the amplifier and other equipment within the testbed. These are, among other things, the electrical mains and lab infrastructure properly suited for the amplifier and the interfacing transformer, if needed. Some amplifiers also require an auxiliary DC power supply which also needs to be selected for the testbed. One may want to look at the standards labeling and main connector types as well. Some amplifier manufacturers may need to customize the power input connections.

BALLPARK CONSIDERATION

The power rating of an amplifier can greatly influence its price and it must always be part of the amplifier selection process. The table below shows how much prices can vary depending on three power rating categories. These ranges are only estimates of the real prices and other factors can influence it. Namely, the chosen bandwidth of the amplifier, the source and sink options and the type of instrumentation and control used in the final system.

The next sections will go into detail about how to make the right choice. Here is a graphic featuring ballpark price estimates based on the power of the amplifier. Prices will vary considerably based on the four criteria explained in this document.

Selecting the right operating rage can be a daunting task since so much depends on the intended purpose and the many variables involved in the final system. Section 3 on sourcing and sinking will help clarify another essential part of the selection process.

Power Rating	Price estimation in USD for 3 Phase	
	Low bandwidth amplifier (< 3kHz)	High bandwidth amplifier (> 5kHz)
< 10 kVA	4,000$/kVA to 8,000$/kVA	6,500$/kVA to 20,000$/kVA
10 kVA to 100 kVA	1,500$/kVA to 4,000$/kVA	6,000$/kVA to 12,000$/kVA
> 100 kVA	1,000$/kVA to 3,000$/kVA	2,000$/kVA to 7,000$/kVA

Fig. 5: Ballpark estimates of amplifier cost sorted by power rating

3 | Third Consideration

Source & Sink Capabilities (4 Quadrant Capabilities)

The third important element to consider when selecting a configuration is its source and sink capabilities. An amplifier with a sinking capability may be up to twice the price of a standard sourcing amplifier. Depending on the application, a simulator is often required to provide power to a load (known as sourcing) and/or to absorb power from a generator (known as sinking). For example, the energy generated from braking in a motor control application may be recycled to recharge its battery. Likewise, the excess energy generated by a microgrid application may be sold to the main grid, which can, in turn, push power back to the microgrid. Hence, if the energy flow of an application is required to go in both directions, an amplifier that does both sinking and sourcing is needed.

Amplifiers with this bidirectional capability are often referred to as 4Q amplifiers. This is because they can function in all quadrants of the four-quadrant Power Schematic, as shown below. As *Fig. 6: Operating power quadrants (current measured as flowing out of the amplifier)* below shows, an amplifier can act as a load if the current flowing out of the amplifier and voltage are of opposite signs, and act as a power supply if they are of the same sign. It must be noted here that a 4Q amplifier is required to feed pure reactive (inductor or capacitor) loads with an equal power rating in each quadrant. The load power factor will affect the power rating of each quadrant.

