HOW INVERTER PRODUCTION QUALITY CONTRIBUTES TO GLOBAL ELECTRIFICATION

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HOW END OF LINE TESTING ENSURES INVERTER PRODUCTION QUALITY

Power inverters are essential to many of today's electrification technologies – but they must be of excellent quality to fulfil their role. This article looks at the issues around the end of manufacturing line testing strategies essential to assuring this quality. Renewable energy and electric vehicles are two leading examples of the world's drive to go green and mitigate global warming.

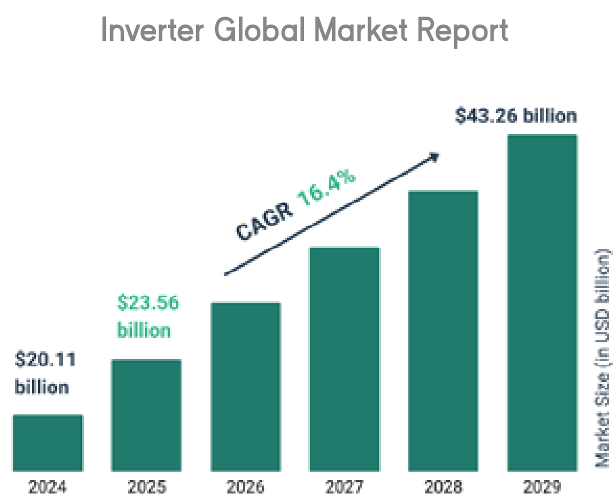
This article looks at the architecture of these devices, and the testing strategies essential to ensuring their production quality.

Although widely diverse, these applications share a need for safe, efficient, reliable, and competitive power inverters. It next considers the practical challenges of performing such tests at the end of the production line and then describes some innovative technology now available for addressing these challenges.

Inverter market growth and challenges

The inverter market is expected to grow from an estimated US$39.6 billion by 2028 from an estimated US$18.9 billion in 2023 at a CAGR of 16% during the forecast period. The demand for inverters is growing due to the increasing adoption of renewable energy sources such as solar and wind power. Additionally, the surge in electric vehicle adoption, advances in inverter technology, and the emphasis on energy efficiency contribute to the expanding demand for inverters in various applications across residential, commercial, and industrial sectors.

While enjoying healthy growth, the inverter market also faces challenges. With a multitude of both local and international players, product quality is a crucial factor for market differentiation. The organised sector primarily serves industrial buyers and upholds elevated product standards which meet relevant industrial norms. However, there are local manufacturers in many countries competing fiercely with global suppliers by offering inexpensive but lower quality products.



In the solar PV market, the diminishing overall costs of solar systems across residential, commercial, industrial, and utility sectors necessitate price reductions from inverter companies. Solar inverter manufacturers find it challenging to adapt to this shift and implement price reductions[i]. These factors highlight the critical need for reputable manufacturers to preserve their product differentiation and their reputation by using end of line (EOL) product testing to ensure a manufacturing output of consistently high quality.

Yet EOL also brings its own challenges, and it must be carefully implemented to overcome these while adding minimal extra cost to production. Accordingly, after reviewing the key inverter technologies involved, the article discusses the practical issues of implementing a suitable EOL strategy, and some innovative ways of overcoming them.

Popular solar PV inverter technologies

Solar PV inverter installations are usually either central inverter or string inverter types. Central inverter systems are based on multiple PV panels feeding into a single large inverter hub. By contrast, string inverter systems place the inverters together with smaller "strings" of PV panels. These sub-systems are then combined before output. Historically, central inverter systems have been dominant, but string inverters are becoming more popular due to their falling costs and modular design, which simplifies maintenance and reduces downtime[ii].

Different inverter topologies are available. NPC (Neutral Point Clamped) and ANPC (Active Neutral Point Clamped) are widely used in 1500V multistring inverters. Mixed voltage NPC (MNPC) is still used in residential and commercial 1000 V systems but is gradually being replaced by NPC. Three-level and four-level flying capacitor inverters are becoming popular in the latest systems.

