Design of an End-Effector for High-Voltage Power Modules

Application to (1) DC–DC Residential Energy Converters and (2) AC–DC 1000 V DC Fast-Charging Power Stages

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Abstract

This report describes the development of a mechanically guided, electrically insulated end-effector that enables safe and repeatable contacts to high-voltage (HV) power modules during manufacturing and laboratory tests. Two target products are considered: (i) a DC–DC residential energy converter that needs reproducible HV and low-voltage access, and (ii) an AC–DC 1000 V DC fast-charging power stage in which DC rails and auxiliary lines must be contacted temporarily.

The tool can be mounted to a robot or an XYZ positioning system and uses fork-type guides, spring contacts and an insulated body to achieve: (a) positionally consistent insertion without side-loading the DUT terminals, (b) low and stable contact resistance at high current, (c) compliance with creepage/clearance for up to 1000 V DC, and (d) safe behaviour in case of misalignment. Reference photographs define the available envelope. The report explains use case, constraints, architecture, safety and verification.

1 Introduction

HV power-electronic products — wall-mounted home-energy converters and DC fast-charging modules — need a short, reliable and easily removable connection to the device under test (DUT) during end-of-line (EoL) and R&D characterization. Manual test leads are common but:

- slow to position,
- operator-dependent,
- often marginal on creepage/clearance,
- and hard to repeat over many cycles.

A better approach is to integrate the contacting function into a *robotic end-effector*. Such a tool must (1) locate the DUT connector or busbar, (2) close without damaging copper or plastic guides, (3) present a defined pinout, and (4) fail safely when misalignment occurs.

The photographs supplied with the task show a high-current fuse/busbar assembly with spring-loaded terminals and a handheld connector block with a front alignment feature and rear multi-pin interface. The design below generalizes these parts into a reusable test-bench tool.

2 System Overview

2.1 Target Assemblies

DC–DC residential energy converter. This module raises or lowers battery-side DC to a building DC level (home battery, inverter DC link, DC microgrid). Typical values:

- Input: 350 to 450
- Output: 380 V to 420 V, optionally bidirectional
- Channel current: 80 A to 200 A

For factory tests the fixture must inject DC, read back voltages, perform insulation tests and read temperature/sense lines.

AC–DC 1000 V DC fast-charging stage. This module rectifies three-phase AC (typically 3×400 V or 480 V) to a regulated DC output up to 1000 V. During EoL it must be possible to contact HV^{+} and HV^{-}, pilot/ interlock lines and sometimes a low-voltage service connector. A dedicated docking tool removes slow manual bolting.

2.2 Operating Environment

- Location: indoor test bench / R&D lab.
- Structure: aluminum T-slot frame or gantry.
- Protection: IP20 is acceptable; live conductors must be backed by insulating inserts.
- Durability target: $\geq 10\,000$ mate/demate cycles.

