Thermal Behaviour of Low Voltage Cables in Smart Grid – Related Environments

Nicolas Höning, Erik De Jong, Gabriël Bloemhof and Han La Poutré

Abstract—**Low voltage cables in distribution grids will operate under harmful conditions more often in the near future, due to the integration of renewable energy sources and the addition of powerful consumption appliances. It is crucial to evaluate smart solutions that can prolong cable lifetime. Because most knowledge about thermal behaviour of cables has been collected in the medium and high voltage grids, it is also important to study, in real-world circumstances, the precise thermal reaction of low voltage cables to novel types of usage spikes and to protection mechanisms. We emulated a low voltage cable of a Dutch neighbourhood in a laboratory and conducted several overheating experiments for multiple hours. One scenario involved the usage of a smart battery with a control algorithm for the protection of the cable from overheating. We report on results of systematically varying currents and cable insulation. We demonstrate the positive effect of regular interruptions of high currents on cable temperature and that even a small battery (e.g. a used EV battery) can make a significant contribution to the reduction of overheating.**

Index Terms—**low voltage cables, renewable integration, smart battery operation**

I. Introduction

Attention to the health of low voltage infrastructure is increasing due to the expected increase of novel appliances attached to the distribution grids, e.g. heat pumps, electric vehicles and solar panels. Their high aggregated load or generation can surpass the maximum rated capacity of cables, increasing their temperature. The temperature of cables is highly influential for their expected lifetime. Another effect of capacity violations is that emergency protection mechanisms will cut off customers when network assets are strongly overheated. This usually leads to high fines for the DSOs.

Our energy infrastructure needs to support the transition to a modern energy future, but major updates of network assets are very expensive. A recent report suggests that asset investment costs of up to 800 million EUR might be necessary within the next 35 years to only accommodate EVs in The Netherlands [1]. Protection of low voltage assets can often be a better alternative than outright replacement of cables. Prolonging the life time of some cables can make a big difference to the strategic financial outlook of distribution operators, as it helps them to stretch out the upcoming necessary infrastructure investments. When designing smart protection mechanisms, it is also paramount to study the thermal behaviour of low voltage cables, in real-world circumstances, under a variety of what-if conditions. Most knowledge about thermal behaviour of cables has been collected in the medium and high voltage grids, which are, unlike most low voltage cables in Europe, not underground. Studying thermal behaviour can also give an indication of the effect of protection strategies.

In laboratory experiments at the FPG Lab[1] in Arnhem, The Netherlands, we emulated several overheating scenarios and studied heating and cooling of an LV cable over time. We used 30 meters of a common low voltage cable to resemble a street with domestic households. Adjustable consumption and generation devices (represented by resistances and a diesel generator, respectively) were connected to the cable. At the end of the cable, we placed a battery emulator, so we could simulate a scenario in which a smart battery performs protective actions. This scenario is based on earlier work at the CWI Amsterdam [2], where a steering algorithm for such a battery for LV cable protection was proposed. We tested the smart battery solution found in [2] and evaluated the results.

This paper proceeds as follows: Section II discusses related work and provides context on the proposed protection algorithm of [2]. Section III then explains the setup of devices in the laboratory and provides details about the smart battery solution from [2]. In Section IV, we discuss the experiments and the results. We first look at the influence of currents and insulation on temperature, where we experiment with several variations. We also measure the effects of heating and cooling on different parts of cable segments. We then pay attention to the effect that controlling the currents has on cable temperature. We simulate regular interruptions of continuous power flow and finally conduct an eight-hour scenario with realistic load patterns, where battery actions are determined by a battery control algorithm from [2]. We show that even a battery with little capacity (we used only 12kWh in the model) can make a significant contribution to avoiding overheating.

II. Background

The fact that the expected increase of activity on low voltage levels can significantly reduce the expected lifetime of cables (which were not designed for this activity) has only recently become an active topic of research among electrical engineers (e.g. [3]). Kadurek et al. (2011) [4] describe this challenge in more detail, highlighting that conventional protection schemes will not be able to tackle overloading. They note that different

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[1] http://www.flexpowergridlab.com/

segments of a cable can be in different states and that only a more sophisticated measuring infrastructure (e.g. by smart meters) can allow the Distribution System operator to identify the critical segments and in which state they exactly are. They thus make the case for a novel use case for sensory data, in which intelligent actions based on these data are of high societal benefit (because the lifetime of an expensive underground cable can be prolonged).

