LOW-VOLTAGE GRIDS IN TRANSITION – AUTOMATIC GRID RECONFIGURATION APPROACH FOR FUTURE SMART GRIDS CHALLENGES

Daniel Herbst[1*], Robert Schürhuber[1], Mike A. Lagler[1], Ernst Schmautzer[1], Sawsan Henein[2], Paul Zehetbauer[2], Alfred Einfalt[3]

[1]Graz University of Technology – Institute of Electrical Power Systems, Graz, Austria
[2]AIT Austrian Institute of Technology GmbH – Center for Energy, Vienna, Austria
[3]Siemens AG Austria – CT RDA IOT, Vienna, Austria
**daniel.herbst@tugraz.at*

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Abstract

Current trends, such as the increasing spread of electric vehicle charging stations (EVCSs) with and without battery storage combined with heat pumps (HPs) and air conditioning systems, replacing classical heat supply, are challenging the operation of low-voltage (LV) grids. This can result in noteworthy load flow and short circuit problems in traditional existing power LV grids. A crucial example is the overloading of line segments by loads with significant simultaneity (e.g. EVCSs, HPs, air conditioning systems). Moreover, high local infeed caused by decentralised power generators (e.g. photovoltaic (PV) systems, small hydropower plants, battery energy storage systems (BESSs)) can lead to power quality problems (e.g. voltage limit violations, voltage drop, very short interruption). The project 'Power System Cognification' (PoSyCo) defines six Use Cases (UCs) to tackle these challenges. It aims to implement a 'SOFTprotection' system, which contributes to fault prevention and serves as an add-on for the conventional 'HARDprotection' (fuses, circuit breakers (CBs)). This paper presents an overview of PoSyCo's UCs but is focusing on algorithm for UC4: overload prevention by temporary meshing.

1. Introduction

Low-voltage (LV) distribution grids form the basis for supplying a large number of customer plants (CPs) in the household and commercial sectors. Because of climate policy goals and obligations, the proliferation of power plants using renewable energy sources (RES) is being pushed forward [1]. More and more decentralised plants for generation and storage of electrical energy are realised in addition to the large-scale projects already widely implemented. Furthermore, there are regulations (e.g. [2]) in force related to the expansion of electric mobility, especially battery electric vehicles (BEVs), which in turn is leading to rapid growth in the required charging infrastructure. RES based distributed generation and electric vehicle charging stations (EVCSs) are very much integrated in the low-voltage distribution grid. This results in increasing challenges for the LV grid, mainly due to bidirectionality and the extent of current resp. load flows. Depending on the national implementation of the relevant European Union (EU) directives (e.g. [3]), the formation of regional or local energy communities may intensify this development. Historical load-dominated planning criteria are losing their validity and – for economic reasons – there is a desire to operate low-voltage grids closer to their natural limits. In the course of the project PoSyCo (Power System Cognification), a broad-based project consortium from research and industry, together with a distribution system operator (DSO), analyses these new requirements from different perspectives. Innovative solutions will be developed to guarantee personal and plant protection as well as safety of supply to ensure the transition from a conventional LV grid to a more flexible Smart Grid. PoSyCo aims to implement a 'SOFTprotection' system, which contributes to fault prevention and serves as an add-on for conventional 'HARDprotection' (fuses, circuit breakers (CBs)). Therefore, six Use Cases (UCs) were defined to tackle these challenges in the project. This paper focuses on PoSyCo UC4 on "overload prevention by temporary meshing". The algorithm developed for this purpose is shown, as well as initial test and simulation results are presented.

2. Methodology

2.1. Approach by using PoSyCo's Use Cases

During the initial project phase, six Use Cases (UCs) for implementing an integrated SOFTprotection concept were defined and elaborated according to the IEEE 29148-2018 standard [4]. Figure 1 shows the basic overview of UC0 to UC5 combined with their integration into the framework of the physical, information & communication technology (ICT), and process dimension as well as in the three stages aggregation, aggregation & action, and aggregation & action & adaption. The elaborated UC descriptions [5]

form the basis for developing methods and algorithms to realise the SOFTprotection system.

