TOWARDS A MORE EFFICIENT CONGESTION MANAGEMENT FOR THE TRANSFORMATION OF ELECTRIC DISTRIBUTION GRIDS WITH INCREASING SHARE OF SECTOR-COUPLED COMPONENTS

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Abstract

The increasing acceleration of the energy transition is leading to major changes in the entire energy system. Not only are conventional energy generation plants increasingly being replaced by decentralized renewable generators with the aim of decarbonization, but the heating and mobility sectors are also being electrified at a rapid pace. A large share of this transformation is taking place in the distribution grids, especially in low-voltage grids, which are likely to be exposed to grid congestions as a result. In Germany the legislation has decided to support distribution grid operators by the adjustment of the German Energy Act. Controllable consumption units, for example electric heat pumps and non-public loading infrastructure of electric vehicles, have to adjust their consumption in grid congestion situations according to the requirements. This will solve some of the problem situations, but further aids are needed. In this paper two different grid congestion management strategies based on the current legal framework are investigated. The default strategy is handling the congestions by means of current- and voltage-based congestion indicators, the new strategy uses an approach based on the cable temperature. The results show, that even in disadvantageous installation conditions the transient thermal behaviour offers flexibility for congestion management.

1. Introduction

The effort to decrease CO2 emissions is lately increasing in the whole European Union. On the generation side, more and more distributed energy resources (DER) in form of wind power plants and photovoltaics are installed especially in the distribution grids. On the consumer side, the electrification of components from the heating and mobility sector has prevailed. This leads to an increasing share of electric heat pumps (EHP) and electric vehicles (BEV), which are installed in the medium and low voltage distribution grids. Additionally, lots of research efforts in flexibilization and integration of the energy sectors, electricity, gas and heat, propose further incentivising for household electric storages (BES) and coupling components, which again are mostly relevant in the distribution grids. As a result, it is easy to argue that distribution grid operators (DSOs) in particular are experiencing and must continue to expect major changes and challenges, both in the planning and operation of their grids. In Germany the legislators decided to support the DSOs by the latest adjustments in the German Grid Expansion Acceleration Act (NABEG) [1] and the German Energy Act (EnWG) [2]. Giving the DSOs options for action in the prevention and curation of grid congestion situations.

With this paper, the authors continue to support the current transformation. Previous publications [3], [4] have shown that frequent grid congestion situations can already be expected in mid-term future low voltage grid scenarios according to the currently applicable metrics. A unique feature of the approach chosen here is the dynamic simulation over time. In particular, the dynamics of the controllers and efficiency of the power consumption within the household heat supply and the charging infrastructure for BEVs are included. The new addition in this publication is an analysis considering the transient thermal behaviour of single buried power cables in the low-voltage grid and the repercussions on material parameters, grid losses and transient temperature curve in realistic grid situations. This enables the authors to show the potential but also limitations of dynamic cable rating for the grid congestion management in German low voltage grids. Finally, a grid congestion management system based on the current legal framework with and without the inclusion of dynamic cable rating is developed and compared.

In chapter 2 the classification of the contribution and the current legal framework are discussed. Chapter 3 presents the methodology taken to model and generate the grid scenarios with special focus on the transient thermal power cable model as well as the grid congestion management. The resulting grid scenario is then given in chapter 4. Finally, in chapter 5 the grid congestion management with default current-based congestion management (CBCM) is compared to the method using dynamic cable rating based on the temperature and therefore being called the temperature-based congestion management (TBCM) of the cables. This is applied on one day of semi-urban future low-voltage grid simulation.

2. Regulatory Framework and Challenges in the German Distribution Grids

Germany in comparison to other nations in Europe facing the ongoing trend towards renewable generation and electrification integrates more curative grid-oriented methods for congestion dissolution [5]. The preventive and market-based strategies are the classic redispatch, in which German plant operators with a capacity of 10 MW or more must participate, and the Germany-specific Redispatch 2.0, where alongside the Transmission System Operators (TSOs) the DSOs, as well as plant operators with $P_N > 100\,\text{kW}$ are involved in a similar but more complex process. Added to this the German Energy Act now allows DSOs to curatively regulate so called Controllable Consumption Units (CCUs). CCUs are modern comparably small consumption units with a maximum active power consumption $P_{max} > 4.2$ kW. CCU components are non-public loading infrastructure for BEVs as well as EHPs and BESs. Other appliances which are by this law defined as CCUs, but which are not included in the following analysis, are for example air conditioning systems. The regulation of CCUs is only valid in imminent or already occurred grid congestion situations and follows a modular scheme depending on the type of connection. In this paper we only consider the directly controllable CCUs for which a minimum active power consumption of $P_{CCU,min} = 4.2$ kW is guaranteed. With these efforts especially the DSOs shall be supported, but there are already statements that make it clear that this will not be sufficient for future grid scenarios, since it will result in high numbers of curtailment actions causing catch-up effects alongside potential dissatisfaction among the CCU operators. There is therefore a need for new, innovative solution strategies to make more efficient use of the existing infrastructure preventing the effects mentioned. [4], [6], [7]