Electricity storage (i.e. batteries) is a technology which complements many other technologies that are considered primary drivers in smart energy systems. One example is that batteries can buffer the output peaks of intermittent renewable energy generation, a topic which has (mostly for large-scale batteries) received a lot of attention in the last decade (e.g. [5]). Designing battery control algorithms is thus a crucial, but also challenging task.

Batteries can also be used with the objective to protect low voltage cable infrastructure. One of the first contributions to this idea was made by Ramezani et al. (2013) [2]. They proposed heuristic battery control algorithms, which aim to combine two important objectives: to protect the low voltage cable and to contribute towards the cost of the battery by buying and selling electricity intelligently. Several days of domestic consumption and generation activity along a street in a low voltage neighbourhood were modelled in a computer simulation. In addition, two different scenarios for the placement of consumption and generation along the street were modelled. In the “optimistic” setting, consumption and generation devices are placed along the cable in alternating fashion. In the “pessimistic” setting (which we model in this work), consumption and generation devices are grouped together, respectively.

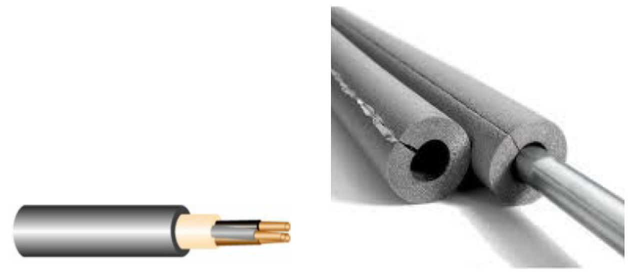
III. Setup

A. Laboratory setup

In this section, we describe the hardware setup we used for our experiments in the FPG lab. We model the pessimistic setting from [2], where all loads and all generation are grouped together. The system voltage across all cables was a constant 230V/400V. For a schematic overview of the experiment setup, refer to Figure 1.

a) Cable: We used 30 meters of YMvK mb cable made by Nexans B.V. (a 4x25mm2 copper cable, rated for approximately 45kW - see Figure 2). The nominal ratings are given for voltage as 600Vac and for current as 127A. The maximum operating temperature is +95 degrees C. We employed three cable segments, each being ten meters long. The beginning of the cable is connected to the MV grid. LV cables are underground in The Netherlands and thus the thermo-conductivity should resemble these difficult-to-observe settings, at least for average conditions. To achieve this, the measured segments were packed in insulation material commonly used to for household CV pipes as thermal barrier, which is very similar to polystyrene.

The third segment is limited by maximal charge level of the battery, therefore we only measured temperature in the first two cable segments. We measure the temperature of the segments on the outside of the cable (but within the isolation material) at 5 points, at the length of one, three, five, seven and nine meters. In addition, the ambient room temperature was measured to serve as a reference.



(a) The YMvK cable (b) Cable insulation

Fig. 2. Illustration of the employed LV cable

b) Loads: We connect one load after the first segment, which represents the aggregated load of several households. We modelled loads with resistances. The FPG lab has available resistances of 24 Ohm and 12 Ohm. We modelled four switches with different resistances each. All combinations of switches thus equaled $2^4 = 16$ distinct settings for the load. In [2], the aggregated consumption load varies between 0 kW and 50 kW, thus we made the following choices for the settings of the four switches: 6 Ohms (2x12 Ohms in parallel), 12 Ohms (1x12 Ohms), 24 Ohms (1x24 Ohms) and 48 Ohms (1x24 Ohms+1x24 Ohms in series). If the resistances of all the switches are on, up to 49.6 kW of demand are simulated.

c) Generation: In the simulations from [2], all generation (10 solar panels[2] with 5kW output each) is either on or off, which makes representing it in the lab straightforward (different to the representation of loads we describe above). We connect a diesel generator after the second segment, which represents high currents from an aggregated number of generators, e.g. assuming a high penetration of solar panels. The simulation traces specify either 0kW or 50kW.