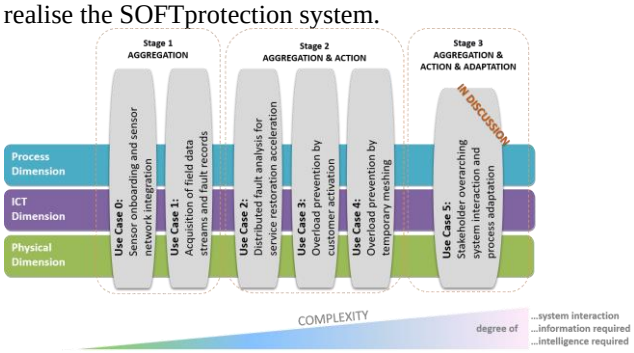


Fig. 1 Overview of PoSyCo's Use Cases

The following six Use Cases are established in the course of the PoSyCo project:

- UC0 – Sensor onboarding and sensor network integration
- UC1 – Acquisition of field data streams and fault records
- UC2 – Distributed fault analysis for service restoration
- UC3 – Overload prevention by customer activation
- UC4 – Overload prevention by temporary meshing
- UC5 – Stakeholder overarching system interaction and process adaptation

This paper is focusing on UC4, which investigates the use of remotely controlled switching devices (such as circuit breakers) to prevent possible local line segments overloading by temporary meshing of LV sub grids, see also [6-7].

2.2. *Methods and Concepts*

Based on the elaborated UC1 and UC2 related concepts as well as methods for the localisation of pending overload situations (like the Show Case in Figure 2) and faults are developed. For this purpose, data aggregated by the SOFTprotection system is analysed according to specific criteria. Examples for this can be the location-dependent violation of an individual voltage band ($V < V_{\min}$ or $V > V_{\max}$) or of a corresponding overcurrent value ($I > I_{\max}$) at certain lines over a predefined time period.

After detecting a state not conforming to normal operation, the affected low-voltage sub grid is examined in detail. First, the sub grid's load flow calculation is used to decide if further action is necessary. If this is the case, e.g. due to an overload of individual equipment, a promising action must be chosen to return to non-critical (normal) operation. This can be achieved by one of the following measures resp. solutions (Figure 2) under appropriate conditions (e.g. availability of adequately dimensioned cables incl. remotely controllable protective elements, applicable grid topologies, controllable customer systems):

- Temporary utilisation of other individual sections or components of the LV grid under appropriate conditions (e.g. planned reserve capacities)
- Grid-related behaviour of customer systems, e.g. controlled EVCSs, battery energy storage systems (BESSs) or heat pumps (HPs)
- Temporary meshing as well as reconfiguration of individual sections of LV grids in order to achieve a more consistent load flow, whereby the prerequisite for the further function of conventional protection (e.g. sustaining the selectivity of all fuses) has to be fulfilled

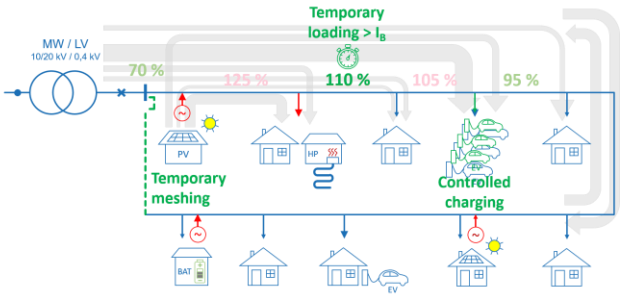


Fig. 2 Show Case – Local Overload Situation: scenario tomorrow with possible solution [8]

3. Developed Concepts

As mentioned in the introduction, modern LV grids are highly penetrated with distributed RES like PV plants combined with localised high power EVCSs or HPs. This situation of decentralised feed-in in one node and high power demand in a neighbouring node can lead to overload situations in line segments between the nodes, which are not necessarily detected by the primary protection devices (e.g. fuses, circuit breakers) next to the distribution transformer (DTR). The example in Figure 2 shows a situation where the LV line is partially overloaded in a range of 105 % to 125 %. One possible solution to prevent this partially overloaded LV line is 'temporary meshing', mentioned in section 2.2.

