GAMESA ELECTRIC · WHITE PAPER

Cooling systems for utility-scale solar and storage inverters

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GamesaElectric | Shaping New Energy

INDEX

Introduction

The increasing demand for utility-scale inverters in remote and high-temperature regions has driven power converter manufacturers to innovate more efficient cooling systems. As power requirements continue to grow, ensuring the reliability and longevity of critical components is paramount. One of the most effective solutions is liquid cooling technology, which provides superior heat dissipation compared to traditional air cooling.

Gamesa Electric has been a pioneer in developing liquid-cooled power converters for wind turbines, photovoltaics (PV), and battery energy storage systems (BESS). With more than 25 years of experience, the company has optimised hybrid cooling solutions that combine the best aspects of liquid and air cooling.

This white paper explores the technology behind liquid cooling in utility-scale inverters, market trends, comparative performance analysis, and Gamesa Electric's experience and lessons learned in implementing this technology.

Market evolution

The demand for large-scale solar PV and Energy Storage projects is growing rapidly. Renewable sources account for more than 90% of new power installations globally, reaching 585 GW of new installed capacity by 2024 [1]. Solar PV together with batteries are the fastest growing technologies, with annual installation forecasts in 2030 of 880 GW for solar [2] and 170 GW for BESS [3]. This growth is driven by:

- Increasing energy demand in developing economies.
- Electrification of demand in areas such as transport, air conditioning and industry.
- Regulatory policies supporting renewable energy adoption.
- Declining costs of lithium-ion batteries and solar panels.

This demand is concentrated in large markets such as the USA, China, India, Australia, the Middle East and Spain, where climatic conditions can be extreme, often exceeding 40°C (104°F) ambient temperature.

Heat generation and heat transfer

In order to be able to optimally design a cooling system, it is necessary to understand how heat is generated and transferred within a power inverter. Let's look at some basic concepts that will help us understand what lies behind the different designs on the market:

HEAT GENERATION

In any electronic device, heat is generated by circulating electric current through resistive elements.

The formula is very simple:

$$Q_{gen} = I^2 R_{int}$$

Where:
I is the current flowing through the device
R_{int} is the internal resistance

HEAT TRANSFER

The main heat transfer mechanisms are conduction, convection and radiation.

Conduction refers to the transfer of heat between materials.

Convection deals with heat transfer between a surface and a fluid.

Finally, **radiation** models heat transfer through electromagnetic waves.

FOURIER'S LAW

Conduction is the main process when designing a cooling system for a high power inverter and this process is modelled with Fourier's law:

$$Q_{cond} = -h\nabla T$$

Where:
h is the conductivity of the material
∇T is the temperature gradient

In other words, the heat conducted in a material depends on the temperature difference and the material's ability to conduct heat. Conductivity varies greatly depending on the material, with conductors such as copper reaching 60 x 10^6 S.m^{-1} while insulating materials such as glass do not reach values of 10^{-10} S.m^{-1}, which is more than 16 orders of magnitude difference.

Types of cooling systems for power electronics

Overheating is one of the main enemies of any electronic device. Excessive heat leads to loss of efficiency, reliability problems, reduced lifetime and higher maintenance costs. That is why cooling systems are a key element to ensure efficient operation of electronics.

In the case of power inverters for large-scale solar and storage applications, these are power electronics devices that are installed in outdoor locations and in many cases reach extreme ambient temperatures, making their cooling requirements even more demanding.

Various cooling systems are used in power electronics to ensure efficient heat dissipation and maintain component reliability. The main cooling methods include:

1. Air cooling

Description:

Air cooling relies on natural or forced convection to dissipate heat using fans and heat sinks.

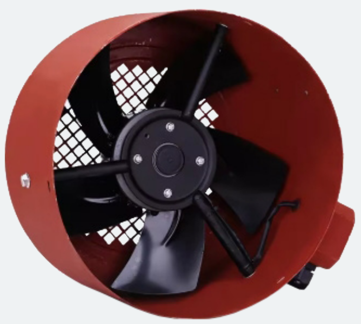


Figure 1. Commercial air cooling system [4].

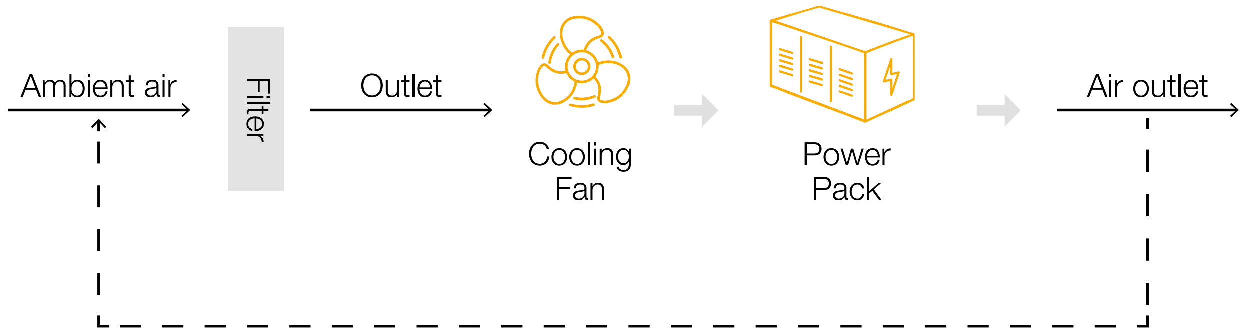
ADVANTAGES

- Low initial cost
- Simple maintenance
- No risk of leaks

DISADVANTAGES

- Lower thermal conductivity compared to liquid cooling
- Higher noise levels due to fans
- More frequent maintenance due to dust accumulation

Air cooling structure diagram



2. Liquid cooling

Description:

Uses liquid coolant (e.g., water-glycol mixture) to transfer heat away from components via heat exchangers.