3. Approach to Analyse the Potential of Dynamic Line Rating for the Grid Congestion Management

In this chapter the modelling and simulation approach will be discussed. The scenario and models are based on previously published articles and will therefore only be discussed briefly. A stronger focus is being placed on the newly integrated transient thermal power cable model for dynamic cable rating and the grid congestion management approach.

3.1. Distribution Grid Scenarios and Models

To be prepared for the rapidly changing infrastructure of the electrical energy systems, due to the installation of DER and the electrification of components, future technology mix scenarios and detailed models are needed. These scenarios can help to analyse the capacity of electric grids in relation to the DER and electrified components as well as support grid operators and researchers to develop new operational strategies. In previously published articles [3], [8], [9] the authors have shown how to generate detailed future medium- and low-voltage grid scenarios. The scenarios are strongly based on the global ambition scenario from the ten-year network development plan (TYNDP 2020) which was produced in collaboration by the association of European Transmission System Operators for Electricity (ENTSO-E) and for Gas (ENTSOG) [10]. The distribution grids are modelled in the acausal modelling language Modelica with support of the open-source TransiEnt Library [11] for modelling of integrated energy systems. The grid topologies are taken from the SimBench-Dataset [12]. In this paper the focus lies on the low-voltage grid level, since the authors have shown in [4] that low-voltage distribution grids are most severely affected by the electrification. The distribution grids are following a bottom-up modelling approach. The key component are producer-consumer households, named Prosumers, which are modelled alongside and inflexible consumption with a scenario-dependent distribution of the following components: Photovoltaic power plants, BES, EHP and BEV. An important aspect of the simulation strategy is the symmetric line loading. This is not completely valid but offers sufficient precision for today's grid situation [13]. For the following analysis the semi-urban low voltage grid scenario given in Figure 1 will be analysed.

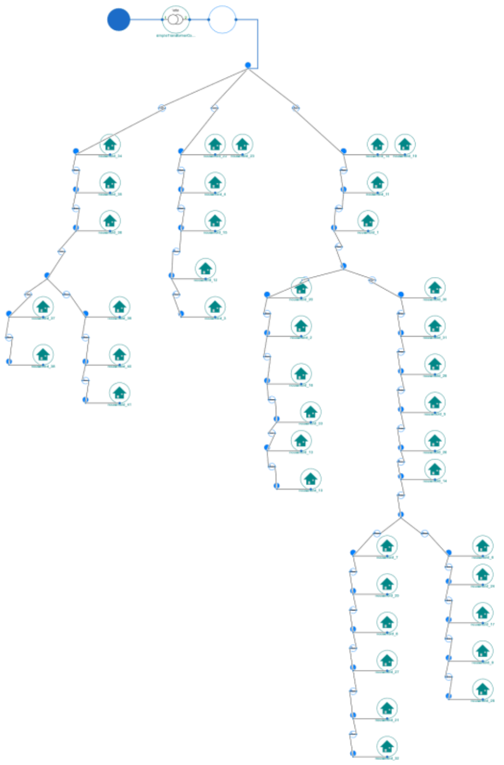

Figure 1: Graphical representation of the semi urban SimBench LV-semiurb-4 low-voltage distribution grid in Modelica. The scenario has 41 Prosumer households.

3.2. Transient thermal-electric cable model for four-core LVAC power cables

Since intermediate and future electric energy system scenarios show to have a high line loading in relevant durations the typically conservative steady-state current rating, usually referred to as ampacity defined in the IEC 60278-1-1 [14], could be replaced by more efficient strategies regarding the existing infrastructure [15]. Up to now, approaches that include the cable temperature have not been used due to the low observability of low-voltage grids. This situation is changing with the ongoing smart meter rollout. Most of the research work focusing on power cables carried out is single or three conductor power cables, which are mostly installed in high and medium voltage grids [15], [16], [17].