3.1. *Switching Management Module*

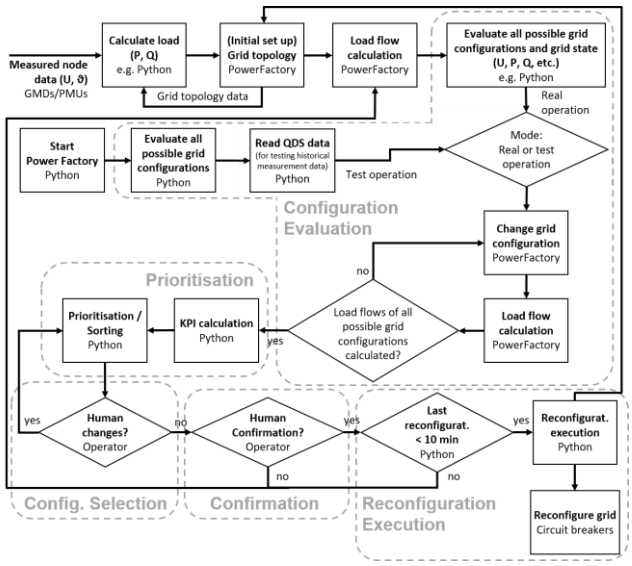


Fig. 3 System Overview of Switching Management Module (SMM) and its relationships [8-10]

To implement this temporary meshing functionality an individual method is developed allowing an automated grid reconfiguration execution. The core of the concept is

the so-called Switching Management Module (SMM), which consists of the following five sub-modules: Configuration Evaluation, Prioritisation, Configuration Selection, Confirmation and Reconfiguration Execution. A corresponding system overview of the basic concept, as well as its functionality, is shown in Figure 3.
The following subsections describe the basic initialisation (pre-settings, parameter) of the system and the five mentioned sub-modules of the SMM regarding their sequence and their functionality.

Initialise automatic reconfiguration: After the first SMM system start by the operator the whole parameter and pre-settings, essential to run the system, are initialised. This dataset contains the basic/default settings like:

- Optimisation objective and priority order (e.g. minimise losses, relieve/unburden a device).
- Switching frequency/strategy.
- Trigger/threshold levels suggested for reconfiguration (e.g. voltage, current, power, cos(φ), temperature).

Configuration Evaluation: SMM starts with evaluating all possible grid configurations out of the existing grid topology together with all its corresponding load flow results. Thereby the following sequence is considered:

- Availability check of installed devices to execute a grid reconfiguration (e.g. available lines, circuit breaker).
- Evaluate possible grid configurations (binary variation of all existing switches).
- Load flow calculation of evaluated grid configurations.

Prioritisation: After the evaluation of all possible grid configurations they are sorted based on the initially defined pre-settings and can be, e.g. based on

- the various grid configurations associated load flow results (e.g. to reduce overload situation, to minimise losses) or
- other parameter data (e.g. to relieve a device).

Configuration Selection: Based on the derived prioritisation, the operator chooses a specific grid configuration based on two principal options:

- Automatic selection of a grid configuration based on the highest priority determined by the SOFTprotection system.
- Manual selection of a grid configuration determined by the operator with expert knowledge of working processes and workflows, e.g. based on planned maintenance work or other reasons.

Confirmation: To designate a responsible person for the system's automatic switching execution, the operator must confirm the reconfiguration procedure.

Reconfiguration Execution: After the operator's confirmation, the SOFTprotection system automatically reconfigures the LV grid by sending specific switching commands to the affected circuit breaker(s) – assuming that such will exist in the future. In order to avoid unsupplied customers, a 'make-before-break' routine must be implemented.

4. Results

As a first step, the developed SMM-algorithm is tested with various LV test grids for different scenarios.

4.1. Typical urban LV test grid

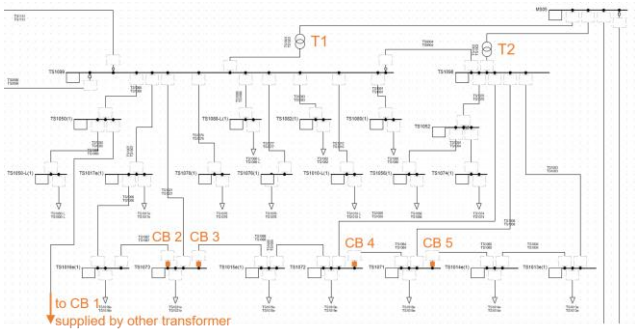


Fig. 4 Seestadt Aspern, sub grid TS 10 [8-10]

Beside other test grids the outstanding Smart City Testbed 'Seestadt Aspern' in Vienna offers a perfect example for a radial, urban LV Smart Grid. Not only the topology and the assets are well-documented but due to almost full coverage with measurement equipment, a perfectly sufficient amount of measurement data is available. This LV grid is chosen as the preferable test grid due to its topology, which offers the possibility to perform realistic tests for automatic reconfiguration procedures. The overall grid consists of 12 substations with 24 transformer units 20/0.4 kV, ~15 km cable and more than hundred residential customers. For the SMM algorithm's first testing purposes, the DTR area 'TS10' (630 kVA, 20/0.4 kV, see Figure 4) is prepared. This sub grid consists of a total cable length of 1.58 km and supplies 17 residential customers at 22 nodes/terminals via 21 lines through two main feeders.