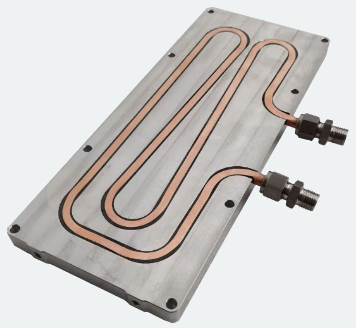


Figure 2. Commercial water liquid cooling plate

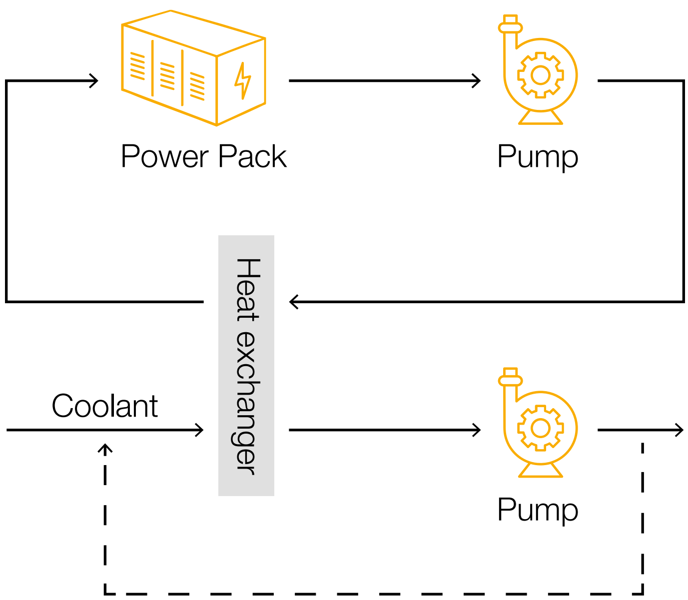
ADVANTAGES

- High thermal efficiency
- Longer component lifespan due to lower operating temperatures
- Suitable for high-power applications

DISADVANTAGES

- Higher initial cost
- Requires pumps and additional maintenance
- Potential risk of leaks

Liquid cooling structure diagram



3. Phase-Change

Description:

Involves phase transitions (e.g., from liquid to vapor) to enhance heat dissipation efficiency.

ADVANTAGES

- Excellent heat dissipation capability
- Compact size and high reliability

DISADVANTAGES

- Complex design and implementation
- Requires sealed enclosures to prevent leaks

4. Thermoelectric Cooling (Peltier Effect)

Description:

Uses thermoelectric modules to move heat away from sensitive components.

ADVANTAGES

- No moving parts (silent operation)
- Precise temperature control

DISADVANTAGES

- Limited cooling capacity
- High energy consumption for large applications

Comparative Performance Analysis

All cooling systems have their advantages and disadvantages and depending on their characteristics, they will be suitable or not for certain applications. In the case of PV and BESS applications, it is interesting to highlight the published study [5] where the main cooling systems in BESS applications are compared using different metrics. A summary of the results is shown below:

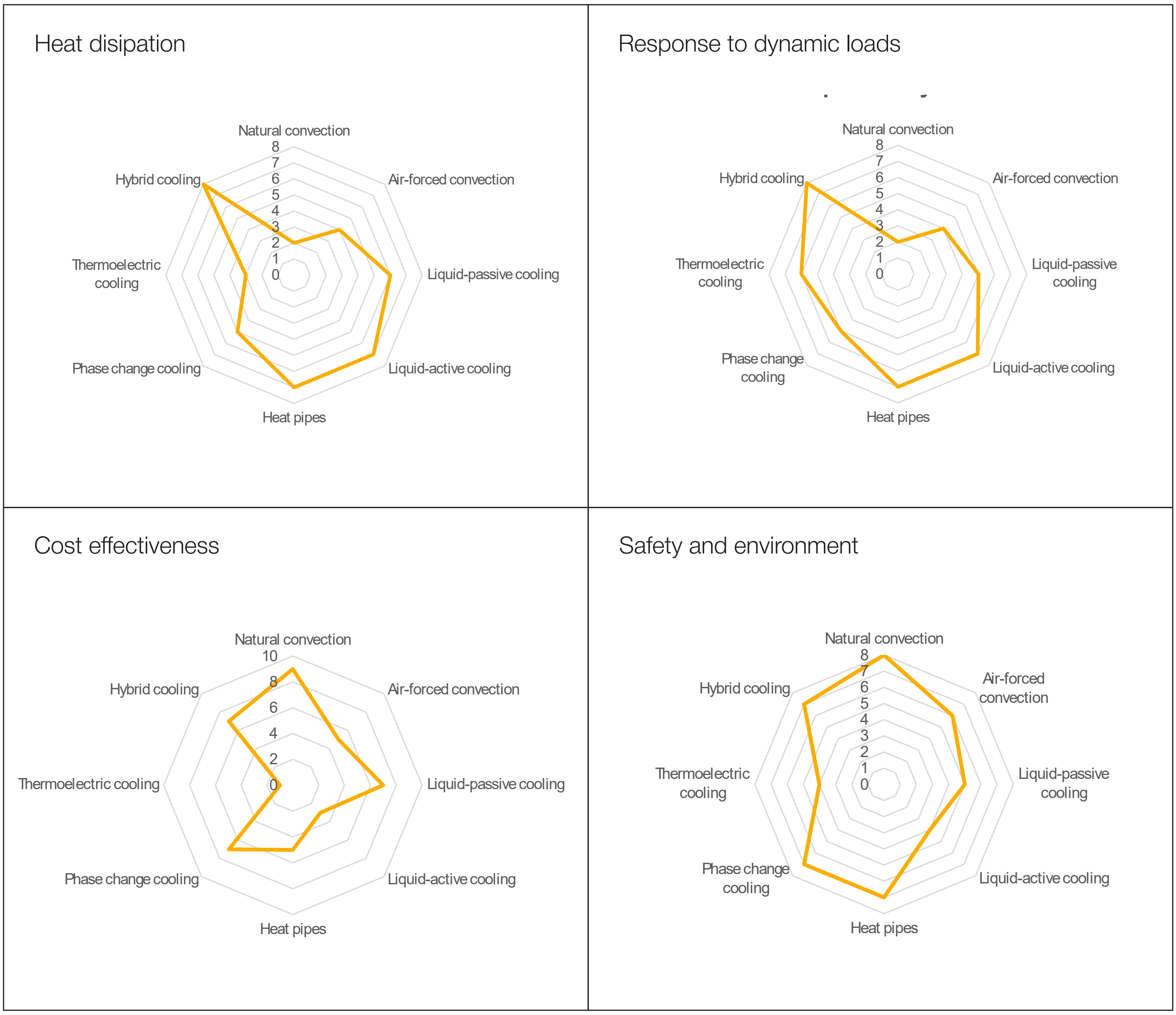
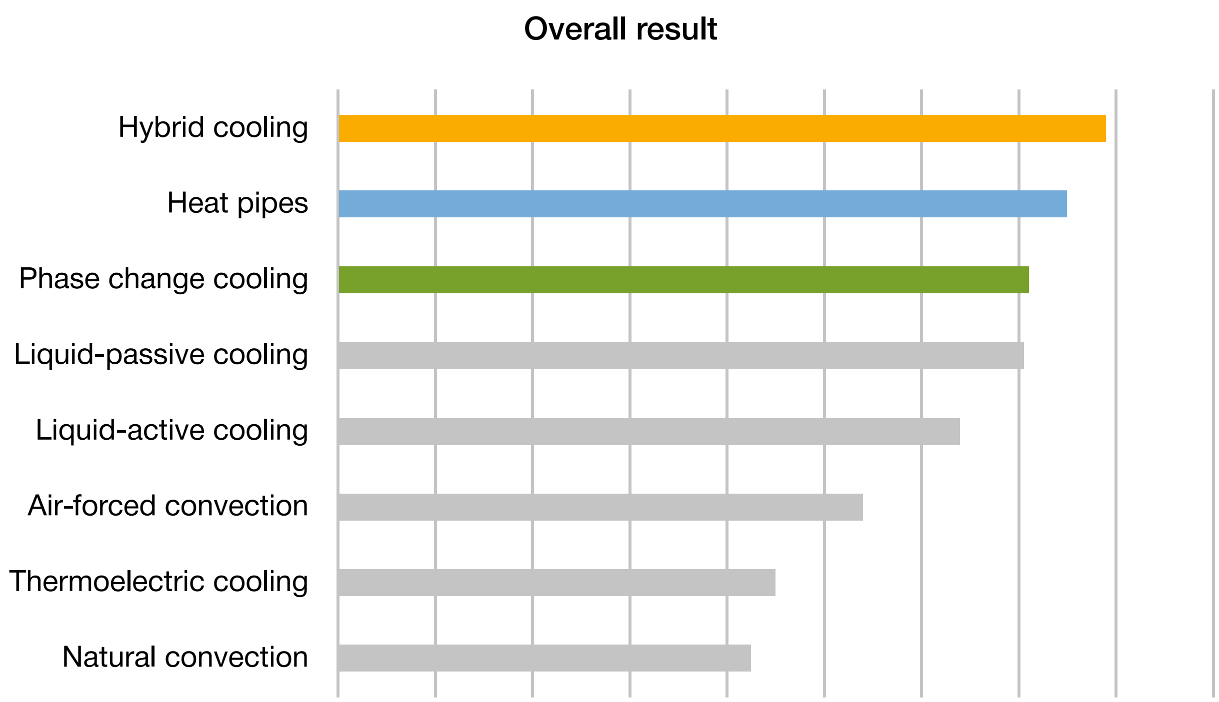


Figure 3. Thermal management system benchmarking [5].