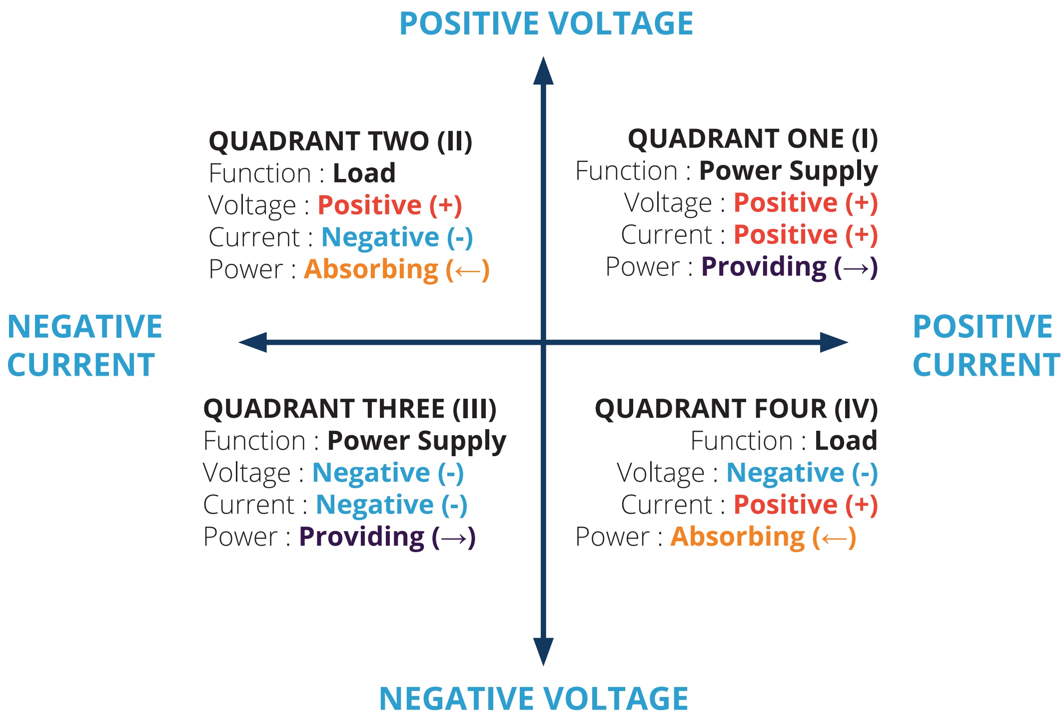

Fig. 6: Operating power quadrants (current measured as flowing out of the amplifier)

There are two types of amplifiers to choose from in terms of source and sink capabilities: the linear amplifier and the switching amplifier.

3| Third Consideration, Cont'd

Source & Sink Capabilities (4 Quadrant Capabilities)

LINEAR AMPLIFIERS

Linear amplifiers work in the linear region of semi-conductor components. These amplifiers normally have a good frequency response above 10 kHz. A downside of these amplifiers is that they are less energy efficient. This should be considered for high power applications. Also, they normally absorb around 30% of their nominal power by design. However, some suppliers choose to provide special options that may sink up to 100% of the power by adding resistive load.

SWITCHING AMPLIFIERS

Switching amplifiers work in the saturation region of the switching element in an AC to DC converter. By their very nature, they are more efficient (>90%) and better suited for sinking power, and normally have a higher power rating as compared to linear amplifiers due to their technology. A downside is that they generally have a lower bandwidth depending on PWM frequency and filtering. New switching amplifier designs can now reach a bandwidth of 5 kHz and higher using faster switching elements like the newer SiC and GaN transistors.

Selecting a Sinking Mode Option

Not all amplifiers are made equally; some are not symmetrical in the way they are built to handle sinking and sourcing modes. Consequently, their safe operating area can be quite different depending on the operating quadrant, especially when dealing with power overload. Some amplifiers, mostly linear ones, consume extra power and output it in thermal energy. Others can offload extra power to the supply grid. These high-end regenerative amplifiers are much more efficient, since less power is lost to heat.

Selecting the source and sink capabilities of an amplifier depends mostly on the application. Once these are chosen, the next logical step is to select the right bandwidth.

4| Fourth Consideration

Selecting the PHIL Bandwith Depending on the Application

It is very important to determine the main objectives of the tests to be performed with the PHIL system. These test objectives will determine the real-time simulator time step and amplifier bandwidth, which are important factors determining the total PHIL system cost. In fact, the total system cost can double if high-frequency amplifiers are needed as compared to a normal low-frequency amplifier.

Motor Emulators

For example, a motor emulator intended to test the thermal capability of the inverter design would require emulating a simple motor model capable of reproducing the RMS value of the motor current under different steady-state and overload conditions. A low-frequency amplifier, capable of generating voltages and currents only at the fundamental frequency expected at the motor terminal is enough. However, high-speed motors with a small number of poles may required frequency capability up to 1000 Hz. A simple motor model capable of computing the motor speed and its back EMF behind the stator inductor is sufficient. In fact, some manufacturers will simply connect the inverter under test in connected back-to-back mode with a second inverter through a series inductor. The required current and voltages for the test are controlled by adjusting the back EMF amplitude and angles of both inverters.