4.2. Simulation Scenarios

Mainly two scenarios are defined for simulations and testing the developed algorithm:
Scenario I: which is the basic grid scenario

- 70 % of load nodes (LNs) have PV (nominal power is 56 % of respective load (RL)).
- 40 % of LNs have EVCS (40 % of RL).
- 40 % of LNs have HP (25 % of RL).
- 60 % of PV are PV-storage (40 % of RL).

Scenario II: is the same as scenario I but without any PVs (distributed generation).
A list of most loaded elements (lines) with the highest occurrence is defined by running quasi-dynamic simulation (QDS) in the corresponding LV grid over one year with a 15 minutes' time interval. The nominal values of RL are obtained using a feeder load scaling approach which distributes the aggregated measurements to all loads according to their nominal power values and time characteristics. The time series used here for loads, PV, EV, HP and PV-storage are generated based on the 'SimBench' [11] dataset in order to derive normalised profiles. The developed algorithm is used to identify the

meshing resp. reconfiguration opportunity that is most effective in relieving the overloaded line.

4.3. *Key Performance Indicators for Prioritisation*

The results of the QDS simulations provide the maximum utilisation values of individual operating devices during one year. The different results of the load flow calculations of the individual grid configurations are prioritised accordingly. This ranking or sorting is done using the following six key performance indicators (KPIs):

- KPI_1 – *voltage limit violations:* number of voltage limit violations, normalised to the highest occurring number of violations related to all grid configurations.

$$KPI_{1,j} = k_1 \cdot \frac{\mathrm{card}(A_{i,j})}{\max\limits_{j=1,\dots,v_n}\left(\mathrm{card}(A_{i,j})\right)} \quad , \quad \begin{matrix} i = 1,\dots,T_n \\ j = 1,\dots,v_n \end{matrix} \tag{1}$$

with $\mathrm{card}(A_{i,j})$ …cardinality/number of set $A_{i,j}$

and $A_{i,j} = \{T_i | V_{T_i} < V_{\min} \vee V_{T_i} > V_{\max}\}$

- KPI_2 – *line loading violations:* number of overloaded lines, normalised to the highest occurring number of violations related to all grid configurations.

$$KPI_{2,j} = k_1 \cdot \frac{\mathrm{card}(B_{l,j})}{\max\limits_{j=1,\dots,v_n}\left(\mathrm{card}(B_{l,j})\right)} \quad , \quad \begin{matrix} l = 1,\dots,L_n \\ j = 1,\dots,v_n \end{matrix} \tag{2}$$

with $\mathrm{card}(B_{l,j})$ …cardinality/number of set $B_{l,j}$

and $B_{l,j} = \{L_l | LineLoading_{L_l} > LineLoading_{\max}\}$

- KPI_3 – *total grid losses:* value of total grid losses, normalised to the maximum occurring overall grid losses related to all grid configurations.

$$KPI_{3,j} = k_3 \cdot \frac{S_{\mathrm{LossGrid},j}}{\max\limits_{j=1,\dots,v_n}\left(S_{\mathrm{LossGrid},j}\right)} \tag{3}$$

- KPI_4 – *line overload reduction:* relief of the originally most loaded line (according to the initial grid configuration QDS result), normalised to the maximum occurring line loading related to all grid configurations.

$$KPI_{4,j} = k_4 \cdot \frac{\dfrac{LineLoading\left(L_{\mathrm{LineLoading}_{\mathrm{QDS,max}}}, j\right)}{LineLoading_{\mathrm{QDS,max}}}}{\max\limits_{j=1,\dots,v_n}\left(\dfrac{LineLoading\left(L_{\mathrm{LineLoading}_{\mathrm{QDS,max}}}, j\right)}{LineLoading_{\mathrm{QDS,max}}}\right)} \tag{4}$$

- KPI_5 – *distance of circuit breaker:* distance between the originally most loaded line and the affected switch(es) / circuit breaker(s).

$$KPI_{5,j} = k_5 \cdot \frac{\min\left(\mathrm{distance}\left(CB, L_{\mathrm{LineLoading}_{\mathrm{QDS,max}}}\right)_j\right)}{\max\limits_{j=1,\dots,v_n}\left(\min\left(\mathrm{distance}\left(CB, L_{\mathrm{LineLoading}_{\mathrm{QDS,max}}}\right)_j\right)\right)} \tag{5}$$

- KPI_6 – meshing: 0 if sub grid is in radial structure, 1 if sub grid is meshed.