NPC, ANPC and flying capacitor topologies provide a higher system blocking voltage than the individual components. For example, an NPC using 950V components will provide 1900V blocking voltage. If a four-level flying capacitor topology is used in a 1500V PV inverter, components with only 650V blocking voltage are sufficient. Typically, components with lower blocking voltages are faster, have lower switching losses and are usually lower cost.

NPC and ANPC topologies have similar losses, and therefore efficiency, when used in systems driving predominantly non-reactive loads. However, the ANPC has clear efficiency advantages for cos Ø<1 and, for the sake of completeness, bidirectional operation. The losses in NPC and ANPC are concentrated in the semiconductors operated with high-frequency PWM. These components are subject to conduction and switching losses. In most cases, the temperature of the fast switching semiconductors limit the maximum module output power.

In general, the losses in a flying capacitor inverter are distributed evenly across all components. This means a flying capacitor inverter has a lower junction temperature than NPC or ANPC for the same output power. Alternatively, a flying capacitor inverter enables a higher output power at the same junction temperature as NPC and ANPC.

The flying capacitor inverter also supports full reactive power and bidirectional operation. A key advantage of flying capacitor inverters is their "artificial" inductor current frequency increase. For a three-level flying capacitor topology, the inductor current frequency is double the semiconductor switching frequency and, in the case of four-level, it's triple. The inductor size can be drastically reduced or, by keeping the same inductor current frequency, the semiconductor switching frequency can be reduced by a factor of 2 or 3 respectively. This reduces the switching losses and results in higher efficiency than NPC and ANPC.

However, flying capacitor inverters can be less reliable than ANPC types, due to higher internal operating temperatures. Nevertheless, this disadvantage can be negated by devices now available with advanced die attach technology which increases reliability at higher junction temperatures.

Design considerations for EV inverters

EVs use inverters – known as traction inverters - in their drive train system to convert DC battery power into AC for driving traction motors such as permanent magnetic machines (PMSM), induction motors (IM), externally excited synchronous motors (EESM), and switched reluctance motors (SRM). A traction inverter also uses recovered energy from the motor to recharge the battery while the vehicle is coasting or braking[iii].

Key design priorities to be considered when assessing traction inverter performance include functional safety and security (which usually follows ISO 26262 or an e-safety vehicle intrusion-protected applications process), weight and power density, efficiency, performance and reliability.

The architecture of a traction inverter varies with vehicle type. Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have a three-phase voltage source inverter topology, with power levels in the 100- to 500-kW range. The battery pack can either directly connect to the inverter DC input or a DC/DC boost converter can be used to step up the battery voltage and supply the inverter with a controlled DC voltage.

The two-level inverter is the most common power converter used in electrified vehicles and in the industry, with power ranges of tens of kilowatts up to hundreds of kilowatts. Usually, the switching frequency is in the range of 5kHz to 30kHz. Currently, three-level inverters are becoming more popular because they offer higher power capability (beyond 300 kW), higher efficiency, and lower harmonic distortion and allow the use of a smaller electromagnetic interference (EMI) filter. Among many topologies, neutral point clamped, and T-type neutral point clamped (TNPC) are the most competitive designs.

Other trends in traction inverter features include:

- Dual inverters to support dual motor architectures, implemented by various vehicles including the Chevy Volt PHEV, Toyota Prius HEV, and Cadillac CT6 PHEV.
- Increasing power levels and Automotive Safety Integrity Levels (ASILs) (100 kW to 500 kW, ASIL C to ASIL D).
- Shifting towards 800-V technology with increased switching transient voltages.
- Easily adjusting the gate-drive strength to reduce overshoot, optimise efficiency, and reduce EMI.
- Employing an inductive position-sensing technology instead of a resolver to reduce costs.
- Integrating active discharge into a gate driver integrated circuit (IC) to reduce costs and save space.

End of Line (EOL) testing for inverters

So far, this article has reviewed the various topologies and technologies available for designing PV and EV inverters. Irrespective of their technology, though, they must be proven to perform safely, reliably and efficiently, to preserve their manufacturer's market edge and reputation.