The model used in this paper is a simplified model for three-core cables adjusted for the in Germany often used low-voltage power cables of type NAYY-J 4x150mm². The simplified transient thermal equivalent circuit (TTEC) is obtained from [16]. Since the low-voltage power cables has four conductors, three for the voltage phases and one neutral conductor, the three-core TTEC needs to be adapted to a four-core TTEC. The strategy given in [16] to simplify a three-core TTEC into an equivalent circuit with one source was used to obtain an analogous result for four-core cables. The result is given in Figure 2.

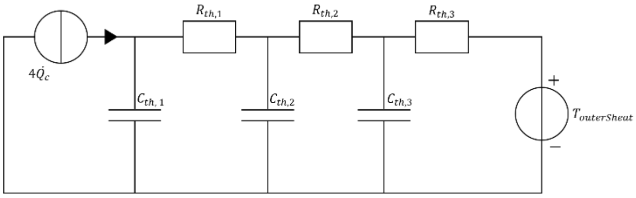

Figure 2: Simplified transient thermal circuit model of four-core buried cables. The model is constructed analogous to the three-core cable model from *[16]*.

Where $4\dot{Q}_c$ is equal to the Joules losses sum from each of the four conductors P_{loss}. The dielectric losses are neglected due their low proportion based on the cable size [16], [18]. The thermal resistances and capacities of the TTEC are given by the material parameters for the aluminium conductor, the polyvinyl chloride (PVC) insulator and sheat and the filling material, which for this cable is polyethylene terephthalate (PET). The insulator and sheat resistances and capacities are calculated by the ring shape assumption. The properties of the filling material cannot be assumed to be a ring shape, therefore the shape factor from [16] for four-core cables is used, knowing that the thermal resistance is probably overestimated leading to higher temperatures. The thermal resistances and capacities are composed as follows in (1) and (2).

$$\begin{cases} R_{th,1} = \frac{R_{th,insulator}}{4} \\ R_{th,2} = R_{th,filling\ material} \\ R_{th,3} = R_{th,Sheat} \end{cases} \tag{1}$$

$$\begin{cases} C_{th,1} = 4C_{th,conductor} \\ C_{th,2} = 4C_{th,insulator} + C_{th,Filling\ Material} \\ C_{th,3} = C_{th,Sheat} \end{cases} \tag{2}$$

The calculated parameters of the TTEC are given in Table 1. For the calculation the most disadvantageous specific heat conductivity λ_{th} and specific heat capacity c_p from the ranges given in [18] were used.

Table 1: TTEC thermal parameters per cable length for the four-core power cable NAYY-J 4x150mm² SE.

Parameter	Th. Resistances in $[\frac{\mathbf{K \cdot m}}{\mathbf{W}}]$			Th. Capacities in $[\frac{\mathbf{J}}{\mathbf{m \cdot K}}]$		
	$R_{th,1}$	$R_{th,2}$	$R_{th,3}$	$C_{th,1}$	$C_{th,2}$	$C_{th,3}$
Value	0.029	0.361	0.110	1457	965.9	399.7

Since the given TTEC is only valid for a four-core cable with symmetric loading on each four conductors a further adjustment is needed. In [18] a current conversion factor k was introduced for a similar NAY2Y-J 4x150mm² SE cable with the purpose to achieve the equivalent maximum temperature with either symmetric four-core conductor current I_{TTEC} for a grid situation with symmetric line loading on three conductors I_{line} and therefore no current on the neutral conductor. The conversion factor given is $k = 1.0875$ [18]. With this the heat flow $4\dot{Q}_c$ for the four-core TTEC can be calculated as given in (3), (4) and (5) from the grid situation. $R(T)$ represents the linear resistive increase of the cable over temperature in relation to a reference temperature T_{ref}, which is often 20 °C.

$$R(T) = R_0(1 + \alpha(T - T_{ref})) \tag{3}$$

$$I_{line} = k \cdot I_{TTEC} \leftrightarrow I_{TTEC} = \frac{I_{line}}{k} \tag{4}$$

$$4\dot{Q}_c = 4 \cdot R(T) \cdot I_{TTEC}^2 = \frac{4}{3k^2} \cdot R(T) \cdot I_{line}^2 \tag{5}$$

In Figure 3 the conductor temperature at the cable's datasheet ampacity of $I_{th} = 270\ \mathrm{A}$ and with $T_{outerSheat} = 40\ °\mathrm{C}$ is simulated with and without resistive increase. The initial state of the thermal capacities is set to $T_{outerSheat}$. One can see that the cable reaches its steady-state temperature after approximately two hours. Obviously, the cable with resistive increase reaches a higher temperature with $T_{max} = 70.68\ °\mathrm{C}$. Note that the time to reach T_{max} can be a useful flexibility advantageous for the grid congestion management. It is also interesting to note that the resistance of the cable increases by more than 20 % at this temperature.