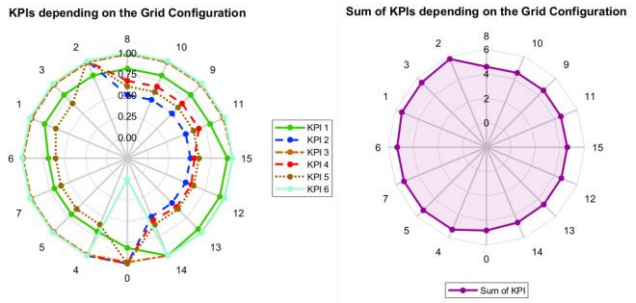
$$KPI_{6,j} = k_6 \cdot \begin{cases} 1 & \text{if} \quad V_j \text{ is meshed} \\ 0 & \text{if} \quad V_j \text{ is radial} \end{cases} \tag{6}$$

For KPI_n, $n \in \{1,2, \dots, 6\}$:

k_n	Weighting factor for each KPI
T_i	Terminal
T_n	Number of terminal
V_{Ti}	3-phase RMS voltage at terminal T_i
$V_{\min}$	Lower voltage limit value for V_{Ti}
$V_{\max}$	Upper voltage limit value for V_{Ti}
v_j	Variation, grid configuration
v_n	Number of variations, grid configurations
L_l	Line
L_n	Number of lines
CB	Circuit breaker, switch

4.4. *Simulation Results of SMM*

The individual grid configurations' prioritisation is carried out through an automated, Python based evaluation using the already described KPIs. Figure 5, e.g. shows the SMM results for a LV test grid (section 4.1) enriched by scenario I-a (Figure 5a with PV) and I-b (Figure 5b without PV) from section 4.2. The chart can be interpreted as a sensitivity analysis where a low value (in the range of 0) of a KPI means little negative impact and consequently a high value (in the range of 1) means a great negative impact.



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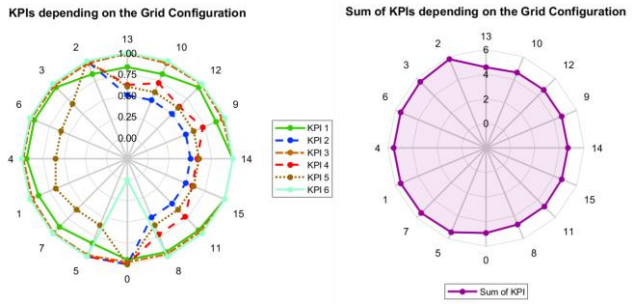


b

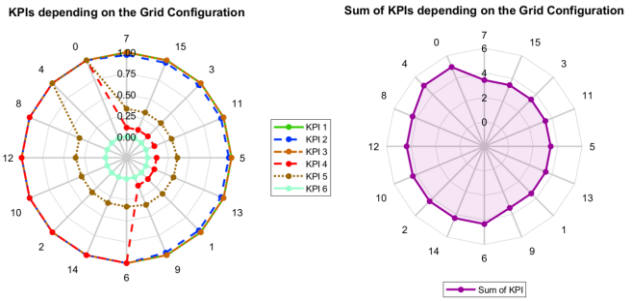
Fig. 5 SMM simulation results of Aspern TS10 sub grid using CB 2 to 5 sorted by priority: (a) scenario I-a (with PV), (b) scenario I-b (without PV)

As an example, in Figure 5a (left), KPI_6 (meshing) shows that only configuration 0 lead to a value of $KPI_6 = 0$. Further, for just the half of the variations (8, 10, 9, 11, 15, 12, 13, 14) KPI_2 is in the range of 0.5 which means that there are less line loading violations expected than with the other variations.

Figure 5a (right) shows the overall sum of KPIs sorted in descending order, corresponding to the different grid configurations' prioritisation. As there have not been any further discussions with DSO regarding individual weighting factors (WF), the WF of each KPI is set to 1.0. Therefore, the sum of all KPIs can only reach a maximum value of 6.0. The variations 0 (all circuit breakers are open) and 15 (all circuit breakers are closed) are not preferable regarding the KPI calculation procedure, which suggests that the reconfiguration approach leads to an improvement of the initial situation. Variation 8 (only

circuit breaker CB 2 from Figure 4 is ON) is determined as the best case or optimal grid configuration.