d) Battery: At the end of the cable, we place a battery emulator provided by EMForce[3]. It emulates a 15kW, bi-directional battery and can simulate battery operation for any continuous value between -5kW and +5kW. The battery can be used to perform protective actions when the current exceeds rated capacity. In [2], a larger example of a battery used in electric vehicles was assumed (with a capacity of 31kWh). In this experiment, we use a size of 24kWh which is found in mass-produced electric vehicles (e.g. the Nissan Leaf[4]) and we also adjust for the assumed advanced lifetime of the battery - we assume the battery is in its so-called ”second life“, not being suitable any more to operate an electric vehicle. Thus, we subtract 50% capacity and use 12kWh. Batteries are assumed not suitable for EVs if the capacity drops below 70% but we assume an even lower capacity to be on the safe side, as capacity also degrades during the second life of the battery.

[2]For an example of such panels, see http://www.eurosolar.com.au/solar-power-systems/systems-with-250w-solar-panels/5-kw-solar-system/

[3]http://www.emforce.nl/

[4]http://www.nissanusa.com/electric-cars/leaf/charging-range/battery/

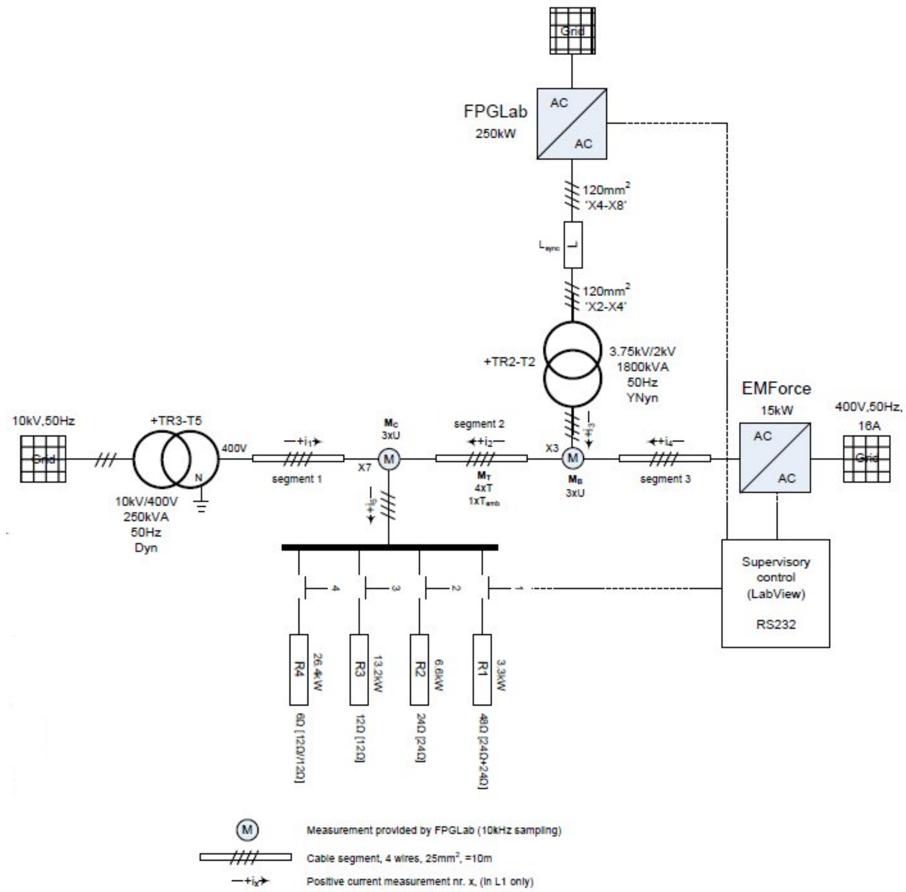


Fig. 1. Experiment setup in the FPG lab

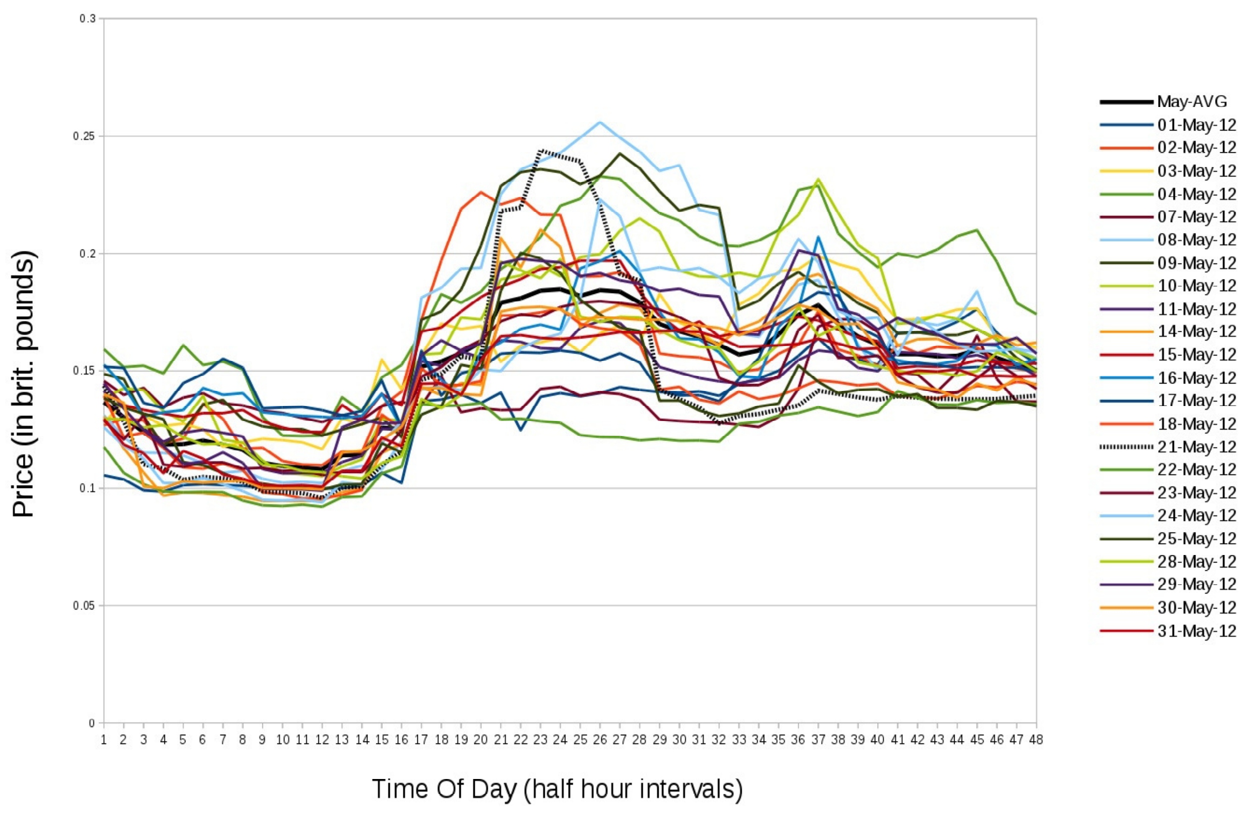


Fig. 3. APX wholesale market prices for all days in May 2012. May 21st is shown in dotted black.

B. Smart battery scenario