On the other hand, the analysis of the capability of the inverter controller to suppress torque ripple requires accurate simulation of high-frequency harmonics, which can reach 5kHz or more depending on motor rotation speed and number of poles. Such torque ripple can be caused by the cogging torque, also known as detent or 'no-current' torque, produced by the interaction between the permanent magnets of the rotor and the stator slots of a Permanent Magnet (PM) machine. The inverter's dead time produces also harmonic currents which in turn induce torque ripple that must be cancelled by special controller algorithms.

> *"Cogging torque of electrical motors is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a Permanent Magnet (PM) machine. It is also known as detent or 'no-current' torque. This torque is position dependent and its periodicity per revolution depends on the number of magnetic poles and the number of teeth on the stator. Cogging torque is an undesirable component for the operation of such a motor. It is especially prominent at lower speeds, with the symptom of jerkiness. Cogging torque results in torque as well as speed ripple; however, at high speed the motor moment of inertia filters out the effect of cogging torque."*
>
> **Source: https://en.wikipedia.org/wiki/Cogging_torque**

4| Fourth Consideration, Cont'd

Selecting the PHIL Bandwith Depending on the Application

Such high-fidelity PHIL motor emulators require a high-bandwidth amplifier controlled by a fast-real-time simulator capable of simulating a detailed model computed by finite element analysis. A simulation time step below 1 or 2 microseconds and an amplifier with a bandwidth above 5 kHz to 10 kHz may be required to simulate harmonic current and torque ripple caused by these harmonics depending on motor speed and number of poles. Motor start-up and faults also generate fast current transients in inverter components which must be detected by protection systems embedded in the controller hardware. Testing such high-speed protection may also dictate the response time and bandwidth required by the amplifier, as well as the simulator time step. In practice, real-time high-fidelity motor models require control of high-bandwidth amplifiers to simulate motor harmonics, and transients are implemented in FPGA chips to achieve a time step below one microsecond.

Power Grid Emulators

The same analysis must be performed to implement distribution and microgrid PHIL emulators in order to determine the frequency contents of the steady-state and transient waveforms to emulate in order to meet test objectives. For example, the testing of a slow global microgrid controller with an update time of 50 to 100 milliseconds would require power amplifiers rated for nominal power grid frequency plus or minus 1 to 5 Hz to emulate power swings. A simulator with a time step of 100 micros would be good enough to control the amplifier voltage amplitude and phase. A real-time electromechnical transient simulator such as ePHASORSIM, with a time step of 10 milliseconds using phasor mode (rms), could also be used if it is necessary to emulate very large power grids to test slow controllers.

Similarly, simulating transient overvoltage and overcurrent induced by fault, transformer saturation and power electronic based systems will require amplifiers with higher bandwidth controlled by real-time simulators capable of achieving a small time step.

4| Fourth Consideration, Cont'd

Selecting the PHIL Bandwith Depending on the Application

PHIL Stability and Accuracy

Additionally, it is vital to analyze the stability of the closed-loop system formed by the amplifier, the load and the real-time simulator (model) as well as all sensors and communication links required to interconnect all these components. The goal is to achieve stability in closed loop operation considering all the delays and transfer functions of all components forming the closed-loop system including model calculation. The classical control theory must be applied to design the compensation function in order to keep the open loop gain smaller than 1, when the phase is 180 degrees.

Several papers listed at the end of this document deal with this subject and propose methods to i) optimize accuracy and stability, as well as ii) overall safe operation of the PHIL system.

In fact, tuning a PHIL system is the same as optimizing a control system! The main conclusion is that stability issues must be analyzed carefully and that all delays induced by the real-time simulator, the amplifiers and interfacing devices must be reduced to the absolute minimum to increase the accuracy and stability limits of high-fidelity PHIL systems. Amplifiers with bandwidth above 5 to 10 kHz as well as FPGA-based simulators with time steps below one microsecond are often required.

The maximum bandwidth of a PHIL application is equivalent to the maximum frequency capabilities required to simulate the specified transients during the test. In motor-based applications, the maximum bandwidth defines the maximum motor speed. But in most other applications, it defines the maximum harmonic that the system can produce. Choosing enough bandwidth is important to ensure closed-loop stability and the capability to meet the test specification, which depends on the application.