The benchmarking conclusions give a clear winner: **hybrid cooling**, namely systems that combine several methods such as liquid with forced ventilation, among others.

These mixed systems are capable of combining a high capacity for heat dissipation and excellent dynamic response with a low cost, making them the best choice for applications with high thermal demands and where cost is a key driver, as is the case with solar and battery inverters.

If we focus on the two systems that are mainly used in the utility-scale inverter market, namely **air-forced cooling**, used in almost all string inverters, and **liquid-cooling**, used in some central inverters, the comparison of characteristics is as follows:

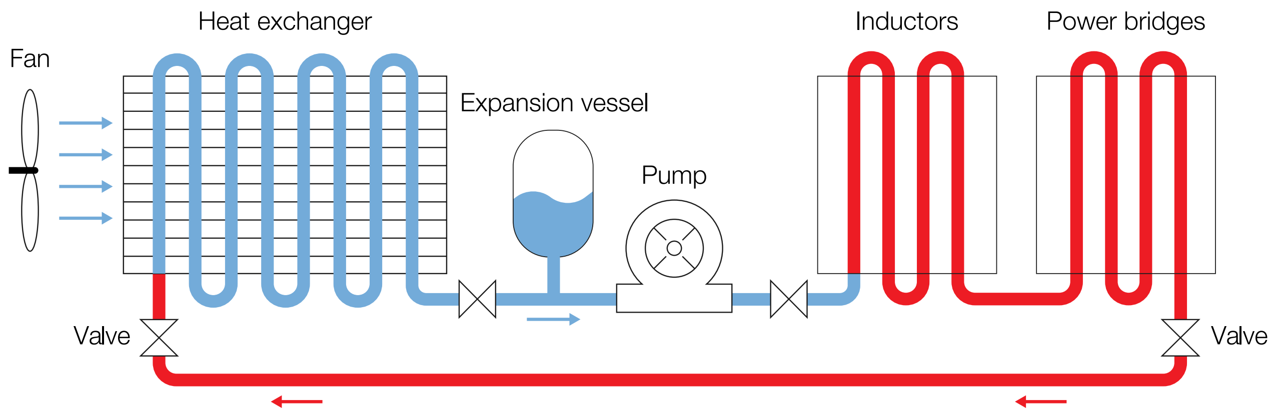
	Liquid-cooling	Air-cooling
Efficiency	99.4%	98%
Thermal Conductivity	20x higher than air	Low
Operating Temperature	Up to 60°C without derating	Up to 40°C with derating
Maintenance Frequency	Every 5-10 years	Every 1-3 years
Lifespan	>30 years	15-20 years
Acquisition cost	Mid	Low

It is clear that liquid-cooled systems are far superior in performance to air-cooled systems. Traditionally, the arguments of the proponents of the latter focus on their lower acquisition cost and simplicity. But the truth is that when calculated in terms of Total Cost of Ownership (TCO), the costs are evened out as liquid-cooled systems are more reliable and last longer.

Liquid Cooling

As explained above, liquid cooling systems use a coolant to transfer and disperse heat. There are two main groups: **passive** systems that do not use any type of pump or coolant delivery system and **active** systems that use both primary and secondary loops as active cooling circuits. The primary loop operates similarly to a passive liquid system but circulates heat using a pump. Instead of a cooler, a high-performance heat exchanger acts as a bridge between the primary and secondary loops, enabling the air conditioning system to function as the secondary loop and provide cooling through evaporation.

The scheme and the different elements of an active-liquid cooling system are as follows:



Coolant (Water-Glycol Mixture)

Provides efficient heat transfer, corrosion resistance, and eco-friendly operation.

Pump System

Ensures continuous liquid circulation to extract heat from high-temperature components.

Heat Exchanger with Speed-Controlled Fans

Transfers heat from the liquid to ambient air, optimising performance based on real-time temperature measurements.

Pressure Sensors and Liquid Heater

Maintain stable operating conditions and prevent condensation in humid environments.

Thermal Expansion Reservoir

Prevents pressure buildup and ensures system stability.

CoolBrid

Gamesa Electric accounts also for more than 25 years of experience in developing liquid-cooled power converters for wind turbines (+ 62 GW of track record) and more than 15 years in PV (+ 10 GW of track record). For its latest Proteus inverter series, Gamesa Electric has developed an advanced hybrid cooling system called **CoolBrid**, achieving very high levels in terms of ultra-high performance, high reliability and lifespan above 30 years.

What is CoolBrid?

CoolBrid is an advanced hybrid cooling system which controls the inner temperature of Proteus inverter through two separated circuits: forced air cooling and a liquid-cooling system; this combination achieves the best performance with a very compact design. It's distributed as follows:

Liquid-cooling system used to cool the inverter's hotter elements such as inverter Power stacks (power semiconductors) and grid filter inductor, which account for more than 70% of the total inverter losses.

Forced-air used for cooling the auxiliary elements of converter: electric and electronic system, DC fuses, main switches and others

There are 2 separated subsystems with different airflows according to inner distribution of the enclosure: output filter cabinet and inverter cabinet.