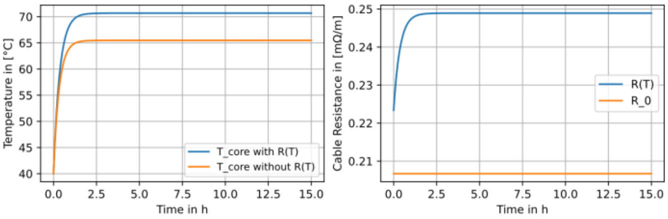

Figure 3: Cable core temperature and resistance in comparison with and without resistive increase and conversion factor. The current I_{line} is equal to the line's ampacity of 270 A.

The given model can be helpful for DSOs but the boundary conditions of $T_{outerSheat}$ as well as the fast dynamics due to the low thermal capacities are obvious limiting the usability. This is due to the fact, that the outside installation conditions are not represented in detail. To further improve the cable models researchers frequently add soil models resulting in the TTEC given in Figure 4 [15]. This also holds the possibility to add ground temperature data from 1m depth which in Germany is available by the Deutsche Wetterdienst (DWD) [19]. Since obtaining knowledge about the soil conditions is rather difficult, in this paper the authors use a dried-out soil given in DIN VDE 0276-1000 as a worst-case modelling condition. With this the cables ampacity is lowered to $I_{th} = 184\,\text{A}$, which is ≈ 68 % of the original cable ampacity, similar to the 70% DSOs of the datasheet ampacity DSOs often use for classifying a grid congestion situation.

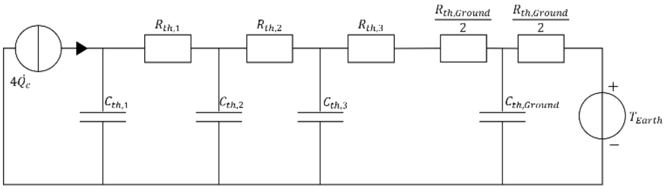

Figure 4: Simplified transient thermal circuit model of four-core buried cables and with one layer of soil.

Table 2: TTEC thermal parameters per cable length for the soil with ring shape approximation.

Cable					TTEC	
$\boldsymbol{\lambda_{th}}$	c_p	r_{inner}	r_{outer}	p	$R_{th,soil}$	$C_{th,soil}$
$\mathbf{0.4\,\frac{W}{m \cdot K}}$	$500\,\frac{\text{J}}{\text{kg} \cdot \text{K}}$	23 mm	223 mm	$1800\,\frac{\text{kg}}{\text{m}^3}$	$0.91\,\frac{\text{K} \cdot \text{m}}{\text{W}}$	$1.4e5\,\frac{\text{J}}{\text{m} \cdot \text{K}}$

The model was compared to the measurement from [18] showing significantly higher steady-state temperatures together with a lower time constant. This is due to the specific heat conductivity being much lower in this worst-case approach. With the same λ_{th} as given by the measurements the steady-state temperatures are only around 2% higher than in the measurements at again lower time constant. In comparison to the TTEC without soil model the rise time is slower but still significantly faster than the real measurements in soil showed.

3.3. *Grid congestion management*

In state-of-the-art grid congestion management systems, the two used metrics for determination of grid congestions are the current-based and voltage-based congestion. Since in chapter 3.2 a TTEC could be derived for the scenario under test, the metric of current-based congestions can be compared to a temperature-based congestion management. The low-voltage grid congestion management used in this paper is a variation from [4] using a sensitivity based curtailment calculation approach based on the German Energy Act. The flow chart is given in Figure 5. In this every minute the grid state is read from the simulation and each cable as well as node is checked for congestions. In practice, this would be achieved via a grid state estimation. Grid congestion are defined as follows:

- Current congestion: $(I_{line}/I_{th}) > 70\%$
- Voltage congestion: $V_{node} \notin [0.9V_N; 1.1V_N]$
- Temperature congestion: $T_{line} > T_{line,max} - 10$

The temperature boundary is chosen as 10 °C lower than the maximum temperature as a safety margin. In case a congestion is detected a sensitivity analysis for every active and available CCU ($P_{CCU} > 4.2$ kW) is performed, resulting in sensitivities S representing the change of the state in the congestion X via the output dX/dP_{CCU}. The sensitivities are assumed to scale linear over the available load change. Sensitivities with reasonable size, standardized to a power change of 1 kW, are chosen and a total curtailment power $P_{curtail}$ is estimated with the distance between the grid state X and the states congestion limit X_{limit}. Afterwards the total curtailment power is distributed as a percentage among the CCUs. In case a CCU reached its ensured power consumption ($P_{CCU,min} = 4.2$ kW) this is set to the limit and the remaining curtailment power needed distributed to the other CCUs.

