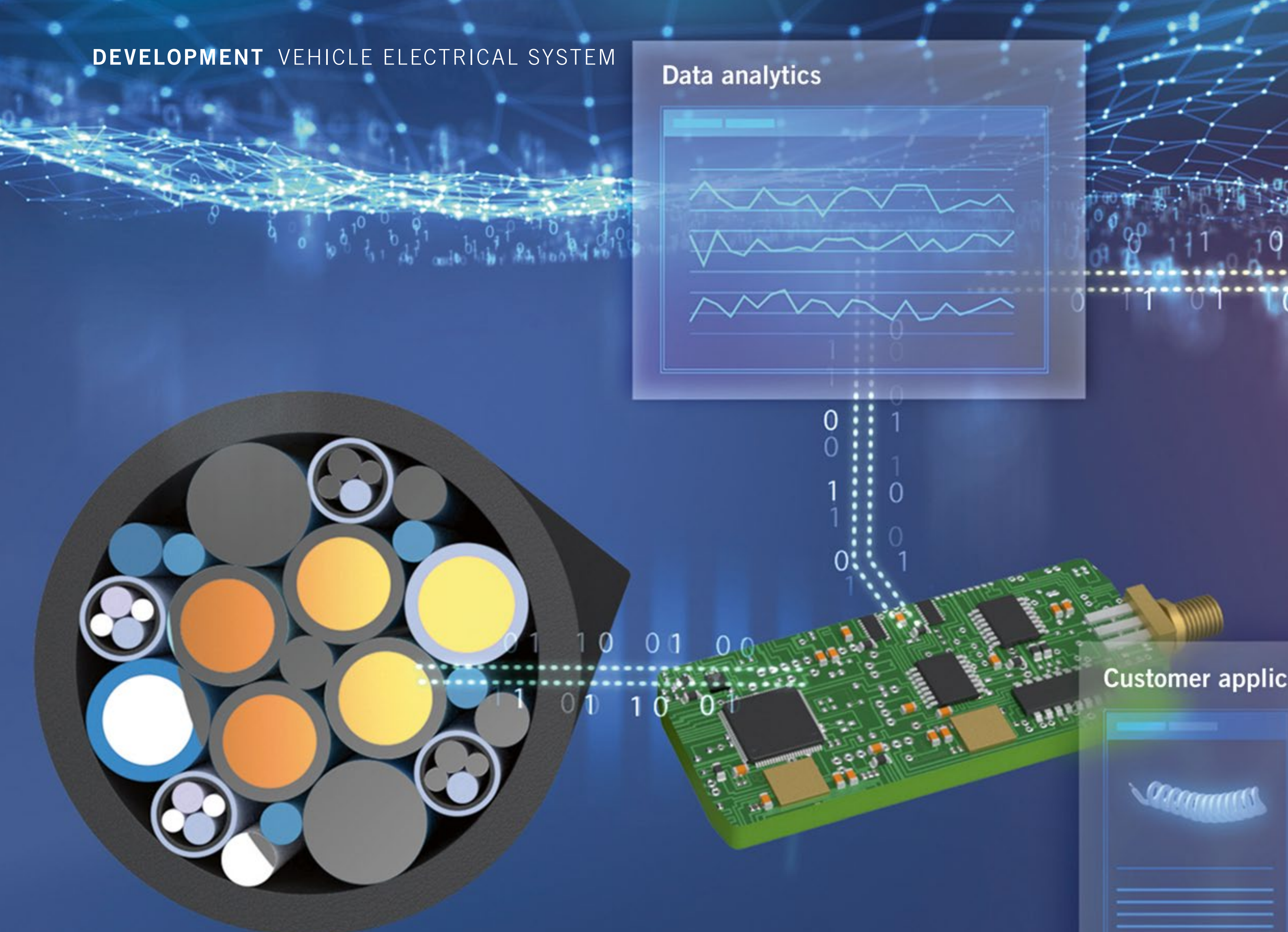

Continuous Condition Monitoring for High-power DC Charging Cables

Ultrafast DC charging with power outputs of 350 kW or more places special demands on charging cables in terms of function and safety. Leoni is working on a hardware and software module that can be used to achieve continuous monitoring of charging cables. The innovative key technology LeoniQ enables the reliable local detection of thermal and mechanical stresses, as well as any ingress of fluids.