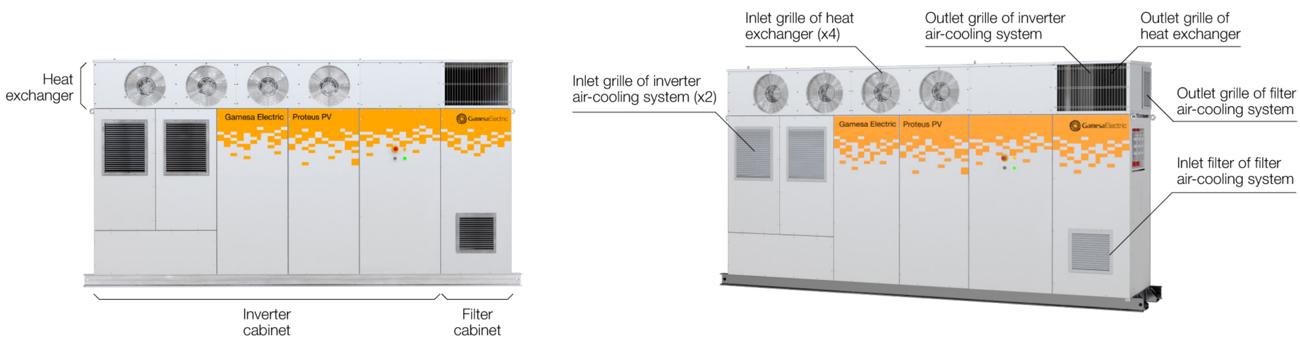


Figure 4. Distribution of Proteus inverter air lets.

The air inlets are located at higher height to minimise filter saturation due to either sand or dust, besides the inverter is completely sealed in its bottom, so no dust entrance is possible. Each cooling subsystem uses different conduits and airflows; therefore they operate independently of each other.

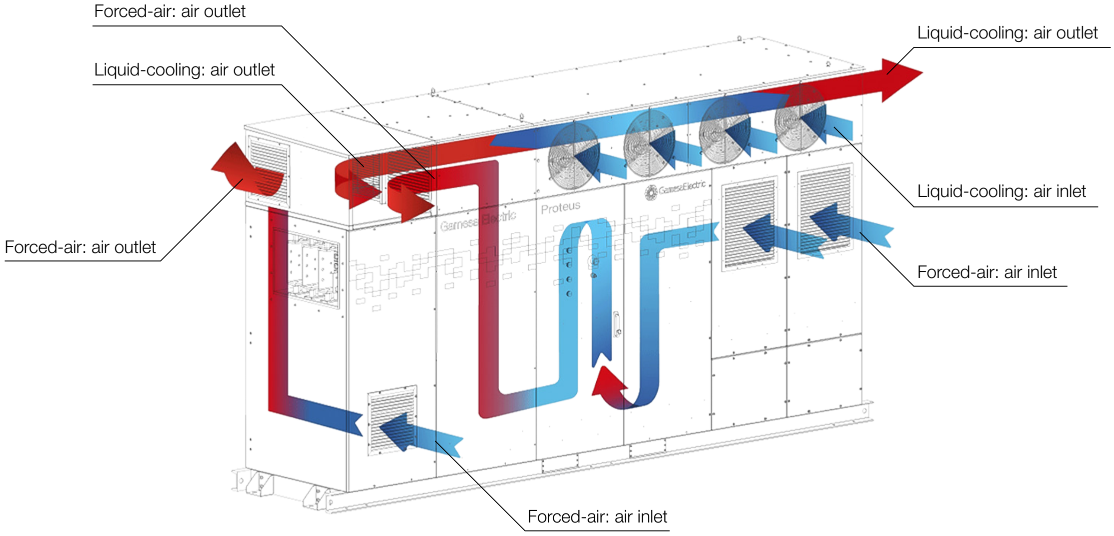


Figure 5. Different airflows of inverter

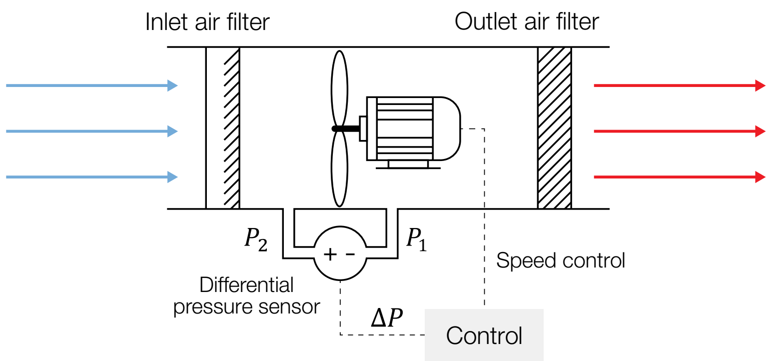
How does the liquid cooling work?

The liquid-cooling systems is a closed-loop circuit that works as follows: the coolant liquid is pushed by the pump and circulates through the pipes. As it passes through the devices to be cooled absorbs their heat, afterwards the liquid passes through the heat exchanger located at the top of the inverter, where it transfers the heat from the liquid to the air thanks to speed-controlled fans. Finally, the cooled liquid returns to the pump. The control speed of the fans is managed based on the measurement provided by temperature sensors, optimising the operation point at every time.

