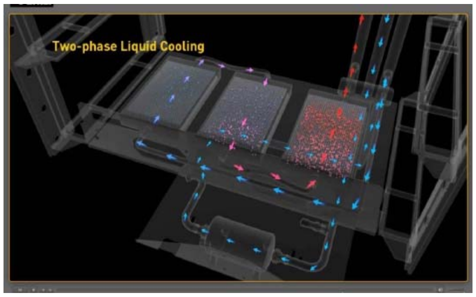
White Paper

Cooling High Performance
Wind Turbine Systems
With Two-Phase Evaporative Cooling

Background



Wind turbine capacity, particularly for offshore turbines, continues to grow each year with 5-10MW on the horizon. Even with efficiency improvements, key power generation subsystems, including generators, power conversion electronics and transformers, are challenged to manage an ever increasing amount of heat within the limited space offered inside the nacelle. In addition, the power losses incurred, even if as little as 3-5%, would require thermal management systems to be sized to support 200-300kW+ of heat dissipation.

While traditional air and water cooled systems have provided the lowest entry cost options, water cooled solutions are becoming much more challenging to implement. Both the installation and maintenance costs required to safely distribute enough water to adequately cool these growing power systems is a major concern. Rising capacity and corresponding power losses are driving thermal solution designers to consider more advanced thermal management in order to minimize the overall growth of the nacelle and wind turbine infrastructure.

Air- and Water-cooling Systems Limitations

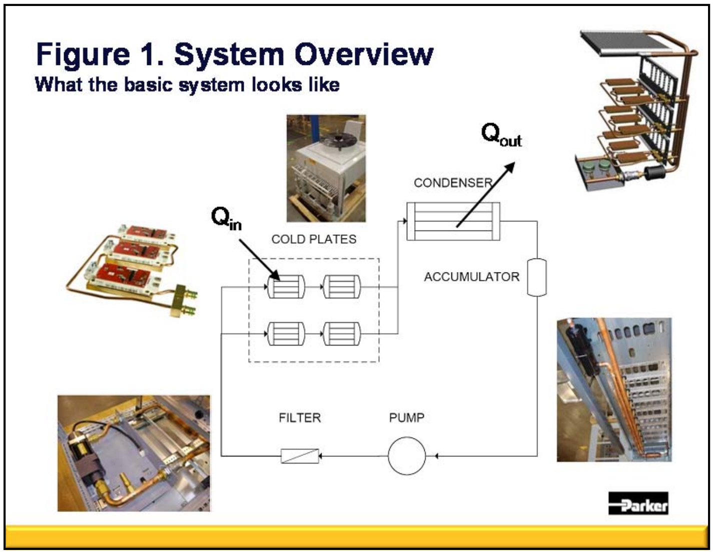
Air-cooling has served small-scale wind turbines well over the years, but has proven impractical when trying to remove the heat produced in a Megawatt-scale system. The thermal capacity of air being so low simply makes it difficult to blow enough air across a motor or through the converter to maintain reliable operating temperatures. For this reason, water-cooled systems are chosen most often as a more efficient thermal solution than air. However, water-cooling systems have their own unique set of challenges.

Not only are the systems themselves large, but the thermal efficiency limitations of this technology require that the size/weight growth of power generation sub-systems tracks with their power throughput. That is, the power density is almost constant due to the thermal performance limitations of water. Thus, the power generation components of a 10MW wind turbine will be nearly twice the size and weight of a 5MW turbine, largely because they cannot adequately cool the additional heat loads without spreading them out. In addition, water's inherent electrical conductivity potential poses the risk of a short in the event of a system leak, which can be catastrophic around such high power systems. Another challenge with employing water is that wind turbines are often located in areas where temperatures routinely drop below its freezing point. Additives such as Glycol are mixed with the water to lower the freezing point, but they also tend to decrease the thermal performance of the coolant. Lastly, system designers must be very careful in selecting dissimilar metals that will be in contact with water. Even with a deionizer or careful monitoring of inhibitor concentrations, water as a coolant is very corrosive. To avoid galvanic corrosion, many system designers will use expensive stainless steel for all of their plumbing and manifolds throughout the water loop to reduce the need for long term maintenance. This is especially important in offshore installations where the remote location and access issues make "maintenance free" systems very desirable.

Alternative Cooling Technology: Evaporative Cooling

To address the unique challenges of cooling high-power electronics in wind turbines, Parker Hannifin (Precision Cooling Systems) has developed a compelling alternative. Namely, Precision Cooled systems employ a non-corrosive, non-conductive coolant (refrigerant) that evaporates on contact with hot electronics, in a small, light-weight, and highly efficient closed-loop system. Much like a water cooled system, it has the same basic components: a pump, a reservoir, cold plate or cooling coils, and a condenser (as shown in Figure 1). The big difference is that in a water system, the liquid doesn't change phase as it passes over the device being cooled – it simply heats up, whereas the refrigerant liquid turns to a vapor.