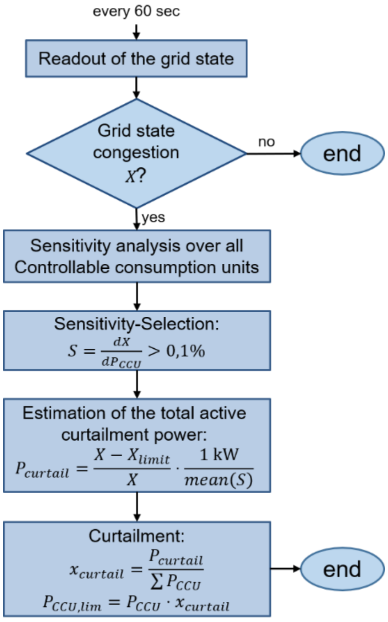

Figure 5: Grid congestion management strategy.

4. Results for the grid situation model

In Figure 6 three similar grid situations for the same, most heavily loaded cable in the grid scenario, described in chapter 3.1, are given. The figure shows the difference in the scenario for a line with PI model without TTEC, with TTEC and with TTEC with soil model. No grid congestion management is considered in this scenario. One can see that the current in all the scenarios is nearly identical and comparably high to today's situation. One can also see, that the temperature between the models varies, where the TTEC model has a boundary of 40 °C and the TTEC with ground model uses the underground temperature for the given location in depth of 1m which is around 7 °C and only slightly decreasing.

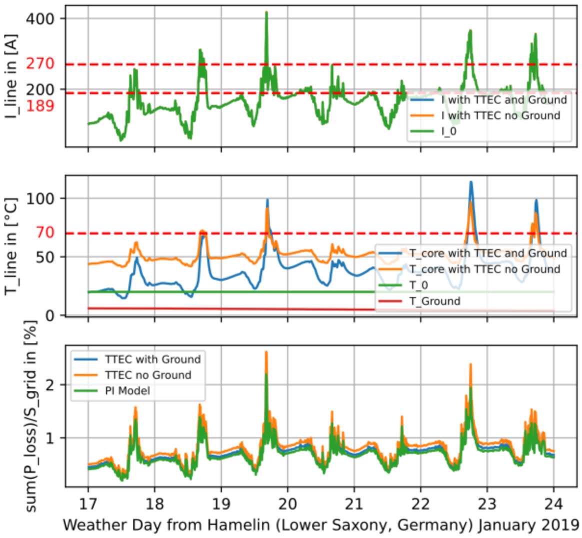

Figure 6: Comparison of Grid situation for one simulation week.

Notice, that the temperature gradient in the model with soil is increasing more rapidly, resulting in higher temperatures in high loading situations compared to the TTEC. In situations with less loading the model with soil returns to lower temperatures then the model with 40 °C boundary condition and therefore more realistic values of the resistances and losses. Both models reach a temperature of $T_{max} = 70$ °C with a $\Delta t \approx 40$ min time difference. The simulation with TTEC and soil model takes longer to reach T_{max}. It therefore provides more operational potential. The TTEC without soil assumes a static outside temperature of 40 °C, which turn out to be wrong under high loads. Since the TTEC with soil has shown before to rise significantly faster than in the measurements this is assumed to be more realistic. Another advantage is the non-static external temperature of the cables sheat. The TTEC with soil model will be used in the following comparison.

