CIRED 2020 Berlin Workshop (CIRED 2020)

22-23 September 2020

Theme 2: Opportunities and Challenges with Operation using Flexibility

Data-driven analysis of distribution cable operating temperature profiles with LEONiQ intelligent cable technology

ISSN 2515-0855
doi: 10.1049/oap-cired.2021.0117
www.ietdl.org

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Abstract: This study presents the first-time application worldwide of the LEONiQ intelligent cable technology, which in this case includes sensor elements for direct temperature measurements inside a regular distribution grid cable, for electric distribution grid operation and monitoring. Key findings of the pilot project, running since early 2019 in a real operational setting in a suburban distribution grid area of EKZ, the Electric Utility of the Canton of Zurich, and the opportunities it gives rise to as part of a more data-driven, and thus more accurate, cost-efficient asset management in distribution grids, are presented here for the first time.

1 Introduction

Asset management and with it the continuous maintenance and renewal, i.e. replacement, of grid assets such as transformers and cables are both a core activity as well as a substantial cost factor for distribution grid operators.

Electric cables are in fact by far the largest part of the asset base, i.e. working capital, for a distribution grid operator. They are typically replaced at the end of their nominal lifetime, e.g. after 40 years, most often without considering the likely remaining lifetime of the individual cable due to lack of operational data and the effective analysis thereof.

Managing the grid asset base can be improved by explicitly including measurements of operation temperature directly obtained from within the distribution cables. This new data source gives rise to more data-driven asset management methods that can analyse cable ageing more accurately, thereby allowing the extension of cable maintenance cycles and with it a reduction of cable investments in the mid-term.

Leveraging data-driven asset management to replace cables closer to their effective life-time end, has the potential to both reduce maintenance costs, i.e. when cables can be used on average longer than the currently used nominal calendar lifetime, and to improve reliability of grid operation, i.e. when cables that age faster due to operational stress or physical damage can be detected earlier. One potential source for increased operational stress and, over time, failure events in distribution cables are sustained loading peaks, as inflicted by peak load situations, i.e. heat pump loads during wintertime and photovoltaic (PV) feed-in peaks on sunny days.

2 LEONiQ intelligent cable technology

Since late 2016, LEONI has developed the LEONiQ technology platform that makes energy and data flows more efficient, secure and transparent for operation monitoring [1].

LEONiQ can record and evaluate such differing parameters as temperature, pressure and media intrusion along almost any given cable system. This key technology facilitates drawing conclusions concerning the condition of the overall cable system as well as controlling it, and it gives recommendations for future development cycles, i.e. cable dimensioning, cable ageing and remaining lifetime and efficient operation strategies.

The main components of an LEONiQ cable, cf. Fig. 1, are:

- application-specific sensor, e.g. temperature-sensitive coax cable,
- small electronics for data acquisition and pre-processing,
- data analytics component, i.e. an edge device on-premise or cloud based with an optional gateway solution.

The LEONiQ sensor technology applied in this use case, comparable to the TDR measurement principle [2], monitors the temperature distribution continuously inside application cables and detect local temperature differences such as hotspots. Depending on the sensor design, it is also capable of detecting and locating media intrusion for damaged cables.

3 Pilot project setup

3.1 Pilot grid area

The pilot region is comprised of a low-voltage transformer area in Bonstetten, which is located in the Canton of Zurich in Switzerland [3]. The grid lies in a residential region, serving around 150 households and a primary school. Apart from one building with an old meter all customers in the pilot region are equipped with smart meters [4]. This particularly good data basis allowed us to complement the measurement values with load flow simulations thus making even more information available about the grid state on a 15 min resolution. There are several PV units present and a high share of customers feature heatpumps for space

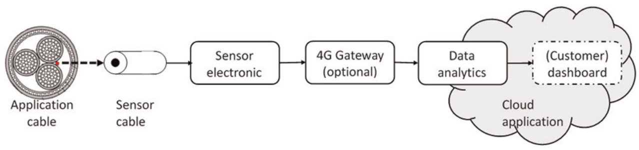

Fig. 1 *LEONiQ cable technology (main components)*

heating. The installed transformer power is 400 kVA with a measured peak of 267 kVA over the course of the project measurement period (March 2019–February 2020).