The main items and specifications related to the amplifier speed and bandwidth are the following:

- Bandwidth: bode plots with gain and phase as function of frequency in current and voltage mode and at different power level and type of load.
- Maximum slew-rate and initial delay
- Communication delays from and to the model executed by the real-time simulator
- Interfacing inductance/transformer/impedance
- Sensor accuracy and delay
- Anti-aliasing filters (for instance if the DuT is an inverter)

The above specification is very important to determine the accuracy and PHIL system stability.

5| Fifth Consideration

Choosing the Right Instrumentation and Control

For PHIL applications, fast control signals and rapid feedback on currents and voltages are required in order to close the loop. If the feedback is too slow, the model won't measure the updated currents and voltages, resulting in an unstable configuration. Since real-time platforms may be interfaced with a wide variety of amplifiers and controllers, choosing the right instrumentation is crucial. In fact, the right equipment can stabilize a model by reducing the feedback time by considerable amounts. With PHIL, we encounter two ways to return current and voltage feedback to the simulator: with digital communications or with analog communications.

Choosing the Right Instrumentation

I) DIGITAL COMMUNICATIONS (USUALLY SFP AURORA)

Higher-end amplifiers often have the option of internally measuring their output and sending the information through a small form-factor pluggable transceiver (SFP) through a point-to-point communication protocol called Aurora. SFP and Aurora ensure digitized measurement and control without noise at high speed in a single point of connection through fiber optics. Aurora also lets the amplifier be configured remotely through the simulator’s interface with specific function commands like the current and voltage limits as well as enabling amplifier output.

Optical fiber interfaces eliminate ground-loop problems and noise interference and provide maximum safety.

II) ANALOG COMMUNICATIONS

Some amplifiers use analog inputs and outputs. In such cases, the simulator must have analog output and inputs to interface the model with the amplifier. Special care must be taken to prevent the induction of noise in the cables connecting the amplifiers and sensors to the simulators. Galvanic isolation is also recommended to prevent ground loop problems as well as to obtain a secure installation.

Signal Measurement and Conditioning

Some amplifiers include embedded sensors to measure current and voltage waveforms. Such signals are available to users to interface with the model either via SFP optical fibers or on analog ports. However, users must verify that these sensors are fast enough (i.e., signal filtering must be optimized to induce minimum delays) for the application. OPAL-RT provides a variety of voltage and current sensors if sensors supplied by amplifier manufactures exhibit too much delay for PHIL applications.

Narrowing Down the Options

Power hardware-in-the-loop simulation represents a natural extension of CHIL in order to increase test coverage before system commissioning. By its very nature, PHIL simulates power-intensive applications, and provides higher test fidelity and test coverage than CHIL testing can hope to depending on test objectives and implementation of the PHIL. Making an accurate PHIL system is, however, a big challenge due to the limitations of amplifier bandwidth and of some real-time simulators. There is always a compromise to make between PHIL cost and accuracy (i.e. bandwidth).

Conversely, several system-level tests would be too expensive to perform with a PHIL setup and other tests may be too dangerous to perform in PHIL mode. Also, Controller HIL enables design and test of the controller when the power devices are not available to reduce the total time-to-market and development cost. Consequently, one must select the use of either PHIL or CHIL depending on both the study objectives and project stage to optimize the total project cost and to decrease project delay and security risks.

When PHIL is needed, responsiveness in PHIL testing comes down to this: fast and dynamic feedback. Without this, real-time simulation of PHIL systems is not possible, and results may not represent their physical live counterparts. Choosing the right solution comes down to five major concepts, as we've discussed: the amplifier's operating range, its cost, its source and sink capabilities, its bandwidth, and finally its instrumentation and control.

This article has simply scratched the surface of the possible configurations and capabilities of such systems—though we hope our experience has started to clarify the way forward for you.

