# Safety recommendations for working in the lab

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Gabriel FERNANDEZ
Operations Manager
imperix

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This guide provides an overview of key points to consider when testing power converters in a laboratory environment, covering personnel safety, equipment protection, and the proper sequencing of initial power tests.

This guide is however neither exhaustive nor universally applicable. Safety measures and procedures vary depending on various factors such as the converter topology. **Careful planning, and situational awareness remain the sole responsibility of the operator**.


Somewhat provocative reminder of the hard reality, especially in research and development environments.

Following this guide does not absolve readers of responsibility. **Operators must exercise their own judgment, apply critical thinking, and adapt procedures as necessary**. Imperix disclaims liability for accidents or damages related to misuse or insufficient precautions.

## Setting up the laboratory environment

## Personnel and facility protection

Similarly to most laboratory equipment, Imperix products are typically protection Class I equipment, relying on conductive enclosures connected to protective earth. This low-impedance connection ensures that, in the event of an insulation fault, a high fault current flows, which promptly triggers a protective device like a fuse or circuit breaker. Therefore:

- **A proper connection to ground is key** to ensure personnel safety, not just electromagnetic compatibility.
- Circuit breakers or fuses must be capable of interrupting short-circuit currents, which can easily reach tens of kiloamperes, especially in DC systems. Undersized devices are ineffective.
- A lower-rated and/or faster protection device will reduce the energy in the default, and consequently also the potential damage. Therefore, the lower the breaker rating, the better the protection.

Beyond this basic, yet vital protection, other precautions are also essential:

- **Prevent access to non-insulated parts**. For example, cabinets should be locked and accessible only to qualified personnel.
- Be aware that a converter may remain electrically charged even when not operating. **Inform others**.
- **Ensure clear signage**, thorough documentation, and proper personnel training are in place.

Imperix controllers feature a dedicated **interlock connector** to integrate these safety signals. It is highly recommended to connect an **emergency stop button** to this input whenever feasible.

# Equipment protection

In addition to personnel protection, safeguarding hardware components is critical to ensure reliability and longevity. However, unfortunately, **semiconductor devices cannot be adequately protected using circuit breakers or fuses**.

To this end, the B-Box 3.0, B-Box 4, and the B-Box Micro provide adjustable over-current and over-voltage protection on each analog input, implementing low and high thresholds. When a measurement crosses either of these thresholds, PWM output signals are inhibited, immediately blocking the operation of the power stage.

Specific advice as well as quick configuration guidelines are given in PN257. The key elements are as follows:

- **Always connect all measurements** to the B-Box. A disconnected sensor is obviously useless for protection purposes.
- When determining the protection thresholds:
  - Always select protection thresholds as close as possible to the planned operating points.
  - Be very careful when including some margin in the selection of the thresholds. The overload capability of power electronic circuits is generally extremely limited.
  - Constantly seek to consider the weakest element in the system, as it may not necessarily be a power module, but a power supply, a cable, etc.
- **Test protections** with lower limits in case of any doubts.

Use particular caution when passive rectification cannot be avoided (e.g., inverters connected to the grid), against which hardware protections are ineffective. Explanation about this topic are given in TN131.

# Anticipating problems

As the adage goes, prevention is better than cure. Therefore, it is essential to identify potential issues and evaluate their possible consequences before they occur. The recommended steps are as follows:

**1)** The first step is to **list all potential issues that could arise**, such as misconfigured settings or hardware faults. For each one, determine whether it is already mitigated by a protection, or not. One approach to creating an exhaustive list of potential problems is to consider each state variable as a possible cause and each potentially fragile element as a possible consequence.

**2)** Once potential problems have been outlined, **evaluate their consequences in terms of energy flows**. Where does the energy come from in the event of a fault? Where will it go? How much energy is involved? Are the affected components capable of safely absorbing it, or could it cause destruction?

- The **impact of a fault can vary significantly**. For instance, short-circuiting a DC bus involves significantly more energy than most inductive nodes. The probable damage on equipment varies accordingly.
- It is equally important to **consider the cascading effects** of a fault. When the first component fails, the energy it contained does not simply vanish. The next element will have to absorb it or will be destroyed in turn. For instance, once a TVS breaks, the faulty voltage becomes applied to the rest of the circuit.

**3)** Special attention should be paid to **unintended power flows**. For instance, if an inverter does not operate as expected, it can draw energy from the grid and feed it into a DC bus. In such a scenario, unless the DC bus/source is reversible, the voltage on the bus can rise uncontrollably, either until a protective device trips or until connected components are damaged.

**4)** Planning for **post-fault actions** is another essential aspect. For instance, even though a converter may be blocked, its capacitor bank(s) could remain charged. Neglecting such situations can lead to risks during subsequent human intervention.

# Sequencing the first tests

The initial testing phase of a converter requires careful planning, methodical execution, and strict adherence to safety principles. The following sequence outlines recommended best practices for conducting first tests in a controlled and reliable manner.