This peak loading of the transformer occurred on a weekday in January 2020 at 17:30 local time and was caused by high household loads, especially from heat pumps, without a compensation by PV units. The peak of PV generation and PV net feed-in to the higher grid level occurred on 21 July 2019 at 13:45 local time. At this time, 227 kW were generated cumulatively by PV units in the pilot region, resulting in 179 kW of net feed-in to the MV grid.

In summary, the pilot grid serves a residential area with a significant share of distributed PV generation. The installed LEONiQ cable (cf. Fig. 2, top) serves a part of the transformer area with a couple of households including a farm with a total PV generation of over 100 kW_p, while not having high load demand. The LEONiQ cable loading pattern is thus dominated by reverse flows by PV units with PV peaks that are more than twice as higher than the load demand peaks.

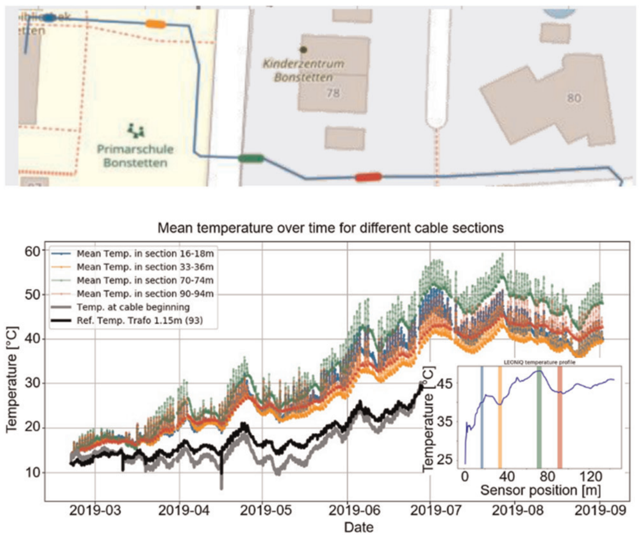

Fig. 2 *Installation setup of LEONiQ enhanced cable (top). Mean temperature of different sections of the sensor cable (March–September 2019) (bottom) with inset (temperature profile over the full cable length with highlighted cable sections)*

3.2 Measurement campaign

An overview of the measurements from the pilot grid area in Bonstetten that were available for analysis and simulation is given in Table 1. The measured voltage at the transformer in combination with the power measurements of the customers allowed us to conduct a load flow simulation covering the most relevant time periods. As an outcome of the power flow calculations, simulated voltage and current profiles of all lines in the grid area also became available with 15 min resolution.

A crucial requirement for load flow calculations is a correct grid model with electrical parameters. For the test area, this grid model was converted from a CIM export (Common Information Model) of the GIS (Geographic Information System) database of EKZ. It was subsequently validated by comparing load flow results with another grid calculation tool for which a pre-existing grid model was available. The LEONiQ cable data was measured in time intervals of 30 s and sent via an LTE gateway to the cloud. The temperature profile along the cable sensor (Fig. 2, bottom) was analysed hourly by taking the average temperature for the last 5 min of each hour.

3.3 Simulation campaign

A load flow simulation was set up for the time period from early summer to winter 2019 and extensively validated with existing grid measurements. The validation showed that the simulated line currents matched the measured ones very well (mean deviations typically below 5%). Active and reactive power measurements from all but one consumer in the grid area; as well as a voltage measurement at the transformer station were used for the load flow simulations. The simulation results provide additional insights of the changing grid status.

In Fig. 3*a*, an example of such a comparison between measured and simulated line current profiles is shown. As can be clearly seen, the deviations are very small.

4 Results

The novelty presented here is the availability of continuous cable temperature measurements over the full cable length. The obtained three-dimensional data is visualised in Fig. 4. Established cable measurement methods typically only deliver temperature measurements at single spots on the cable. From Fig. 4*b*, it becomes clear that the measured temperature differences along the cable can be up to about 20°C. This clearly shows that the thermo-conductivity of the copper conductors itself does not suffice to balance the temperature difference along the full cable length [5].