References & Further Reading

1: *Stability and Accuracy Considerations of Power Hardware- in-the-Loop Test Benches for Wind Turbines,* Antonino Riccobono, Alexander Helmedag, Anica Berthold, Nurhan Rizqy Averous, Rik W. De Doncker, Antonello Monti, https://www.sciencedirect.com/science/article/pii/S240589631733344X

2: *Safety Issues for Power-Hardware-in-the-Loop Simulations,* Georg Lauss, AIT Austrian Institute of Technology ;Felix Lehfuß, AIT Austrian Institute of Technology Vienna, Austria, http://pubdb.ait.ac.at/files/PubDat_AIT_133989.pdf

3: *PHIL simulation for DER and smart grids: best practices and experiences from the ERIGrid project*, ERIGrid Webinar: 5 December 2017, https://erigrid.eu/wp-content/uploads/2017/12/ERIGrid-PHIL-Webinar-Presentations.pdf

4: *Power Hardware-in-the-Loop Conception: How to Design a Field-Test Environment for Large-Scale Smart Grid Integration Studies,* October 2018, Conference: International Conference on the Integration of Renewable and Distributed Energy Resources Project: European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out (ERIGrid), https://www.researchgate.net/project/European-Research-Infrastructure-supporting-Smart-Grid-Systems-Technology-Development-Validation-and-Roll-Out-ERIGrid

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Learn about the benefits and challenges of PHIL simulation, its applications, case studies and much more on OPAL-RT's website or by contacting one of our PHIL specialists.

Contact Us: http://www.opal-rt.com/contact-sales-team

Resource Center: https://www.opal-rt.com/philresources

Key Considerations When Selecting PHIL Configurations

	Typical Power Operating Range	Sink and source consideration	Bandwith (kHz)	Other consideration
Grid and Microgrid Applications				
Grid Emulator (50, 60 Hz)	120 to 208 Vrms, 10 A	Sink and source	5	
Grid Load	120 to 208 Vrms, 10 A	Sink and source	5	Sourcing is needed for power absorption
Wind_generator Emulation - Small Lab Scale	120 to 208 Vrms, 0.2 to 20 kW	Source	5	
Wind_generator Emulation - Medium Lab Scale	120 to 208 Vrms, 0.2 to 200 kW	Source	5	
Grid Inverter Emulation	120 to 208 Vrms, 10 A	Sink and source	10	
Frequency Emulator	120 to 208 Vrms, 10 A	Sink and source	5	Application mainly used for active filters
Photo Voltaic Emulation	200 to 400 Vdc, 200 W to 20 kW	Source	1	
Automotive Applications				
Electrical Power Train Emulation	500 to 1000 kW	Sink and source	15	Everything but the battery is simulated. DC output.
Battery Emulator	20 to 100 kW, 200 to 600 Vdc	Sink and source	1	Only the battery is simulated
Drive Inverter Emulator	500 to 1000 kW	Sink and source	15	DC with inverter simulated. AC output.
Motor Emulator	500 to 1000 kW	Sink and source	15	Only the motor is simulated.
eVehicle Charging Station Emulator	3 to 250 kW, 200 to 600 Vdc	Sink and source	1	Sink for vehicle to grid applications. Smaller charging times for higher power outputs.
Aerospace / Military				
400 Hz Supply Grid Emulator	115 Vrms	Sink and source	50	
Actuator Emulator	Up to 1kW	Sink and source	20	

Founded in 1997, OPAL-RT TECHNOLOGIES is the leading developer of open real-time digital simulators and Hardware-In-the-Loop testing equipment for electrical, electro-mechanical and power electronic systems.

OPAL-RT simulators are used by engineers and researchers at leading manufacturers, utilities, universities and research centres around the world.

OPAL-RT's unique technological approach integrates parallel, distributed computing with commercial-off-the-shelf technologies.

The company's core software, RT-LAB, enables users to rapidly develop models suitable for real-time simulation, while minimizing initial investment and their cost of ownership. OPAL-RT also develops mathematical solvers and models specialized for accurate simulation of power electronic systems and electrical grids. RT-LAB and OPAL-RT solvers and models are integrated with advanced field programmable gate array (FPGA) I/O and processing boards to create complete solutions for RCP and HIL testing.

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