In order to avoid mechanical stress, the system has been designed to operate at low pressure. Furthermore, the circuit has pressure sensors that stop the converter in the unlikely event of either liquid leaks or malfunction.

How does the forced-air cooling work?

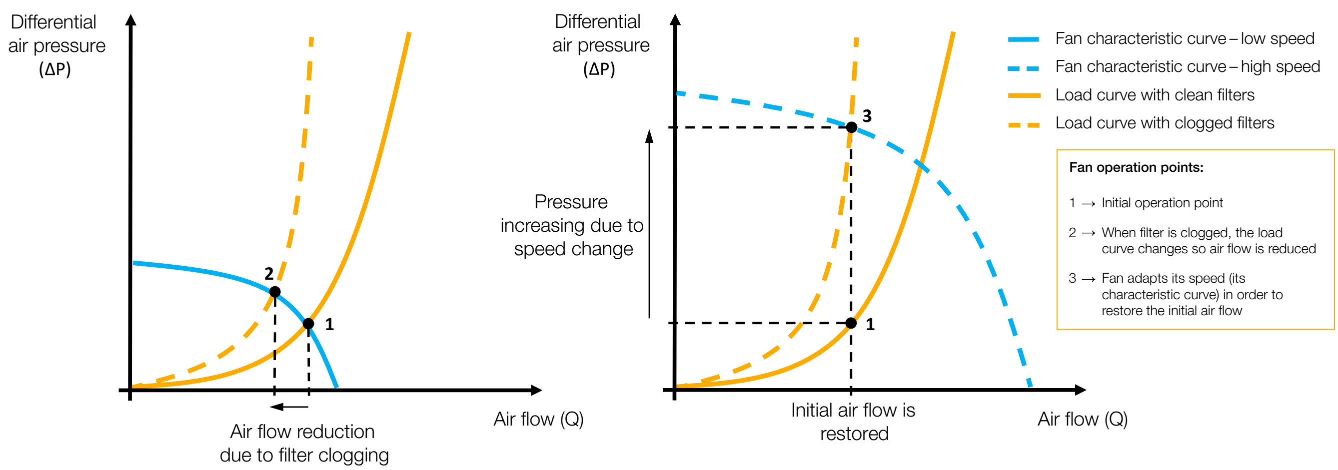
It's a system based on a speed-controlled centrifugal fan that regulates the inner temperature according to information provided by multiple temperature and pressure sensors. Air is taken from front grilles, circulating through an optimised air conduit and finally expelled through a lateral outlet. The air filters avoid the entry of dust and water ensuring the IP55 protection degree (category 1 - devices where the working cycle causes reduction of air pressure within enclosure).



$$Q = k\sqrt{\Delta P} = k\sqrt{P_2 - P_1}$$

Figure 6. Scheme of forced-air system

The variable speed fan is configured to maintain constant the air flow (Q), in case of air filter clogging by dust or sand, the air flow reduction is measured thanks to the differential pressure sensor and the fan speed is increased accordingly, restoring the optimal air flow. This speed regulation ensures the quickest response to temperature changes, optimising the efficiency and noise level during operation and stand-by. In parallel, in case of filters being clogged, an alarm is displayed for service technicians to clean them, avoiding further problems and optimizing the auxiliary's consumption.



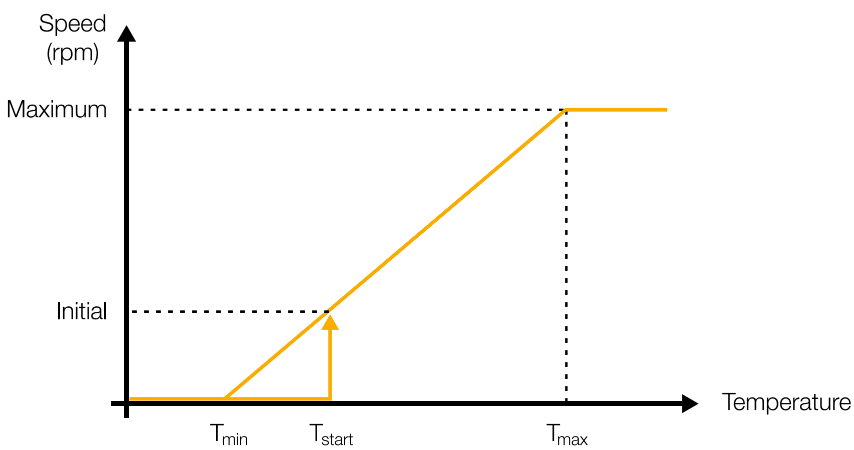
Which coolant liquid does CoolBrid use?

The coolant liquid used in all Proteus converters is a mixture of water and glycol as antifreeze agent which offers several advantages:

- Good heat transfer
- Avoid corrosion
- Temperature range increasing
- Readily available
- Eco-friendly

How can the system's performance be optimised?

The system optimises the operation by adjusting the fans rotational speed (4 units located in heat exchanger) which is regulated taking into account the temperature of IGBTs, inductors and liquid, modifying the speed according to the following curve: The fans start once the minimum temperature (Tstart) is reached, afterwards their speed varies linearly as a function of the temperature within a predetermined range (Tmax and Tmin).



What are the advantages of CoolBrid?