In Fig. 3*a*, the temperature increase induced by high current values disappears within about 4 h in our test case. The peak value of the electric current is not decisive for the temperature reaction, whereas the electric energy transmitted, i.e. the square of the current multiplied by the time-period, is. These two observations

Table 1 Overview of measurement data used for analysis

Source	Variables	Time res., s	Period from-to
smart meters at households	active and reactive power	900	2019-05-02 2020-01-19
smart meters of commercial units	active and reactive power	900	2019-05-02 2019-12-31
dedicated measurements at individual grid feeders	current, voltage, active and reactive power	60	2019-06-06 2020-01-20
meter inside transformer station	current, voltage, active and reactive power	600	2019-06-30 2020-02-11
meter inside cabinet (down-stream end of LEONiQ cable)	current, voltage, active and reactive power	60	2019-06-18 2020-01-26
temperature sensor of LEONiQ cable	temperature (419 locations along cable)	3600	2019-02-20 2020-02-29

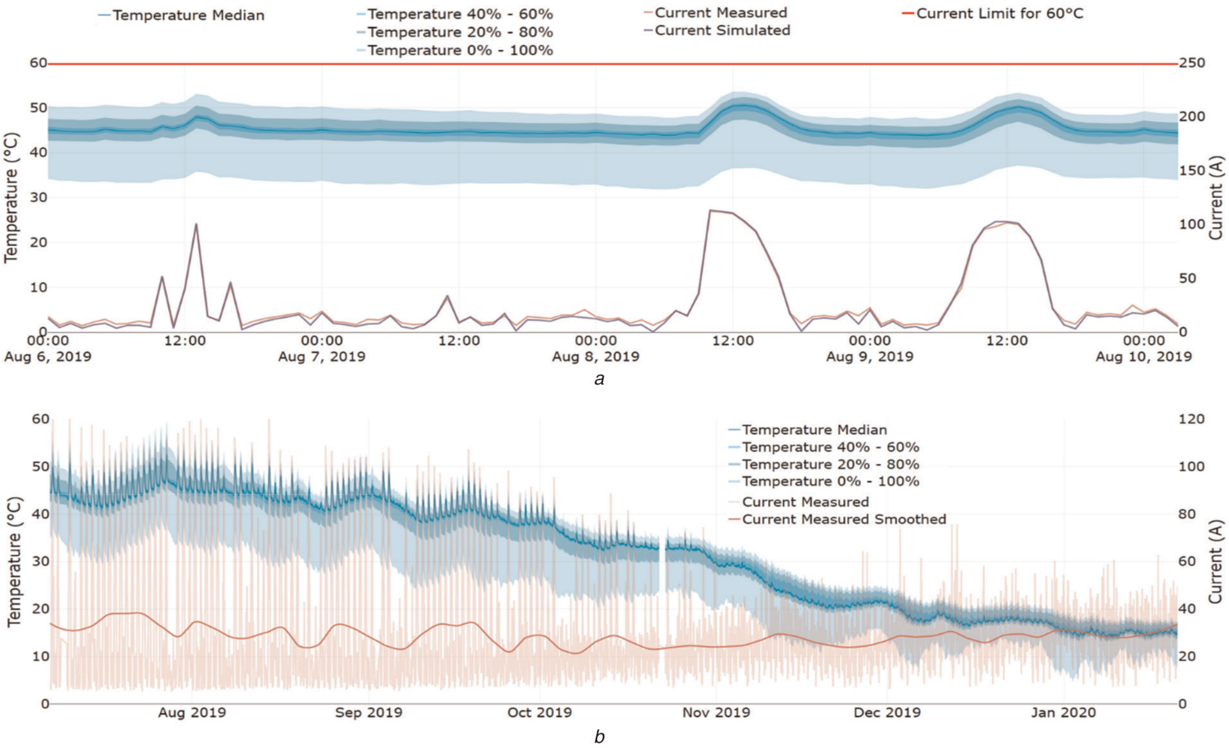

Fig. 3 *Comparison of cable temperature and current short term and on a seasonal timescale*

a Cable temperature during four summer days including the measured and simulated current and the current threshold for keeping the cable below 60°C. Current induced temperature increases move back to equilibrium within about 4 h. The peak value of the current (or power) is not decisive for the temperature reaction, but the energy transmitted is. The cable's operation point was not near any manufacturer limits as seen by comparing the actual current and temperature profiles to the red threshold (250 A/60°C) for the used cable type GKN $3 \times 150/150$ mm^2 (400 V),

b Cable temperature compared to measured current from summer to winter. Measured current and its smoothed profile show that only current peaks are higher in summer, but energy transmitted is similar to winter. At the same time, cable temperature decreases from summer to winter