We now explain how we generated the experiment traces (shown in Table I) which resemble one scenario in [2]. All activity by consumers (and, consequently, by the battery) is based on APX wholesale market traces from 2012. Because we conducted experiments in real time, we had to choose one price series from the 2012 set. We chose May 21st, 9am-5pm (see Figure 3). Consumers act according to their needs and therefore in accordance with the majority of other consumers in the market. They thus consume much when prices are high and little when prices are low (see [2] for more details). Due to the laboratory setup for the load (see Section III-A), we discretised the resulting load profile to the values we could emulate. The activity of solar panels [2] was fixed to be active (full production) from noon to 4pm. During each half hour time step, all activity is kept at constant kW levels.

The activity of the battery is determined by the heuristic algorithm H2 proposed in [2]. H2 has no advance knowledge of prices, but uses instead the average price of the month (for May 2012, see the thick black line in Figure 3) to forecast local consumption and therefore cable conditions. In each time step, H2 creates a schedule for charging and discharging actions, which is based on needed protection (if current exceeds rated capacity of the cable) and thresholds for prices (next to protection, H2 has the objective to maximise its revenue from buying and selling). To take future steps into account is crucial for a storage control problem, due to the limited capacity of the device which should be put to optimal use at the best time. The feasibility of the initial schedule (to stay within battery capacity limits) has then to be accomplished by an advanced computational procedure. For more details, refer to [2].