By taking advantage of the highly efficient evaporation process that occurs when a liquid changes phase to a vapor, 2 to 4 times the amount of heat can be removed for the same given temperature difference (°C/W) when compared to single-phase water cooling. This directly correlates to an increase in power throughput for the same size system, because the limitation in power throughput is dictated by the amount of heat that can be removed from the system at the maximum reliable operating temperature.



The dual-phase cooling process continuously cycles the refrigerant fluid within a sealed, closed-loop system to cool a wide range of electronics. A small pump delivers just enough coolant to one or more cold plates optimized to acquire the heat from the device(s). The coolant vaporizes to maintain a cool uniform temperature on the surface of the device. The resulting coolant is then pumped to a heat exchanger where it rejects the heat to the ambient and condenses back into the liquid, completing the cycle.

Increased Power Density, Safety & Reliability

The two-phase evaporative approach eliminates the safety and maintenance issues associated with water cooling, and at the same time enables greater system level power densities. The isothermal nature of the two-phase cooling system also reduces thermal cycling, which increases the lifespan of the turbine's electrical components. Sub-systems like generators, transformers and power conversion electronics can be reliably driven to support up to 40% more power for the same size/weight simply because the additional thermal loads are removed without raising the temperature of the sub-systems.
To illustrate this point, *Figure 2* shows an example of 1MW power inverter reduced in size by a factor of 3:2 when converted from air to water cooling, and then 2:1 when converted from water to two-phase refrigerant (evaporative) cooling. When cooled more effectively, fewer power modules and supporting mechanical and electrical infrastructure are required at the same given power throughput. As a result, not only is the size and weight reduced by moving to evaporative cooling, but the overall system costs are reduced due to the use of fewer components.

System-Level Size, Efficiency and Cost Benefits

As shown in Figure 2, the two-phase precision cooling technology dramatically reduced the number of power components, thereby reducing the overall wind turbine system cost.
The substantial system level size reduction (up to 50%) was realized because the individual power modules could safely operate at higher power levels without overheating. Figure 3 compares a standard IGBT module cooled by air, water, and evaporative refrigerant cooling. With ambient conditions being equal and the power modules limited to the same maximum junction temperature (120°C), the total measured power losses were limited to 600 watts for air cooling, 1070 watts for the best water cooled cold plate, and 1461 watts for the evaporative cooling solution.

In the comparison, ambient conditions are equal and the power modules are limited to the same maximum surface temperature (120°C). As the chart illustrates, the total measured power loss was the greatest for the evaporative cooling solution. Additionally, the temperature uniformity, another performance parameter

Figure 2: Power Inverter Size Reduction

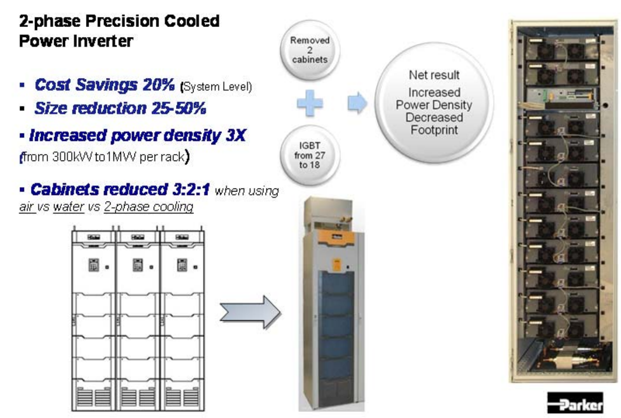
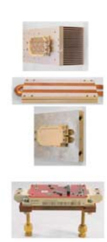


Figure 3: Cold plate performance comparison



All tests performed at same ambient (40°C)	Module Loss (W) for IGBT die 120°C junction temperature	Temp. spread across IGBT cold plate	Cold plate to fluid thermal resistance °C / W
Air cooled	600	23 °C	0.094
Aluminum, water-cooled, press fit Cu tubing*	736	18 °C	0.051
Aluminum, water-cooled internal fin passage*	1070	19 °C	0.035
Water cooled using Copper Cold Plate*	1040	23 °C	0.037
Evaporative cooled using Cu cold plate (2-phase cooling)	1461	6 °C	0.009

*Water cooled cold plates used 5x the flow rate of VDF cold plates known to impact the reliability of electronic assemblies, was much better with the evaporative cooling system (6°C) than the water cooling system (19°C).

Benefits of smaller thermal system in the nacelle

The system's smaller and lighter footprint than that of alternative thermal management solutions, coupled with its ability to reduce the size and weight of power systems, allows it to free up valuable space in the nacelle. Notably, all of the thermal performance benefits presented in Figure 3 were achieved with evaporative cooling flow rates that were only one-fifth the flow rate than when water was used. The thermal capacity of the evaporative process is significantly greater than that of single-phase water cooling and results in less fluid needed to acquire the same amount of heat. The impact being, the two-phase precision cooling technology employs smaller and lighter pumps that draw less power, as well as simpler and smaller diameter hoses and manifolds that hold less coolant.