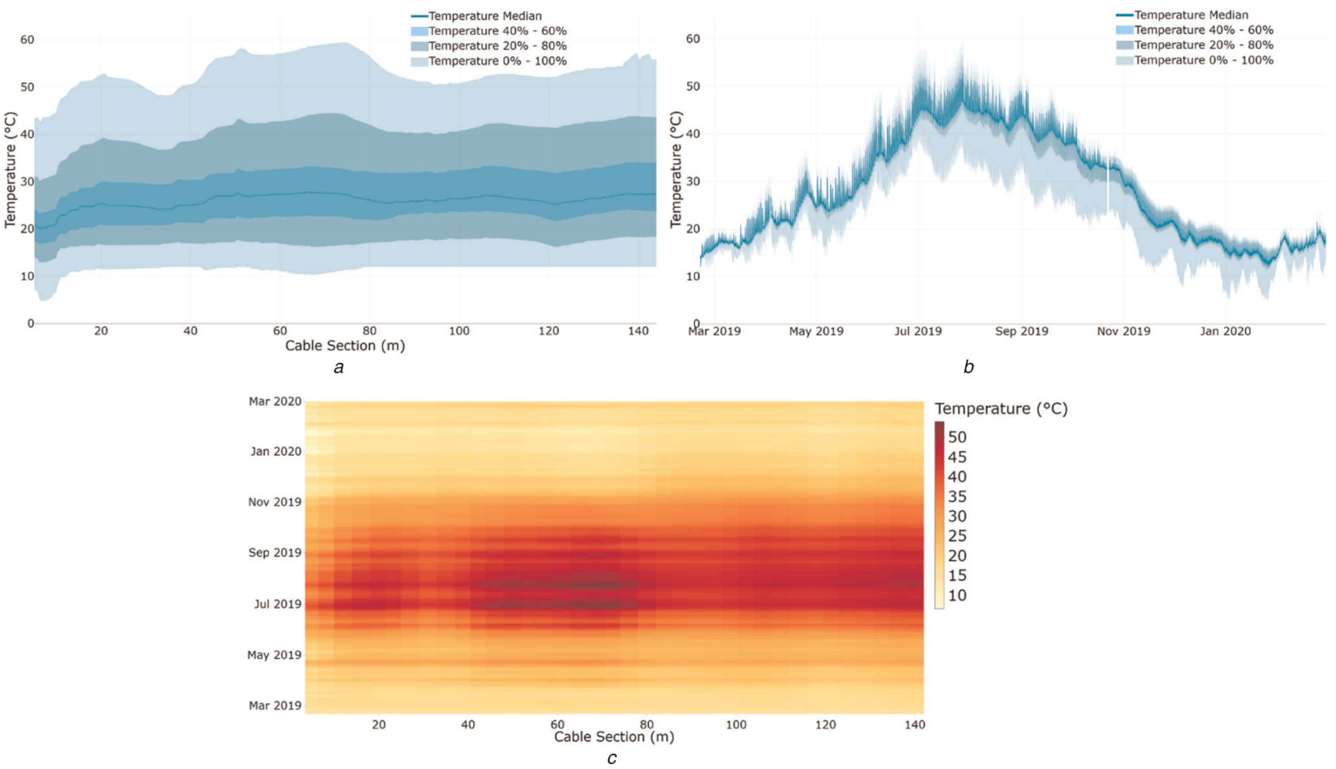

Fig. 4 *Illustration of relationship between cable temperature, time and cable sections. The measurement period is 1 year from March 2019 to February 2020 with a resolution of 1 h*