As a hybrid system, it combines the best of both systems, high performance and high dissipation capacity thanks to the liquid cooling system, together with the simplicity and low cost of the fan system.

HIGHER YIELD

The ability to deliver power is directly conditioned by inverter bridge and grid filter working temperature. The use of liquid-cooling system in those components allows Proteus converters to reach the highest performance on the market in extreme temperature environments compared to pure air-forced solutions.

- Improvement of temperature derating for utility-scale central inverters that translates directly in more production in high-temperature projects.
- Higher efficiency, reaching 99.4%, the highest in the market

BETTER RELIABILITY

- Low thermal stress in power semiconductors and grid filter. Components working far below their thermal limit reduces failures increasing lifespan and reliability.
- Unlike other fully air-cooled equipment, the Proteus inverter forced-air system manages less than 30% of the total losses, which translates into a lower fan operation speed and air filters take longer to clog. The result is a cooling system that makes the inverter less sensitive to dust and sand.

EASIER TO MAINTAIN

- Visual inspection of air filters is not necessary, in case of filter clogging the inverter automatically sends a signal to the SCADA.[1]
- Air inlet filters can be easily replaced without opening the doors.
- The liquid heat exchanger does not need air filters.
- The use of quick-disconnection fittings in liquid-cooling pipes makes any maintenance task easy. Additionally, they include a mechanism that prevents the liquid from escaping once disconnected.

1. Gamesa Electric recommends the periodic inspection of the filters to ensure optimal equipment operation throughout its entire service life, regardless of the alarm status.

Real-life examples of CoolBrid in operation

The best way to assess the liquid-cooling system performance is through real operating data [6]; the next figures represent the data recorded by power plant data acquisition system of the same PV inverter working under extreme conditions, showing the evolution of apparent power, coolant temperature, ambient temperature, IGBT temperature and inductor winding temperature over a full day for 2 different scenarios:

SCENARIO 1

During the hottest day of the year where the maximum daily temperature achieved was 48 °C (118.4 °F). Here, the maximum temperature achieved by IGBT is 73.8 °C (164.8 °F) and 99.5 °C (211.5 °F) by inductor.

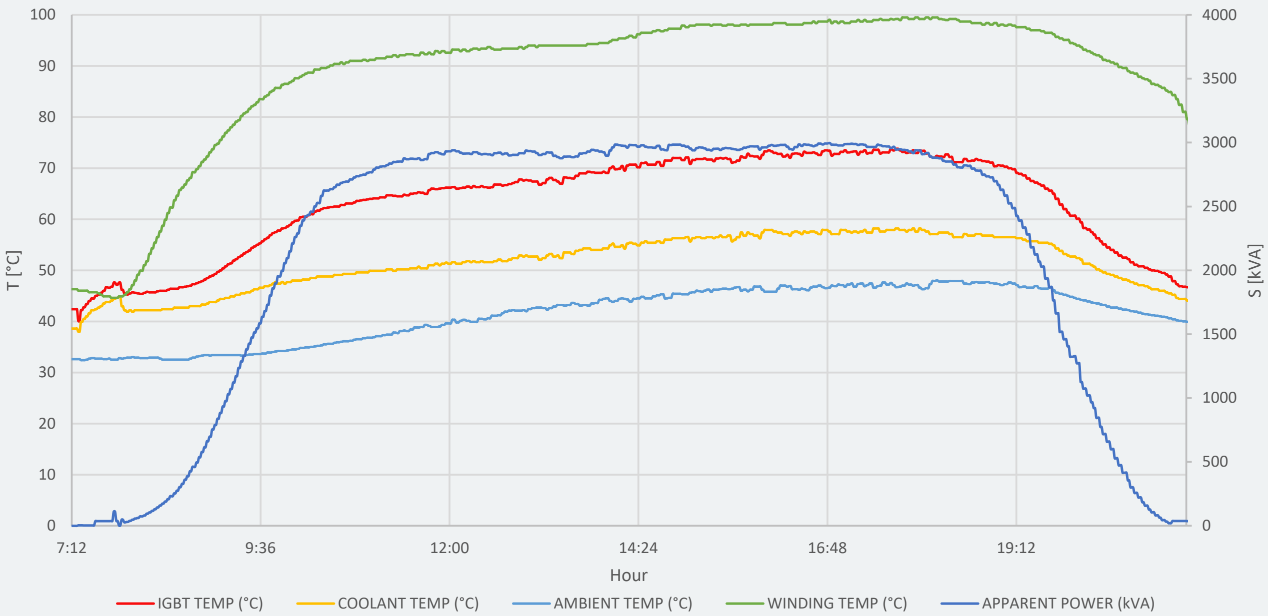


Figure 7. Power and Temperature evolution during a hot day

SCENARIO 2

During a day with abrupt irradiation changes where the inverter apparent power changes more than 3 MVA (>75% of nominal) within a few seconds, the liquid-cooling system provides a damping to prevent large temperature fluctuations, minimizing the thermal stress. This fact is reflected in the temperature behaviour of each component:

- Power semiconductors (IGBT temp) are more sensitive to power changes; however, thanks to liquid-cooling system, the temperature oscillation range is lower than 15 °C (59 °F).
- Inductors (winding temp) have a slower thermal inertia than power semiconductors, so the temperature takes longer to change. In this case, the temperature oscillates in a range of less than 10 °C (50 °F).