In comparison, Figure 5b (right) shows a changed prioritisation due to the used scenario I-b (without PV, therefore with a changed load situation), whereby grid configuration 13 instead of 8 is determined as the best.



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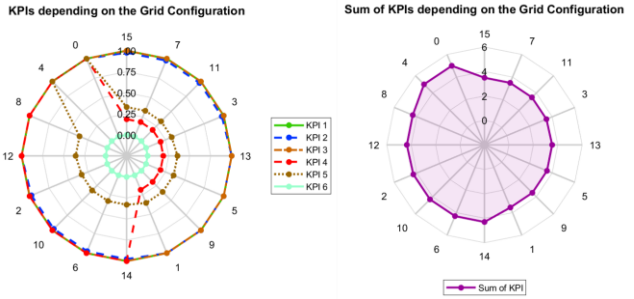

b

Fig. 6 SMM simulation results of alternative test grid [12] using four CBs sorted by priority: (a) scenario II-a (with PV), (b) scenario II-b (without PV)

Figure 6 shows the SMM results for a further LV test grid (generated Kerber grid, [12]) enriched by two scenarios called II-a (Figure 6a with PV) and II-b (Figure 6b without PV). Due to the entirely different grid topology compared to Aspern TS10 the KPI calculations lead to different results. Comparing the scenarios II-a and II-b, the resulting prioritisations differ only marginally from each other. For example, this means that the four first-best variations from scenario II-a (7, 15, 3 and 11) also represent the first-best variations in scenario II-b, only in a slightly different order (15, 7, 11 and 3).

5. Conclusion

The developed SMM algorithm (prioritisation of grid configurations/variations using KPIs) can be verified by comparing its results (grid configurations with the highest priority) with separate QDS analyses of the individual variations. In almost all simulations it can be seen the overall performance of the test grids improves accordingly after an automatic reconfiguration measure. The post-processing results showing, e.g. a decreased loading of transformer T1 (Figure 4) from 58 % to 48 % by reconfiguring the system by closing all five CBs.

The algorithm is to be subjected to an SRA (Scalability and Replicability Analysis) concerning other test grids. Initial hardware-related tests are planned using a laboratory setup (specially designed for that purpose) with four circuit breakers.

6. Acknowledgement

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7. References

[1] Republic of Austria - Federal Ministry for Sustainability and Tourism, Republic of Austria - Federal Ministry for Transport, Innovation and Technology, '#mission2030 - The Austrian Climate and Energy Strategy', Vienna/AT, 2018

[2] Regulation (EU) 2019/631 of the European Parliament and of the Council: 'setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011', 2019

[3] Directive (EU) 2019/944 of the European Parliament and of the Council: 'on common rules for the internal market for electricity and amending Directive 2012/27/EU', 2019

[4] ISO/IEC/IEEE 29148: 'ISO/IEC/IEEE International Standard - Systems and software engineering -- Life cycle processes -- Requirements engineering', 2018

[5] Project consortium PoSyCo, 'Deliverable D2.1 - Defined Use Cases and Required Components', Vienna/AT, 2020

[6] Herbst, D., Lagler, M., Schuerhuber, R., et al.: 'Anforderungen an Niederspannungsnetze und deren Lösungsansätze am Beispiel des Projekts PoSyCo', 16. Symposium Energieinnovation, Graz/AT, 2020

[7] Einfalt, A., Brunner, H., Prüggler, W., et al.: 'Efficient Utilization Of Existing Grid Infrastructure Empowering Smart Communities', IEEE ISGT NA, Washington, DC /USA, 2020

[8] Herbst, D.: 'A contribution to new approaches in low voltage protection (working title)', PhD thesis, Graz University of Technology, in progress

[9] Project consortium PoSyCo, 'Deliverable D3.1 – Report on developed concepts', Vienna/AT, 2020

[10] Project consortium PoSyCo, 'Deliverable D3.2 – Mathematical models are developed, tested and reported', Vienna/AT, 2021

[11] 'SimBench – benchmark data set for grid analysis, planning and operation', https://simbench.de/en/, accessed 14 February 2021

[12] 'Kerber networks', https://pandapower.readthedocs.io /en/v1.3.0/networks/kerber.html, accessed 14 February 2021