a Cable temperature range over measurement period of each cable section. Narrower quantile bands are plotted on top of wider ones. The cable temperature range is considerable at all cable sections,

b Cable temperature range over cable length during measurement period. Narrower quantile bands are plotted on top of wider ones. The cable temperature follows the seasonal outside temperature. Temperature differences along the cable sections are bigger in summer,

c Cable temperature depending on time point and cable section. There are cable sections which become considerably hotter during summer could be included for the dimensioning of cable diameters for PV-dominated lines. The typical, idealised bell-curve shape of the generated power along with its maximum value can be calculated in the planning stages for PV units. With this information it may be possible to choose an optimised cable diameter by not only considering the expected PV peak but also the time it will last.

Grid operators need to prevent the cable from failing altogether. Cable ageing is directly dependent on the cable temperature and decisive is the section of the cable that becomes the hottest as the cable must not fail due to ageing anywhere along its length. Fig. 4*c* clearly shows that the cable temperature can deviate considerably along its length. It is evident that the temperature amplitude increases during summer when the average temperature of the cable is higher. This observation indicates that the deviations could be caused by differing albedos of the ground surface material thus leading to a varying heat-up of the cable insolation. The comparison of the smoothed current measurements with the cable measurements in Fig. 3*b* shows that the cable temperature features a strong seasonality that is not caused by the current flow in the cable itself. The seasonal behaviour of the cable temperature is likely caused by the seasonally changing temperature of the surrounding soil. In countries with distinct temperature differences between the seasons, this observation should be considered for grid planning: in case ambient temperatures are lower there is considerably more leeway for transient temperature increases caused by a high-power flow through the cable. For Switzerland this implies that winter load peaks, e.g. caused by heat pumps, can be larger than summer generation peaks, e.g. caused by PV units.

During the measurement campaign 2019/2020, the LEONiQ cable's operation point was never close to any manufacturer limits, as illustrated in Fig. 3*a*. An interesting application of the LEONiQ technology is the assessment of the guidelines for cable dimensioning, by analysing to what temperature levels certain power flows in the cable can lead. Such an assessment is especially interesting close to a cable's current/temperature rating (shown in red in Fig. 3*a*). Unfortunately, this could not be conducted here due to low cable loadings in the test setup. The extensive validation of load flow simulation results with available grid measurements proves that a carefully set-up simulation using power values delivered by smart meters gives ample potential for grid analysis. A potential use case for the LEONiQ cable technology is the collection of representative data on the relationship between cable temperatures and line loading for different real-world situations. The relationship is important as it determines the cable sizing with the goal of choosing a cable diameter, which lies at the optimum of the trade-off between additional cost for thicker cables and cost for cable replacement due to ageing defects.

5 Conclusion and outlook

The results of the LEONiQ cable technology project for the real-world setup of EKZ's pilot grid in Bonstetten show that

- temperature measurements from the LEONiQ cable can be obtained continuously over the full cable length and with good quality in a real-world operation setup,
- cable temperature measurements provide valuable insights of the operational stress seen by individual cables, which gives rise to both new grid planning guidelines particularly for the robust dimensioning of cable diameters of PV-dominated power lines as well as new applications in data-driven grid asset management [6].
- A potentially promising use case for the LEONiQ cable technology is the targeted, extensive collection of representative data on the relationship between observed cable temperatures and actual line loadings for different real-world situations. The relationship is important as it determines the cable sizing with the goal of choosing a cable diameter, which lies at the optimum of the trade-off between additional cost for thicker cables and cost for cable replacement due to ageing defects.

The LEONiQ cable technology pilot project showcases that a future, smart distribution grid is not only made of intelligent measurement points at grid nodes but may just as well benefit from measurements from within smart cables.

6 Acknowledgments

Many people inside EKZ, LEONI and Adaptricity have contributed to the realisation and success of this pilot project. The main author would like to particularly thank Beat Kaltenrieder, from whose decades of cable expertise the project has benefited tremendously, as well as Adriano Beti, Torsten Schierholz and Michael Koller for facilitating the project activities and providing all the needed resources.

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