For these reasons, EOL plays a vital role in helping manufacturers achieve these assurances. Yet the EOL system itself must be built to fulfil its role successfully, without creating problems for its users.

Accordingly, the article now looks at EOL test requirements for PV and EV inverters, before considering the challenges involved, and an innovative solution.

Key test parameters for all inverter types include efficiency, voltage regulation, current regulation, waveform quality, and maximum power output. Safety features like overvoltage and overcurrent protection are also essential, as is insulation resistance testing.

Beyond this, PV and EV inverters have somewhat diverging test requirements, reflecting the differences in their application.

PV inverter testing

Power conversion system (PCS) performance tests evaluate the overall performance of the power conversion system within the inverter, checking key parameters including efficiency, power factor, and response time. Efficient, effective inverter operation is also essential for maximising energy efficiency.

Input and output tests focus on the inverter's behaviour under varying input conditions, such as solar irradiance and temperature. They also verify that the inverter can handle various voltage and current levels while maintaining a stable output.

Protection is essential, so the inverter's protective features, such as overvoltage, overcurrent, and anti-islanding protection should be tested. Anti-islanding protection ensures that the inverter disconnects from the grid during a power outage to prevent backfeeding.

The inverter's response to varying PV array conditions should be tested. This includes maximum point power tracking (MPPT) efficiency and dynamic behaviour during rapid irradiance changes.

The overall goal is to verify that the inverter meets industry standards and specifications, with assured product quality and reliability. Standards also provide references for manufacturers.

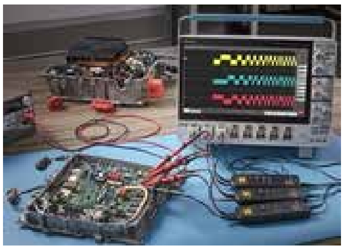
EV inverter testing

Function testing is used to verify that the EV inverter performs its intended functions correctly. This includes assessing its ability to convert DC power from the battery to AC power for the electric motor. Calibration and adjustment ensure that the inverter's parameters are correctly calibrated. This involves fine-tuning settings related to voltage, current, and frequency.

Safety testing validates safety features such as overcurrent protection, overvoltage protection, and thermal management. Safety is critical for EV components.

Performance testing evaluates the inverter's efficiency, power output, and response time. This ensures optimal performance during operation.
For highly non-linear drives used in current vehicle programs, powerful hardware-in-the-loop (HIL) systems can replace passive loads and accurately emulate the behaviour of the real motor during testing.

Note that specific test protocols may vary based on the manufacturer and inverter design.



EOL testing – practical considerations and challenges

End of Line testing assesses not only the quality of the product, but also the stability and yield of the production process. Reliable detection of non-functional units is the primary objective of the test, but reducing the rejection rate and maximising the output is the ultimate goal[iv]. Ensuring that products meet calibration standards is also essential.

With the increasing complexity and specialisation of manufacturing processes, EOL testing has become more sophisticated, which can make it harder to implement. Space constraints in EOL testing can pose significant challenges, particularly as automated testing systems become more complex and integrated into production lines.

Overall, EOL testing challenges include:

- Need to accommodate all necessary test equipment within limited production area space.
- Need to integrate multiple instruments into a unified test strategy.
- A single manufacturer may be producing various models which require different test hardware and procedures.
- Industry has stringent quality requirements, making it essential for EOL testing to be highly accurate
- Testing all these functions within a limited time frame is a significant challenge. Using automated test systems with high parallelism can help address this issue by significantly reducing the test time.
- Customised report generation as per the customer requirements, call for customisable testing software.
- Clearances for safe operation and maintenance.
- Efficient flow through testing without causing bottlenecks.
- Minimising power consumption in EOL test equipment is also essential, especially as the equipment often runs continuously or for extended periods during manufacturing operations. In particular, efficiency should be optimised to:
    - Reduce costs.
    - Reduce environmental impact and improve sustainability. In fact, some industries have regulations regarding energy consumption, so using low power EOL test equipment can help companies stay compliant with these standards.
    - Cut heat generation: Reducing power consumption reduces heat generated, which can improve the reliability and lifespan of both the test equipment and the products being tested.