3 Reference Hardware

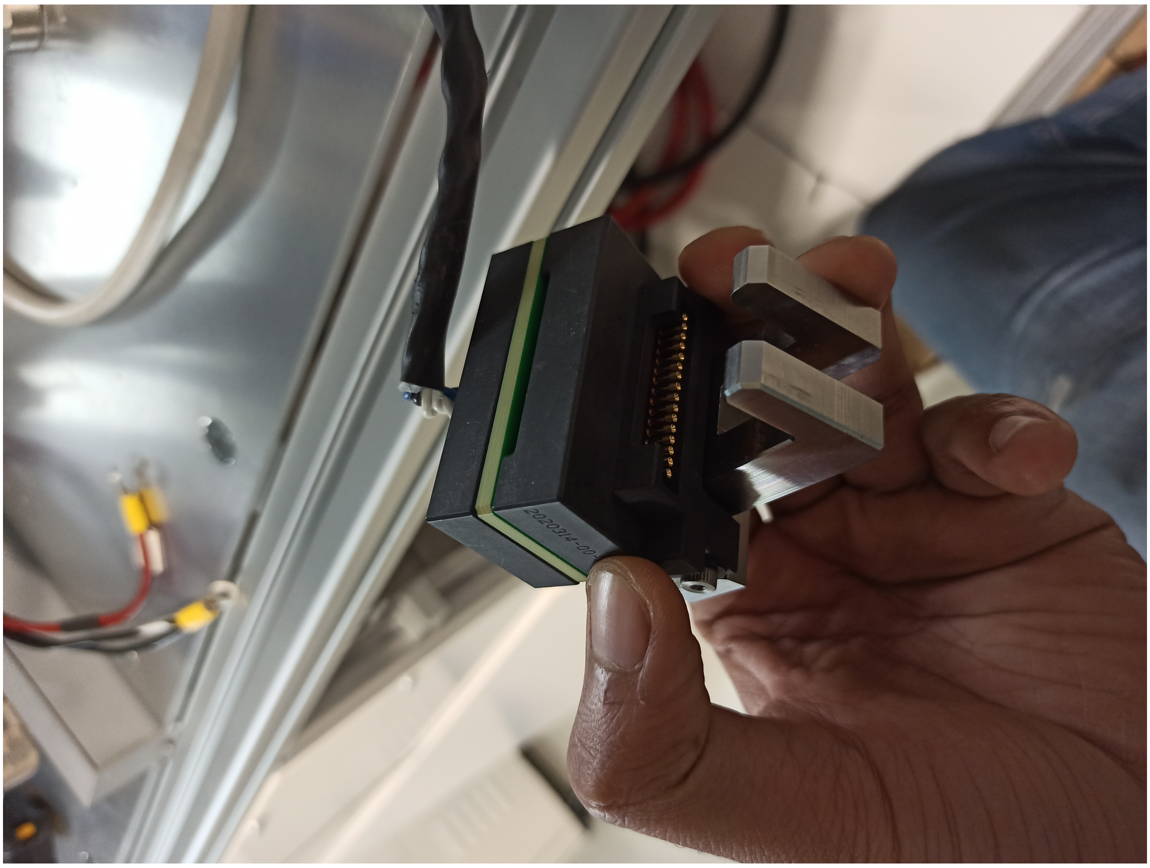

Figure 1: Handheld connector / end-effector with twin aluminum forks and rear multipin connector.

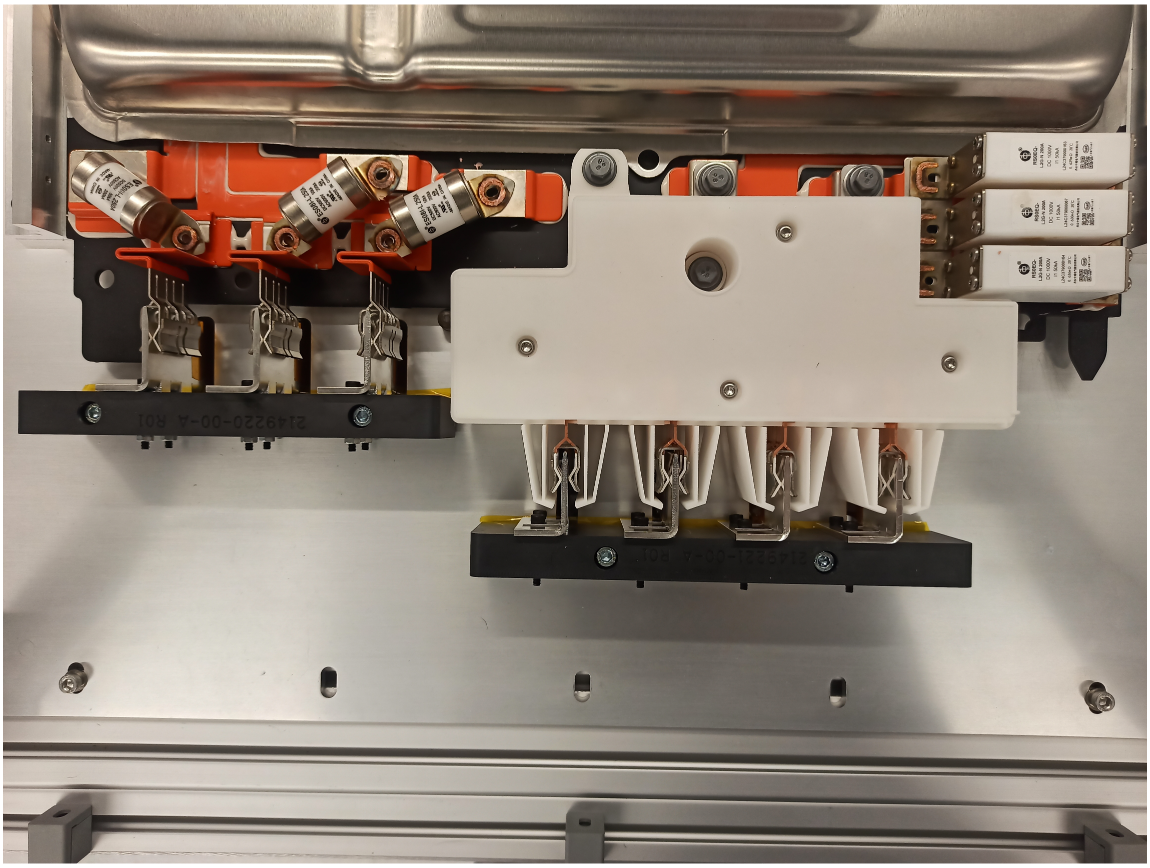

Figure 2: HV fuse and busbar assembly with protective cover.

The white plastic cover and the lower copper contact row define the fork spacing.

4 Design Requirements

4.1 Functional

FR1: Guide onto vertically oriented copper/plated terminals without side loading.
FR2: Provide electrical continuity from DUT terminals to the rear multipin connector.
FR3: Tolerate misalignment of about ± 0.5 mm laterally and $\pm 1^\circ$ in pitch/yaw.
FR4: Allow manual handling with one hand.