## During assembly and wiring

The assembly phase is often when subtle, yet critical mistakes could occur. Key points include:

1. Verify all polarities carefully, as polarity markings are sometimes small or ambiguous. Incorrect polarity may cause irreversible damage and is difficult to debug afterward.
2. Differentiate clearly between voltage and current sensors, as they have significantly different impedance characteristics.
3. Check PWM wiring particularly carefully, especially for complementary signal pairs. If pairs are cross-wired, a 1-1 condition may occur, potentially resulting in a shoot-through condition.

## Testing sensitive functionalities

Before performing any full-power test, the most sensitive and safety-critical functionalities must be validated. Here, “sensitive” refers either to elements involving hazardous sources (e.g., grid) or to fragile components that could be easily damaged. At a minimum, ensure the following:

1. Test the most critical protection mechanisms, including DC bus overvoltage protection (which is essential) and overcurrent protections. Minor changes in current thresholds may have a limited impact, but inadequate voltage thresholds may render the protection ineffective.
2. When working with the AC grid:
    - Validate the correct operation of grid-connection relays, ensuring they close and open as intended and in the correct sequence.
    - Validate the proper operation of precharge circuits, soft-start mechanisms, and state machines. See TN131 for more details about this.
    - Check the phase-locked loop (PLL) for stable frequency and quadature voltage outputs. The phase sequence or PLL tuning may be wrong otherwise.

## Progressive testing

A progressive testing approach helps isolate issues and limits the energy involved at each stage:

1. Validate each converter stage independently, such as the boost stage or inverter stage. Testing them separately allows easier debugging.

2. Test control loops incrementally, starting with inner loops (e.g., current controllers) before validating outer loops (e.g., voltage controllers). Cascaded structures are easier to stabilize when validated sequentially.
3. Generate transients to evaluate dynamic behavior. Small steps are generally sufficient. Insufficient stability manifests clearly during transients.
4. Whenever possible in early tests:
    - Replace uncontrollable sources (e.g., batteries, supercapacitors, or the grid) with controllable alternatives such as programmable DC sources or grid emulators.
    - Apply current and power limits on controllable sources to reduce the available energy in case of faults. Beware of the implications of these limits on the system as well as their coordination with other protections. Pay attention to reverse power flows, especially when leading to a special behavior.
5. Start with low voltage and low current, gradually increasing both toward the nominal operating point as confidence in the system grows.
6. Beware of losses. They are often negligible during the first tests, but they may play a significant role as the current and voltage increase:
    - Conduction losses rise quadratically with current, affecting cables, connectors, and passive loads. Monitoring temperature is often helpful.
    - Asymmetrical losses between semiconductor devices (e.g., between high-side and low-side switches) often go unnoticed, as temperature protection on the power modules does not prevent damage caused by such asymmetry.

Audible cues are very valuable indicators. Unusual sounds (buzzing, rattling, or high-frequency tones) may signal instability or improper control. For this reason, operators should avoid wearing headphones or listening to music during tests.

# Typical pitfalls

The following list highlights frequent issues encountered in laboratory setups with power converters. This list is obviously not exhaustive, but understanding the corresponding causes and consequences may be helpful in other similar situations:

- If an inverter with an empty DC bus is connected straight to the grid without a pre-charge circuit, extremely high uncontrolled inrush currents occur, generally leading to the instant destruction of all power semiconductors. Always ensure that the bus is properly precharged and monitored before connecting to the grid. See TN131 on this topic.
- With grid-tied voltage-source converters, over-current protection is perfectly effective provided that the DC bus voltage is higher than the naturally-rectified

AC voltage. Uncontrollable diode currents occur otherwise (see above). Guaranteeing this condition is simple but essential.

- When a DC source is sinking power from the DC bus of an inverter, improper (negative) current limitation can cause catastrophic overvoltage if the source blocks its operation before the inverter. Proper DC bus overvoltage protection is vital to stop the converter before the source is destroyed.
- Confusion may occur when wiring power modules, between the ordering of the phases seen from the front as opposed as seen from the back. The numbering of the modules should typically be done from left to right at the front, and right to left at the back.
- When using PEN8018 NPC-type modules: failing to check the balance of the half DC buses or misconfiguring the correspdong voltage selector (up or low) may lead to uneven voltages. Implementing two independent measurements and protections is necessary.
- Incorrect use of the EMC filter for grid-tied connection can lead to high common-mode currents. The recommended connection strategies for the passive filter box are indicated in its datasheet.
- When using the pre-charge circuit of the grid connection panel, currents may flow through the precharge resistors and the capacitors of a grid-side filter, even though the inverter may be blocked. These reactive currents may lead to excessive losses in the resistors if 1) the pre-charge is closed and 2) the bypass is open during a long time.
- As the dead-time is configured by software and carried along the control code/model, inadequate values can be inadvertently applied when switching between control files that were originally intended for different power modules. In this case, using conservative values is recommended. See PN115 on this topic.

# Conclusion

Careful planning, proper protections, and step-by-step testing are essential for safely working with power converters in the lab. In most cases, things don’t work perfectly the first time, especially during the early testing phases. By anticipating potential faults and minimizing risks, operators can significantly reduce the likelihood of accidents and equipment damage.