An innovative EOL solution

After 15 years' experience in electrification and energy transition, Barcelona-based Cinergia Power Solutions has introduced its new Rack Series family, which combines all of the company's know-how into a compact and highly efficient unit designed especially for applications like EOL testing.

The test system is implemented in a 7u rack. Its functionalities include AC Grid Simulator, AC Electronic Load (sink/source), DC Bidirectional (source/sink), Battery Test/Cycle and Emulation, and PV Emulation. Operational modes include Programmable Current, Programmable Power, Programmable Voltage, and Power Amplifier. 22.5kW and 30kW models are available.

This functionality enables the system as a valuable tool for testing inverter assembles. Additionally, though, it offers many features to mitigate the challenges facing EOL strategy designers as discussed above.

Its compact standard 19” rack mounting design makes a crucial contribution to saving space in limited production floor areas. With modular, scalable design, it can be configured to meet test requirements precisely, and then rapidly reconfigured to accommodate different products under test.

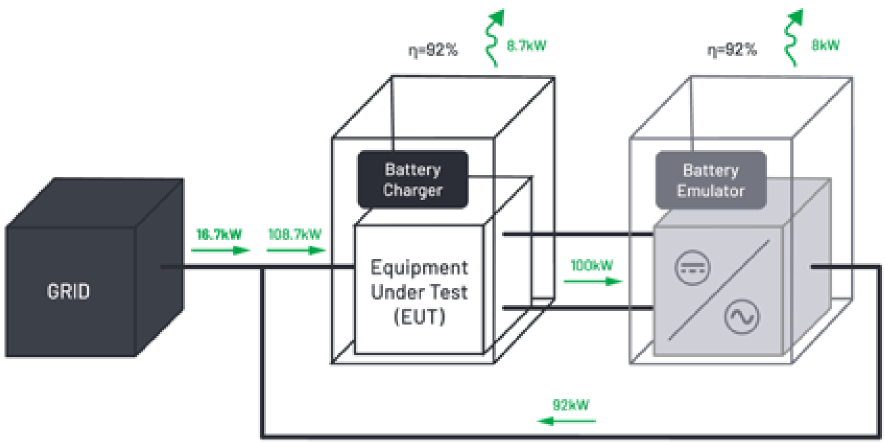
Once configured, the European-designed and manufactured units offer reliable 24/7/365 operation, supporting extended-period continuous tests and minimising EOL delays and production line downtime.

Multiple units can be run in parallel, with multichannel DC outputs available from each unit - a capability not found in competing products.

High power efficiency and power density

The Rack series significantly improves power efficiency and power density through two of its inbuilt technologies – regenerative operation and SiC semiconductor technology.

Like all Cinergia products, the Rack series uses bi-directional topology, which enables regenerative operation. This allows the re-injection of the used power back to the grid, resulting in a reduction of both the consumed energy during the tests and the power required from the electrical installation.



Energy consumption is further reduced, along with high power density, by utilising SiC MOSFETs in both converters of the back-to-back configuration. This boosts the peak efficiency of the entire system to above 94%.

The Rack unit offers a higher power density than any other product the company has manufactured, making it more lightweight and compact.

Software and communications

The Rack's user interface provides operators with total control of the device, allowing them to fully leverage its capabilities. It also enables programming and execution of standardised or user-generated tests.

Modbus/Ethernet Open protocols are available for communications with other instrumentation devices.

One remarkably innovative feature of the Rack's new software is its Steps functionality. Step test files are saved and executed by the internal DSP allowing deterministic timing with a resolution of 66µs. The user gains access to all of the Rack's registers to create complex test sequences which it runs internally without needing an external computer.

Conclusion

As inverters and related electronic devices become ever more complex, so do the EOL strategies needed for testing them. Utilising instrumentation, which is modular, scalable, and programmable, while offering compact size, high power density and high power efficiency allows manufacturers to future-proof their EOL facility against these inevitably developing trends.

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