4.2 Electrical / HV

ER5: Nominal current per main contact: 150 A DC for 30 s.
ER6: Short-term withstand: 300 A for 3 s.
ER7: Max system voltage: 1000 V DC.
ER8: Creepage/clearance HV^{+}–HV^{-}: ≥ 12 mm in air (IEC 60664-1, PD2).
ER9: Target contact resistance: $< 100\,\mu\Omega$ per pole.

4.3 Mechanical

MR10: Total mass < 600 g.
MR11: No sharp metal edges near live parts.

MR12: Replaceable/sacrificial forks fastened with M4 countersunk screws.
MR13: Visual alignment mark (green stripe) on the front.

5 Concept and Architecture

5.1 Overall Structure

The tool is made of the subassemblies in Table 1.

Table 1: End-effector subassemblies

ID	Name	Function
A	Front guiding forks	Machined Al profiles matched to DUT slot pitch.
B	Insulating spacer block	FR4/PA6 block fixing fork spacing and creepage.
C	Contact carrier	Holds spring/leaf contacts and routes to rear connector.
D	Rear electrical interface	30-pin (or similar) connector to test rack.
E	Strain-relieved cable	Shielded harness exiting on top.

The robot or operator advances the forked nose into the DUT. The DUT's plastic features steer the forks; when fully seated, the internal springs land on the copper lugs. The green stripe serves as a "seat line": invisible stripe = fully engaged.

5.2 Guiding Forks

Two U-shaped Al forks with tapered entries:

- Material: EN AW-6061 or EN AW-6082.
- Surface: natural/hard anodize.
- Geometry: generous lead-in to correct small misalignment.
- Tip radius $\geq 1.5\,\mathrm{mm}$ to avoid damage.

5.3 Contacting Principle

Two options:

1. Spring / leaf fingers on flat copper tabs (preferred, robust, high current).
2. Replaceable pogo-pin bar for signals / low current.

Because up to 150 A is required, tin-plated CuBe spring fingers with 15 N to 20 N per pole are selected.

5.4 Electrical Interface

Rear 30-pin connector groups pins as:

- 1–4: HV^{+} (paralleled),
- 5–8: HV^{-} (paralleled),

- 9–12: PE / shield,
- 13–20: sense, temperature, interlock,
- rest: reserved.

Parallelization lowers current density while keeping the connector compact.

6 Applications

6.1 Application 1: DC–DC Power Pack

Enabled test flow:

1. Dock tool; confirm by force or switch.
2. Run continuity check at 24 V.
3. Read LV I/O (temperature, fan PWM, comms).
4. Run functional DC test with external source and load.
5. Undock and retract.

Advantages: fewer polarity errors, faster cycle time, less wear on the product's molded plastic.

6.2 Application 2: 1000 V DC Fast-Charging Stage

HV-specific points:

Clearance: high DC voltage requires larger air distances; the original plastic creepage former must not be bypassed.

No load docking: mating under load must be prevented using an interlock.

Recommended sequence: verify 0 V output, dock and confirm seat, close rack contactor, run tests, open contactor and discharge, then undock.

For an initial CAD layout, measurements from Fig. 2 suggest

$$s_{\text{outer}} \approx 26\,\text{mm}, \quad s_{\text{inner}} \approx 18\,\text{mm},$$

to be validated with a 3D-printed gauge.

7 Safety, Risk and Validation

7.1 Risks

1. Shorting adjacent HV rails due to deformation or debris.
2. Accidental touch of live conductors.
3. Damage to DUT guides or copper from misalignment.

7.2 Mitigations

- Seat interlock: enable HV only on verified seating.
- Insulating fork caps so only the inner spring is live.
- Robust strain relief for the harness.
- DC hipot between HV^{+} and HV^{-} at 1000 V under high humidity, aiming for $> 100\,\text{M}\Omega$ leakage.

7.3 Verification

1. Dimensional check of fork spacing vs. DUT plastic.
2. Contact resistance at 10 A and 100 A using $R = V/I$.
3. Durability: 500 cycles without noticeable wear or R increase.
4. Dielectric withstand: 2 kV DC for 1 min.

8 CAD and Manufacturing Notes

8.1 Tolerances

- Fork-to-fork parallelism: ≤ 0.05 mm.
- Lead-in chamfer / taper: $\pm 1^\circ$.
- Rear connector hole pattern: per manufacturer.

8.2 Prototype Strategy

1. 3D-print forks (PETG/PA12) for clearance checks.
2. Machine in aluminum and anodize after validation.
3. Test on the real DC–DC pack.
4. Adjust cable exit angle to clear housing.

9 Conclusion

The proposed end-effector turns a manual, operator-dependent HV connection into a repeatable, automatable operation. By matching geometry to the DUT's plastic guides, offering a rear multipin interface and meeting 1000 V creepage/clearance, one tool body can serve:

1. DC–DC residential energy converters, and
2. AC–DC DC fast-charging power stages.

Future work: integrate voltage-presence indication and add keyed variants for other pole counts.

References

[1] IEC 60664-1, *Insulation coordination for equipment within low-voltage systems.*

[2] IEC 61851, *Electric vehicle conductive charging system.*

[3] R. Mroczkowski, *Electronic Connector Handbook*, McGraw-Hill, 1998.