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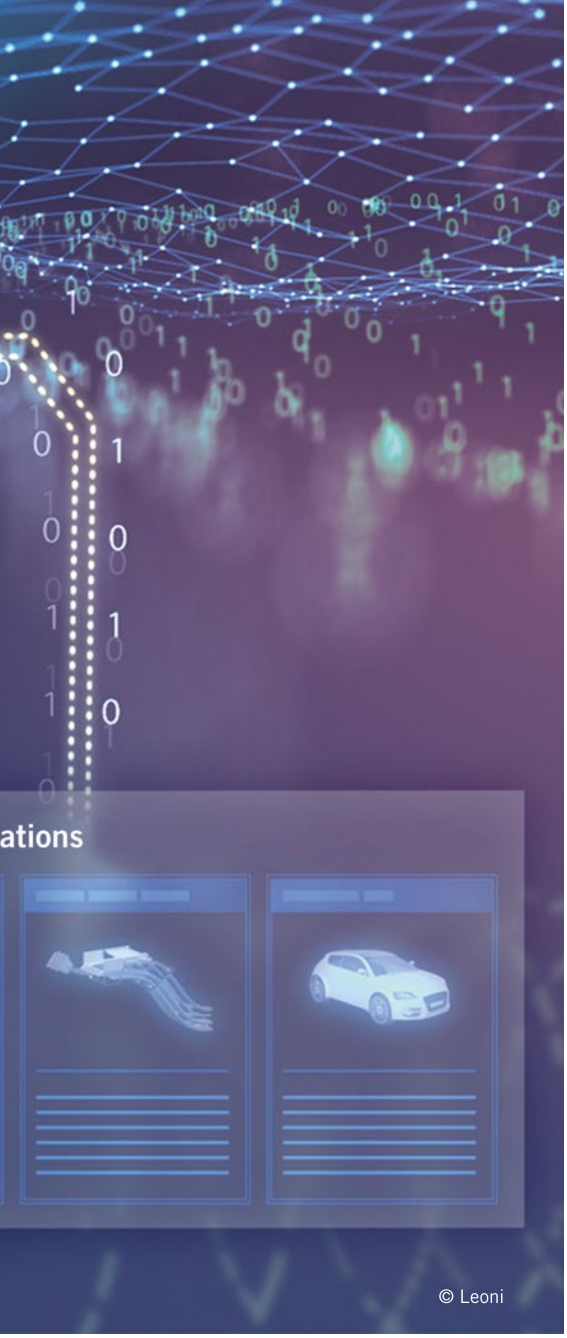

REQUIREMENTS FOR CHARGING CABLES AT VERY HIGH CHARGING OUTPUTS

Today, Leoni is already designing and manufacturing all of the electrical cable technology that is required to operate Electric Vehicles (EVs). This technology covers the full range of EV cables, from the charging socket to the vehicle's high-voltage harness and high-voltage battery. It also reflects all other components of the charging process, such as the charging cables in the Electrical Vehicle Charging (EVC) station and the networking of charging points with the national grid and its providers. Accordingly, Leoni is positioned along the entire ecosystem for EVC. At the moment, publicly accessible charging infrastructure is typically based on Alternating Current (AC) stations with a maximum charging output of up to 22 kW. By mid-2018, only 13 % of the approximately 13,500 charging stations installed in Germany were fast-charging stations running on Direct Current (DC). All of the key automotive markets are now pushing forward the establishment of an ultrafast charging infrastructure with power outputs of 350 kW and more. As a comparison: he output of five ultrafast charging points roughly matches the total connected load of a mid-sized production plant.

As power level increases, the power load on the charging cable used by the driver of the electrical vehicle rises significantly. Plans have therefore been made to introduce a suitable cooling system for charging stations with power outputs over 200 kW. This system will also enable reduced cable cross-sections and therefore reduce cable weights. The considerable investments required to set up these charging stations also mean that these stations have to be operated and supported with 24/7 availability. A maintenance model for the replacement of cables worn out by mechanical and thermal stresses is therefore likely to be essential. Traditionally, this would be addressed by regular maintenance intervals. If an adequate volume of operational data is available, however, dynamic intervals can be implemented using predictive maintenance, so as to optimize the overall costs of the system.