IV. Experiments

This section describes four experiments we conducted in the FPG laboratory. The first two experiments examine base levels of thermal reactions. We vary currents and insulation change in Experiment A and then look into the difference of temperatures across the cable segments in Experiment B. In the following two experiments, we pay attention to the effect that controlling the currents has on cable temperature. In Experiment C, regular interruptions of power flow are conducted. Finally, Experiment D conducts an eight-hour scenario with realistic load patterns and a battery control algorithm from [2].

All reported temperatures are in degree Celsius and denote the difference between the measurement point on the cable segment (at the length of 5 meters) and the ambient room temperature. We conducted these experiments in the summer of 2013 at well above 20 degrees Celsius ambient temperature. The results will show that temperatures of over 70 degrees were recorded frequently on the outside of the cable (see Section III-A), thus the cable core was even hotter.

A. The influence of currents and insulation on temperature

We first look at the influence of currents and insulation on temperature. For more than two hours, we tested constant generation of 45kW and 50kW with one insulation layer. We also tested generation 50kW with three insulation layers. We measured the temperature on cable segment 2 (note that the load has no influence on the temperature of this segment). The effect of adding 5KW of current or two additional insulation layers is comparable and can in both cases add several degrees to cable temperature (see Figure 4).

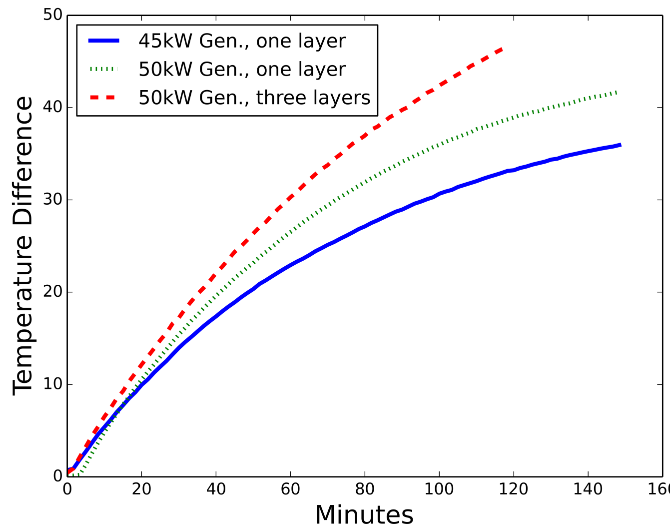


Fig. 4. Results of Experiment 1, temperature on segment 2.

B. Difference in temperature between cable segments

In this experiment, we report on the individual sensor results along cable segment 2. First, we conducted a three-hour run of constant generation activity (of 50kW). Figure 5 shows minutes 90 to 180 of this activity. It is clearly visible that, as expected, middle segments of the cable become hotter than outer segments, as those are connected to other equipment which does not heat up.

We then stopped generation activity and observed letting the cable cool down. Figure 6 shows minutes 120 to 210 of this phase. In addition to the cable adjusting to ambient room temperature, we cooled only the middle part of cable segment 2 by fanning (beginning at minute 170, with a short interruption at minute 175). Contrary to our expectations, the effect on neighbouring parts is negligible. Apparently, axial conditions have much less influence on temperature than radial conditions.

C. Regular interruptions of power flow

Experiment C tests how beneficial it is (for the reduction of temperature) to regularly interrupt a continuous power flow, i.e. to prevent a build-up of temperature by consecutive high currents. This is to be expected, but here we measure the percentage. In one condition, we generated 50kW consecutively for four half-hour intervals. In a second condition, we interrupted each interval with one half-hour interval of no generation. Again, we report on the temperature of segment 2. The results in Figure 7 show that in the second condition, the peak temperature difference builds up to 60% of what the first condition exhibits.