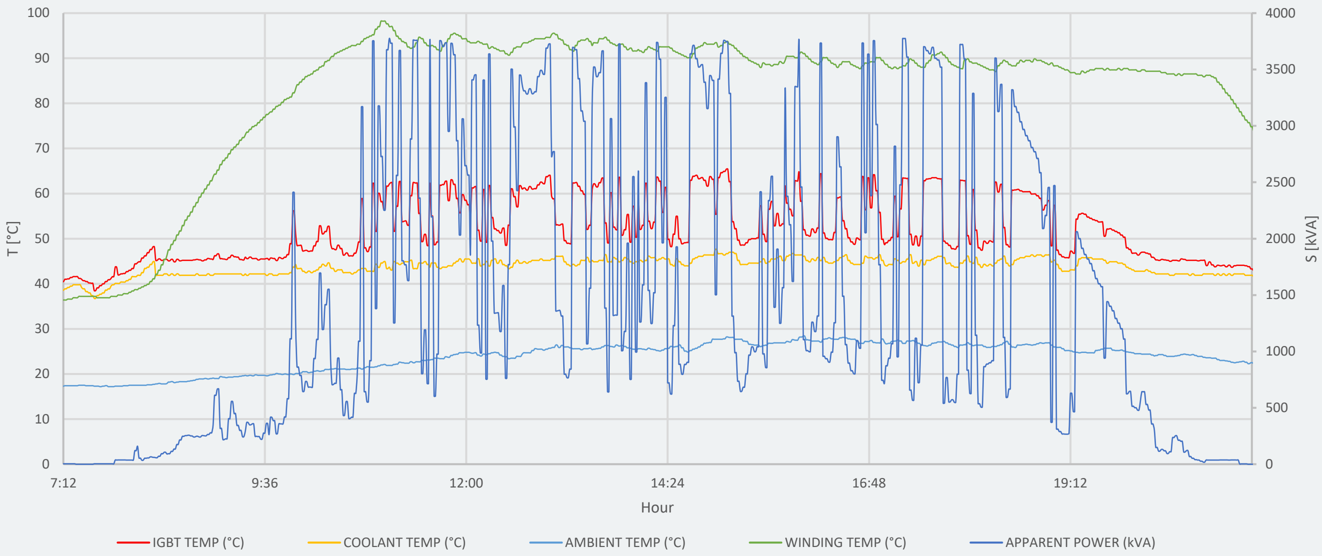


Figure 8. Power and Temperature evolution during a day with abrupt power changes

Lessons learned

Through years of research and field experience, Gamesa Electric has refined its liquid-cooling systems to maximize performance and reliability. Key lessons learnt include:

- **Optimised Hydraulic Connections**: Non-drip quick connections prevent pressure loss.
- **Smart Pump Control**: This is the most critical component of the system as it ensures stable liquid flow, preventing water hammer effects. For this reason, Gamesa Electric only uses components from leading quality suppliers.
- **Liquid-cooled systems** are easy to operate and have extremely low maintenance. However, following maintenance manual is key to avoid failures.
- **Consumable management** is essential to ensure a failure-free system. The 3 main components that should be available as spares are the water pump, liquid coolant and flexible connectors.

Future trends in Cooling systems

- **Hybrid cooling systems**, which combine different passive and active techniques, are at the forefront of thermal management innovation. They offer tailored solutions for heat dissipation, balancing safety and environmental considerations. The integration of advanced materials like nano-enhanced phase-change materials and liquid cooling technologies has significantly improved their efficiency and scalability. These systems are designed to adapt to various operational conditions, ensuring optimal performance while minimising environmental impact. The strategic selection of cooling components and the configuration's adaptability are key to achieving a sustainable thermal management solution.

- **AI-driven thermal management** is another field that is developing very fast and will further optimise the operation of systems, especially hybrid systems that combine different systems and whose interactions can be complex.

- **Wide-bandgap semiconductors**, the development of new power electronic devices, such silicon carbide and gallium nitride semiconductors, has introduced new thermal management challenges due to their higher operating temperatures and power densities.

Conclusion

Cooling systems are a key component in ensuring the efficiency and reliability of any electronic device. But there are a multitude of different applications with varying levels of demands and requirements, so it is key to design the best cooling option to meet the needs at the lowest possible cost. **This is where hybrid systems fit perfectly as they allow for greater flexibility in combining performance, reliability and cost.**

In demanding applications such as solar and storage power inverters that suffer from high temperatures and handle high power, **active liquid cooling** is the option that provides the best results in terms of heat dissipation and reliability.

Gamesa Electric has developed **CoolBrid** as a cooling system for its Proteus inverters, combining the high performance of an active liquid system with the simplicity and cost optimisation of a forced-air ventilation system. This hybrid solution is the result of more than 25 years of experience in this field and incorporates improvements and lessons learned from more than 70 GW of wind, solar and battery inverters installed worldwide.

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Gamesa Electric Headquarters
Parque tecnológico
de Bizkaia, Edificio 206
48170 Zamudio
Vizcaya (Spain)

www.gamesaelectric.com