While the technical data shown in Figure 3 was focused on the power conversion electronics that would be used in a typical wind turbine converter, the same thermal benefits are achieved when comparing evaporative cooling for liquid cooled generators and transformers. Today, most large systems use copper coiled water jackets to remove the heat from the generator stator and transformer windings. Once the power density reaches the same fundamental limits of water cooling the generator and transformer components have to grow to increase power throughput. As was shown with the power conversion modules, using a pumped evaporative refrigerant unit with the same copper coils already embedded into the generator or transformer can increase the power throughput capacity by as much as 30-40%. Almost an instant size/weight reduction can be realized without a system redesign.

Maintenance Benefits in Wind Applications

The evaporative precision cooling system requires no regular service. This is of particular importance with offshore wind farms, where accessibility for routine servicing and maintenance is a major challenge and, in many cases, results in costly downtime. During harsh winter conditions, an entire wind farm may be completely inaccessible for a number of days due to sea, wind and visibility conditions. The Parker two-phase precision cooling system is virtually maintenance-free due to the following features:

- It is hermetically sealed and the pumps are designed for over twice the reliability of comparable water pumps.
- It is leak-proof, but should someone inadvertently damage the system causing a leak to occur, the non-conductive coolant will flash to gas and not damage any electronic components.
- The coolant does not freeze by nature and does not require any additives.
- The coolant is non-conductive and does not react with any metals.
- The coolant is non-corrosive. The only filter included in the system is a "dryer" provided for removing any residual water/humidity out of the system upon initial charge – thus eliminating any corrosion potential.
- No deionizer required
- The system can be equipped with dry break connectors for ease of module replacement, minimizing downtime during component failure replacement.

System Integration: Rack-ready or Drop-in Replacement

Parker's precision cooled rack-ready thermal system can be integrated directly into the system rack housing the converter, as well as connect to other sub systems like the reactors, generators and other electronics. If desired, the system can also be configured as a drop-in replacement (Figure 4) to easily retrofit legacy water or air cooling systems. The drop-in replacement solution would consist of a stand-alone base pump and dispenser unit, and a condenser, coupled with configurable plug and play cold plate kits to integrate into various subsystems.

To replace an existing water cooling solution with two-phase precision cooled system, technicians would simply remove the water cooling and water hose attachments and flush out the remaining water in the motor coils or power module cold plates. They would then install the Precision Cooling Unit and condenser and run dedicated hoses from the cabinet to the various sub-systems and configurable cold plate kits installed therein. This is an ideal solution where a central cooling loop is desired that can support the generator, power conversion electronics, and reactor.

For an even smaller, more integrated solution, Parker offers the system in a rack-ready modular design (Figure 5) to enable high-density power converters and inverters at capacities starting at 1.5MW. Modular inverter sections can be paralleled for high power installations. The system features electrical connections to power bus and no-leak refrigerant loop connectors for an easy plug-in replacement, and scales up to more than 100kW heat rejection.

Conclusion

In conclusion, for higher power density wind turbines, this two-phase closed-loop thermal system by Parker Hannifin, presents a technically superior solution, allowing engineers and integrators to enable higher density power systems with fewer components, while reducing overall system level costs, size, weight and maintenance, and increasing safety and reliability of the system. Finally, the ability to choose an integrated rack-ready design, or drop-in stand-alone replacement unit for legacy water and air systems, provides ultimate flexibility.

Figure 4 : **Precision Cooling Unit**

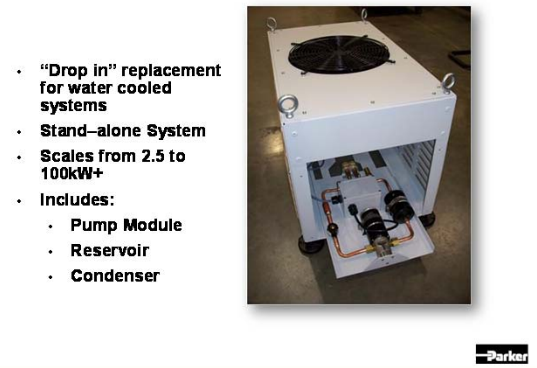
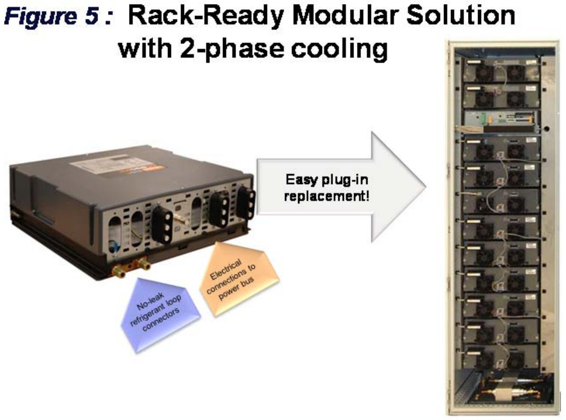


Figure 5 : **Rack-Ready Modular Solution with 2-phase cooling**



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