Minutes	Aggregated Load	Aggregated Generation	Segment 1 (no battery activity)	Segment 2 (no battery activity)	Battery action by H2 algorithm	Segment 1 (with battery activity)	Segment 2 (with battery activity)
0	26.45	0.0	26.45	0.0	0.0	26.45	0.0
30	26.45	0.0	26.45	0.0	-1.99	24.46	-1.99
60	42.98	0.0	42.98	0.0	-5.0	37.98	-5.0
90	42.98	0.0	42.98	0.0	-5.0	37.98	-5.0
120	49.6	0.0	49.6	0.0	-4.6	45.0	-4.6
150	46.29	0.0	46.29	0.0	-1.29	45.0	-1.29
180	46.29	-50.0	-3.71	50.0	5.0	1.29	-45.0
210	42.98	-50.0	-7.02	50.0	5.0	-2.02	-45.0
240	36.37	-50.0	-13.63	50.0	5.0	-8.63	-45.0
270	33.06	-50.0	-16.94	50.0	5.0	-11.94	-45.0
300	23.15	-50.0	-26.85	50.0	1.87	-24.98	-48.13
330	23.15	-50.0	-26.85	50.0	0.39	-26.46	-49.61
360	19.84	-50.0	-30.16	50.0	0.09	-30.07	-49.91
390	19.84	-50.0	-30.16	50.0	0.03	-30.13	-49.97
420	19.84	0.0	19.84	0.0	1.02	20.86	1.02
450	19.84	0.0	19.84	0.0	0.22	20.06	0.22

TABLE I
AGGREGATED CONSUMPTION AND GENERATION TRACES TO SIMULATE MAY 2012, 9AM-5PM (FOR EXPERIMENT D) AND THE RESULTING POWER ON SEGMENTS S1 AND S2 WITHOUT AND WITH BATTERY ACTIVITY. ALL VALUES (BESIDES FIRST COLUMN) IN KW. VALUES FOR LOADS ARE POSITIVE AND VALUES FOR GENERATION ARE NEGATIVE (IMAGINE A METER AT A HOUSE, IT RUNS BACKWARD WHEN NET GENERATING).

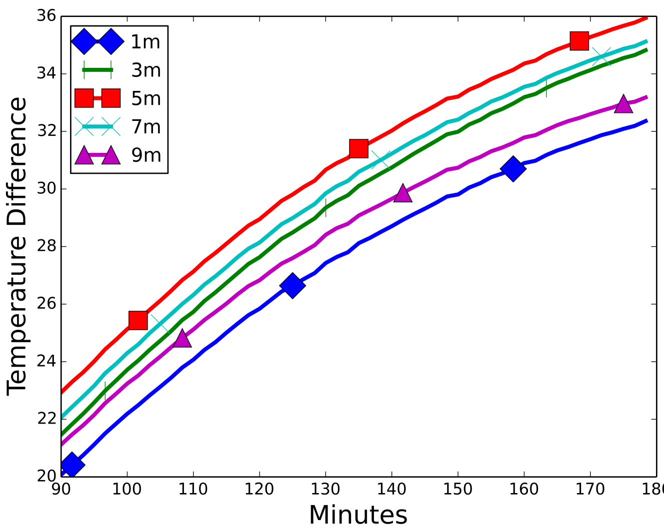


Fig. 5. Results of Experiment 2, heating phase. Temperatures of individual sensors on segment 2

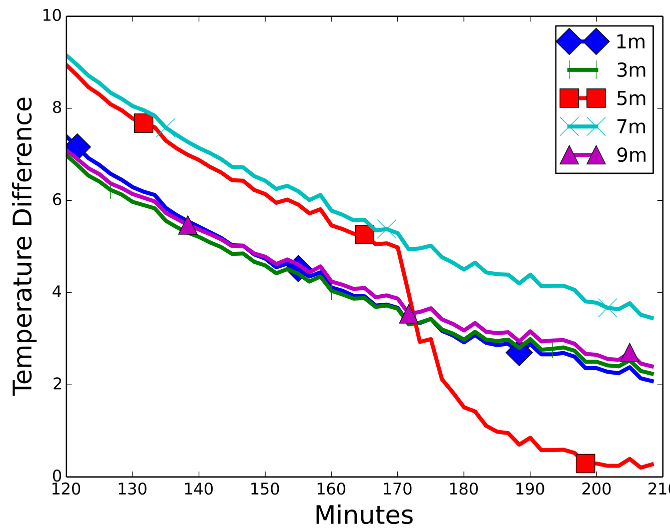


Fig. 6. Results of Experiment 2, cooling phase. Temperatures of individual sensors on segment 2

D. Realistic load patterns and smart battery operation

Finally, we run an eight-hour experiment with realistic load patterns and a battery control algorithm, which we described in Section III-B. In this scenario, both the load and the generation are (during some time intervals) overloading the rated capacity of the cable (on segment 1 and segment 2, respectively). Before the actual experiment started, we brought the cable into a thermal state which approximated the conditions which would exist due to previous activity before 9am. To this end, the load and generation levels of the first 30-minute time step (see Table I) were performed for 90 minutes. We report the temperature of both segments, for the case with no battery activity and for the case with smart battery operation present.