5. Results in grid congestion management

To compare both grid congestion management strategies, CBCM and TBCM, both where simulated on day 18 from the grid situation in Figure 6. Both simulations are modelled with TTEC and soil model. The results are given in Figure 7 and Figure 8. The comparison shows that the CBCM curtails all active and available CCUs over the course of the day and still does not manage to solve the congestion which is defined as 70% of the datasheet ampacity. Additionally, in comparison to the TBCM strategy the line temperature stays lower with a delta of $\Delta T_{max} \approx 2.8°C$ comparing both maximum temperatures. Now focusing on the TBCM method, one can see, that the amount of curtailment actions is lower and in a shorter time frame while still maintaining a temperature which in maximum is only moderately higher than the grid congestion managements goal of 60°C. This leads to a higher supply rate and therefore more efficient allocation of the lines current capacity. Compared to the CBCM the TBCM the number of interventions is reduced by more than 30%. In the long run the TBCM lowers possible catch-up effects and is therefore advantageous for the DSO. The drawbacks are slightly higher grid losses which occur due to the higher line temperatures but as can be seen in Figure 6 are manageable. On the other hand, the lower amount of curtailment actions is also positive for the owners of the appliances since for example the efficiency of the charging infrastructure in BEVs is lower at reduced charging rates. Finally, it should be noted that the analysis chosen here only reflects the situation in winter with a single buried cable in average soil temperature of 7 °C at a depth of 1 meter. At higher soil temperatures, for example in summer, or with multiple cables nearby the line ampacity therefore decreases.

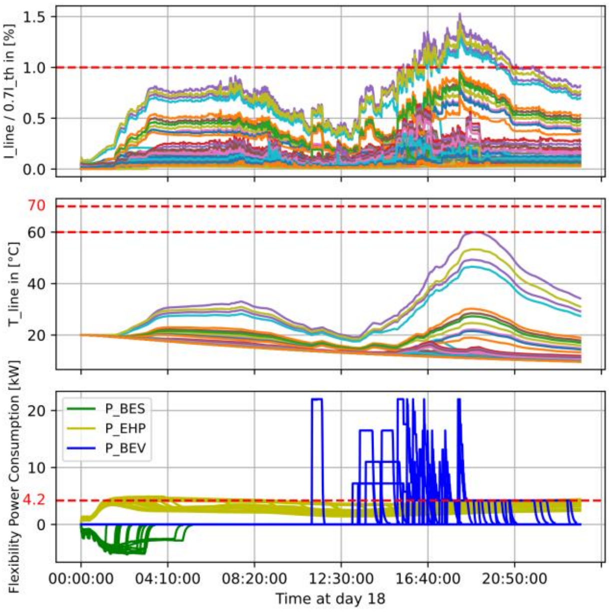

Figure 7: Current-based grid congestion management. The grid congestion condition is the line loading $I_{line}/0.7I_{th}$.

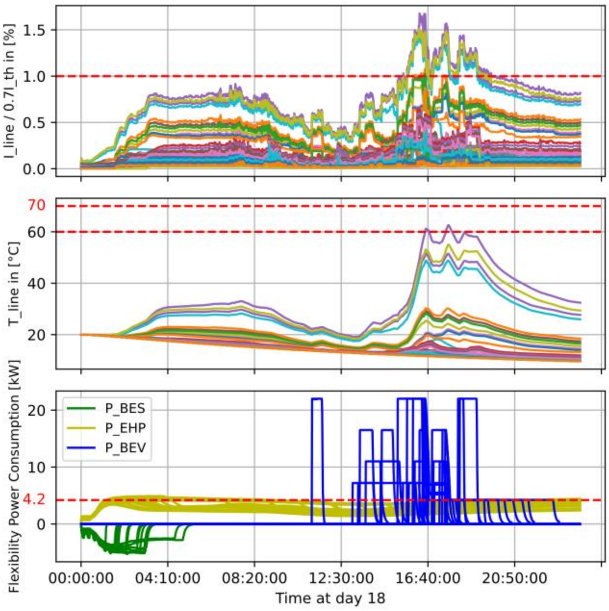

Figure 8: Temperature-based grid congestion management. The grid congestion condition is the line core temperature $T_{line} > T_{max} - 10°C$.

6. Conclusion

Modern distribution grid situations become more and more challenging for the operator. Increasing electrification and installation of DER lead to a high need for expansion. Given the high speed at which these components are being integrated into the energy system, there is a risk that expansion will proceed too slowly. Therefore, DSOs need new tools to ensure security of supply while at the same time satisfying the customers. This paper provides an analysis for the potential of dynamic cable rating by using the transient thermal behaviour of single buried power cables in low voltage grid for the grid congestion management according to the current legal framework. The authors compared based on this two grid congestion strategies, the current-based and temperature-based congestion management, on a future dynamically-modelled semi-urban low-voltage grid scenario and showed that even for a single buried cable in bad installation conditions the potential in winter scenarios offers a significant decrease in curtailment actions needed. With further information about the installation conditions the potential might significantly increase. The authors therefore see potential for predictions on soil conditions, for example using existing weather forecasts.

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