Leoni is currently setting up a digital ecosystem that enables the collection, sharing and evaluation of operational data from electrical cable systems. This approach is based on equipping the cable with sensors that monitor energy and data transfers across its entire length, and therefore enable faults to be localized precisely for subsequent reporting and analysis. Other sources can be used as a supplement or substitute for this data, to enable potential outages to be predicted in good time.

To use this operational data, a digital model of the physical system is required. This model is first used to simulate and design the charging cable and the overall system, from the charging point to the battery in the EV. The integrated sensors then provide real data from the cable which can be compared with target data from a suitable ageing model. This approach also requires a digital model ("digital twin") for each physical cable, permitting the unique assignment of operational data for each cable. Thanks to LeoniQ, any cable or cable system can already be monitored almost in real time: Previously a black box, cables have now become fully transparent and connected with the cloud.

DATA PROVISIONING AND EVALUATION – SENSOR INTEGRATION IN THE CABLE

For the design and especially for the operation of charging cables in an ultrafast charging infrastructure, precise localization of stress factors along the electrical cable is required. While optical technologies for determining these influences were already available in the past, they have proved to be too expensive for use in EV infrastructure applications. The key technology LeoniQ is based on the principle of installing an additional, small sensor element in any standard cable. Using an electrical signal coupled to this sensor, the cable can be continuously monitored for parameters critical to its proper function. Faults encountered along the cable cause a phase shift in a special measurement signal. Accordingly, deviations in the signal and its corresponding transmission enable the identification of fault causes and their precise localization along the cable system. Both signal amplitude and interval vary over time, and can be adjusted to match the respective measurement parameter (such as temperature, mechanical stress or fluid/media ingress) as well as the specific use case. **FIGURE 1** shows measurement principle for LeoniQ cable sensor.

This approach enables the monitoring of a cable's temperature across its entire length without needing to attach several, separate temperature sensors at critical locations. Local resolution of the electrical signal is also possible for cable

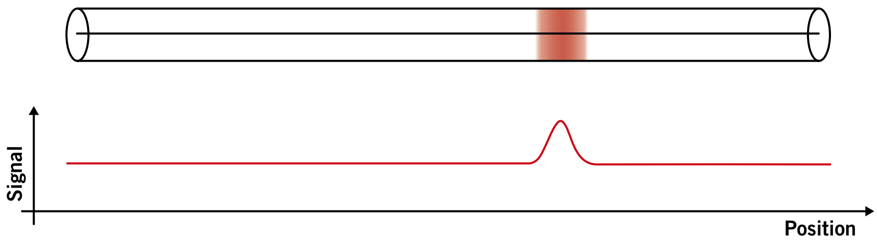

FIGURE 1 Measurement principle for LeoniQ cable sensor (schematic presentation) (© Leoni)

lengths of up to 100 m. As simulations conducted by Leoni show, it is also possible to clearly distinguish between two separate hot spots, **FIGURE 2**.

Mechanical stress that leads to a local change in the geometry of the cable also generates changes in the signal. Thanks to their characteristic curves, these signals can also be distinguished from signals that have been generated by thermal stresses. The ingress of fluids – which could occur in liquid-cooled cables that have become damaged, for example – can also be successfully detected by the LeoniQ technology.

Functionality and safety requirements for ultrafast charging cables are extremely demanding, due to the high thermal and mechanical stresses they are exposed to. High torsional forces have to be expected, especially very near to the plug. Monitoring the values for mechanical stress, temperature gradients and cooling liquid ingress is therefore recommended across the cable's entire length. Because LeoniQ uses cable sensors with a diameter of 0.7 to 2.5 mm (depending on the use case), installation space requirements are minimal. Particularly in the cable design layout for DC charging, there is usually enough filling material available for integrating the additional sensor.

DATA PROVISIONING AND EVALUATION – INTERROGATOR

Signal generation and the initial analysis of the reflected signal, as well as the associated communication, are handled by a small electronic control unit. Developed by Leoni in-house, this component with an integrated gateway creates intelligence in the cable. If required, the signal can be pre-analyzed locally (edge analytics), so as to ensure that only anomalous signal exchanges (events) are forwarded. As an alternative scenario, the full dataset generated can be forwarded for server-based (cloud) analysis. Leoni handles this via various common broadband services, with IoT (Internet-of-Things)-ready communications infrastructure such as Wi-Fi and Bluetooth – and 5G in the future.