The results in Figure 8 show that even a battery with a small energy capacity can make a significant contribution to avoiding overheating: With a battery present, the temperature of the cable is lowered up to 13 percent (5 degrees) compared to when the same scenario is tested without a battery present. Between minutes 180 and 300, the battery is reducing the peak power by 5kW. Due to its low capacity, it cannot sustain this for longer, but a positive effect on cable temperature remains clearly visible even for two more hours of overloading the cable. This can already reduce damage to the cable significantly.

V. CONCLUSIONS AND FUTURE WORK

Low voltage cables in distribution grids will operate in harmful conditions more often in the near future, and protection is often a better alternative than outright replacement. It is crucial to evaluate smart solutions that can prolong cable lifetime. It is also important to study, in real-world circumstances, the precise thermal reaction of low voltage cables to

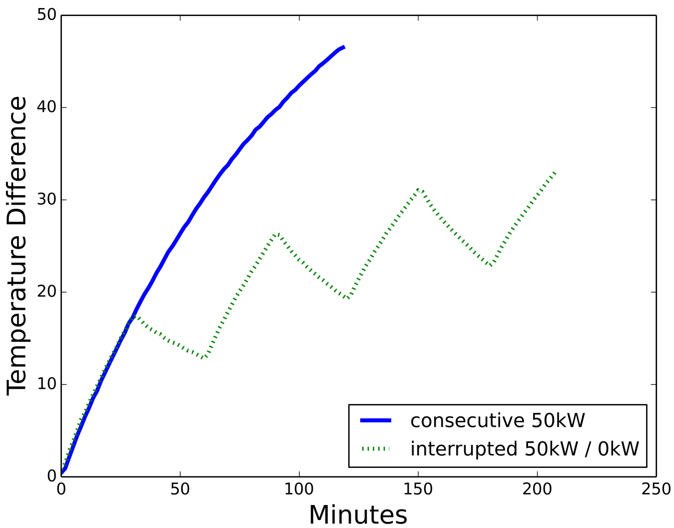


Fig. 7. Results of Experiment 3, temperature on segment 2.

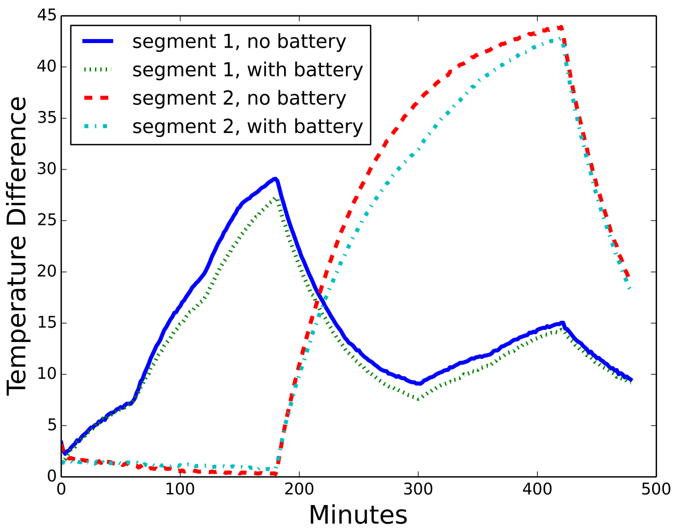


Fig. 8. Results of Experiment 4.

novel usage spikes and to proposed protection mechanisms. We emulated the low voltage cable of a Dutch neighbourhood in the FPG laboratory in Arnhem, The Netherlands, and conducted several overheating experiments for multiple hours. The results of this work can help in understanding how cable temperature is related to different conditions and gives an indication of the effect of protection strategies. For instance, we could show positive effects on reducing cable temperature by operating even a small battery (a used battery from an electric vehicle). Future work could test a protection algorithm which interrupts a long interval of overloading repeatedly (rather than reducing peak temperatures consistently until the battery has no more capacity to do so).

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