DATA PROVISIONING AND EVALUATION – DATA ANALYSIS

In recent years, the IT sector has made huge advances in the further development of relevant technologies for the reliable transfer and mathematical analysis of large volumes of data. These technologies are now offered as commercially available tools. Accordingly, Leoni has decided to set up its own digital ecosystem together with IT companies on the basis of strategic key partnerships. One important strategic partner here is Microsoft, whose specialized MS Azure Sphere microcontroller offers highly secure bidirectional communication with the cloud. In the future, the visualization of the cable state as well as correlative data on the charging process can be presented using a user interface developed by Leoni for IoT applications, **FIGURE 3**. Alternatively, the data can also be integrated into customer-specific dashboards or monitoring systems.

Without any reference to a physical model, data correlations alone are not particularly informative: They may lead in cases of doubt to wrong conclusions and frequent false alarms. Accordingly, Leoni is utilizing the expertise of another strategic partner – PARC – for model-based condition monitoring. Known for its invention of the Ethernet protocol among other things, Xerox subsidiary PARC is providing support for data analysis and the creation of functional system simulations.

As a key technology, LeoniQ is not limited solely to the integrated sensor

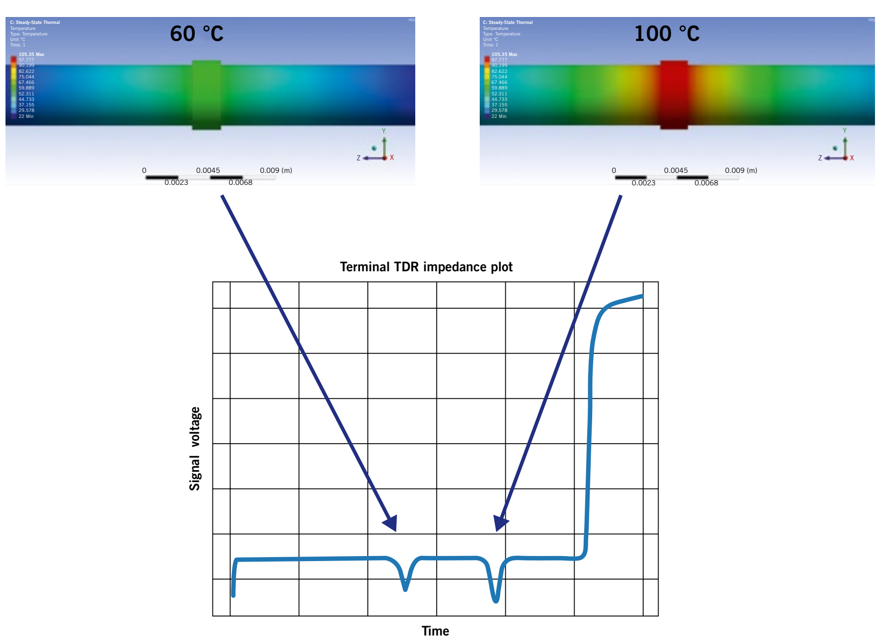

FIGURE 2 Illustration of the detection of two hot spots with LeoniQ (© Leoni)

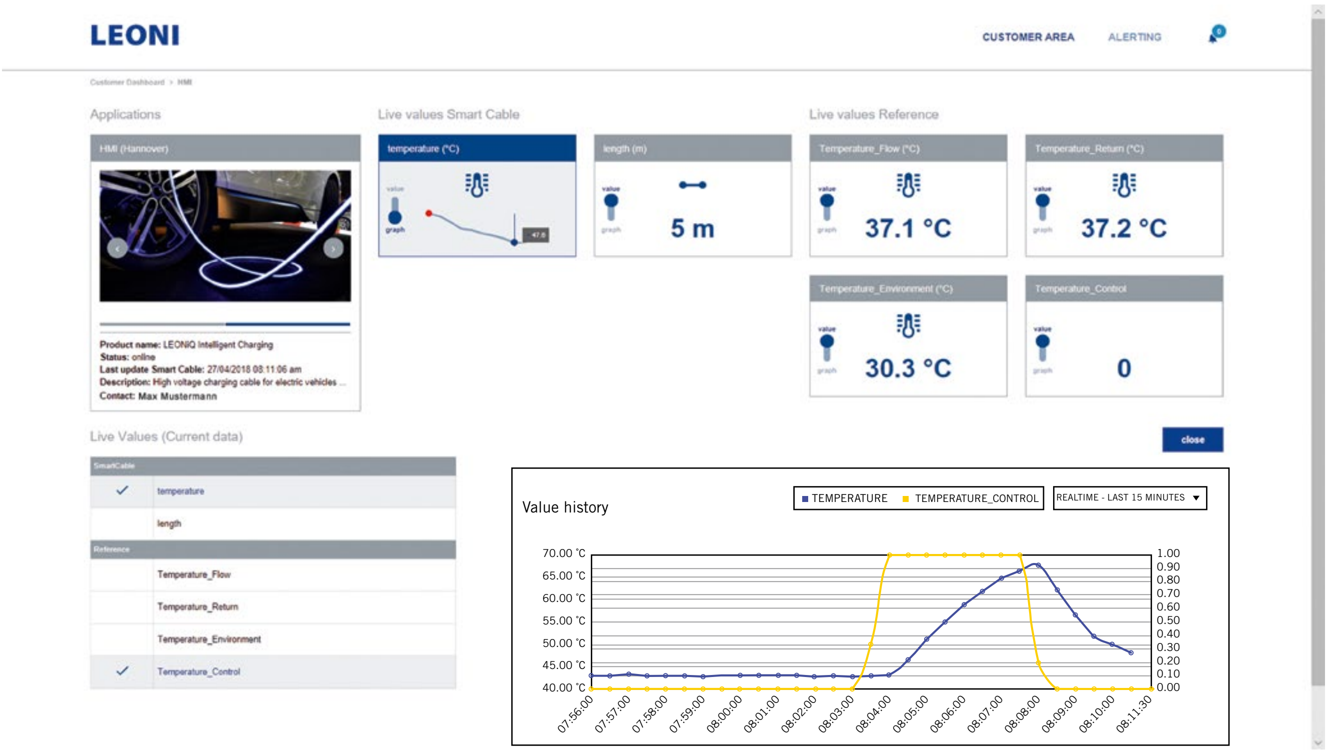

FIGURE 3 Example of an IoT interface dashboard for condition monitoring of charging cables (© Leoni)

system but extends to cover all of the downstream processing of data that is provided to ensure optimal system control. Depending on the design of this system, an alarm could trigger lower power output or terminate all charging processes automatically for safety reasons. If the fault detected does not involve the ingress of liquids, cable cooling could also be intensified by increasing the throughput of the coolant used. Comparisons between the historical data available for the charging cable and the charging station itself also make it possible to proactively trigger maintenance before the charging system, electric vehicle or end user come to any harm.

OUTLOOK – FURTHER APPLICATIONS

The data collection and analysis solution presented using the scenario of fast-charging electric vehicles can also be utilized in a wide variety of other applications. Apart from the automotive industry, Leoni successfully does business in many other sectors, which could also benefit from LeoniQ. Alongside the safe, fast charging of EVs, other use cases that stand to benefit in particular from the continuous monitoring and data analysis of cable systems include:

- dresspacks and cable carrier (drag chain) systems for industrial robots
- cable carriers in industrial applications
- active junction boxes as used in photovoltaic systems
- energy cables in wind turbine systems
- inter-vehicle cables for rolling stock.

Common to all of these applications are the high mechanical or thermal stresses the electrical cable is exposed to during operation. Also important are the high follow-up and downtime costs resulting from the incident. Investments in improved data availability and analysis can pay for themselves in a short space of time thanks to maintenance intervals driven by usage (predictive maintenance) that work to increase both productivity and resilience. A positive secondary effect also results, namely that a design can be chosen that is optimized for functionality and needing less reserve capacity (such as a smaller cable diameter) – even at an early stage of development and together with the customer.

Thanks to LeoniQ, the interconnection system is now becoming intelligent for the first time.

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