Intelligent Power Routing in Low-Voltage Grids for Efficient Utilization of Line Capacities

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Abstract

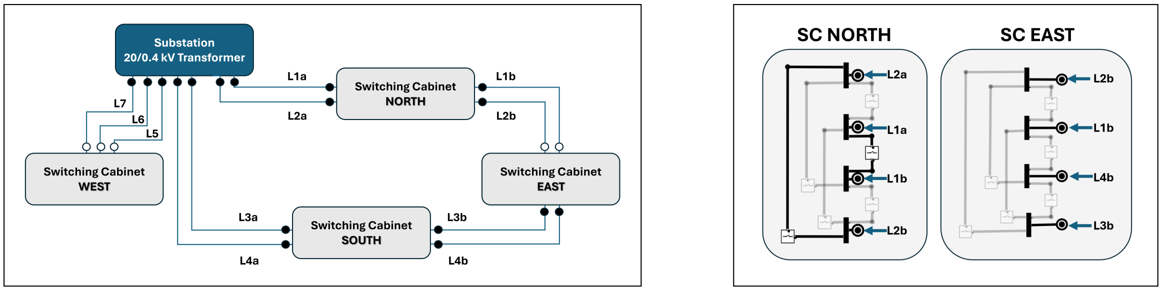
The increasing integration of photovoltaic systems (PV), electric vehicles (EV), and heat pumps (HP) is expected to cause local bottlenecks, particularly at the lowest voltage levels, which could jeopardize supply security. A possible quick and temporary remedy could be the installation of a power flow controller at selected grid points, which enables the routing of power flow. This contribution investigates potential remedies in a real-life suburban low-voltage power grid and discusses various options, including power routing.

***K*eywords** Power Flow Controller · Power Routing · All Electrical Society · Low-Voltage Grid · Congestion Management

1 Introduction

Electrical distribution grids worldwide are facing new challenges, primarily due to the ongoing transition of the power system, driven by the increasing integration of renewables. The lowest grid levels are undergoing a significant change with the increased installation of photovoltaics (PV), heat pumps (HP), and electric vehicles (EV). If no measures are taken by the distribution system operator (DSO), this development can lead to grid bottlenecks and jeopardize a reliable energy supply [1].

To address this challenge, strategic reinforcement and expansion of the grid at specific locations can provide a solution, though such infrastructure improvements require significant financial investment [1], [2]. Generally, power flow controllers (PFC) have the technical capability to alleviate this problem. PFCs represent a controlled voltage source that can establish a complex voltage drop between two grid points, thereby governing the magnitude and direction of the power flowing between the two grids [3]. The power shift between neighboring grid areas could then decrease the loading of electrical grid equipment, such as cables, transformers, overhead lines, and switchgears. In practice, various technical approaches exist for implementing a PFC. One possible solution is the back-to-back converter (B2B), which is especially suitable for shifting active power [3]. This contribution demonstrates how a PFC in a low-voltage (LV) grid achieves a more uniform load distribution among the feeders, thereby alleviating a bottleneck.



(a) Structure of the studied part of the LV grid.

(b) Model of the switching cabinets North and East.

Figure 1: Structure of the study area with one substation containing a 20/0.4 kV transformer and four switching cabinets (SC). The topology illustrates the Base Scenario, where the LV grid operates in radial mode.

2 Problem description

In our previous study [4], we examined a future energy systems scenario, which is characterized by a very high number of active prosumers in the low-voltage (LV) grid given future 100% renewables-based energy systems. The so-called All Electrical Society (AES) was analyzed using data modeling methods that describe the power consumption behavior and power generation patterns through time series for 78 prosumers in a low-voltage grid. Each prosumer is fully equipped with a rooftop photovoltaic (PV) system, two battery electric vehicles (BEVs), and a heat pump (HP). Quasi-dynamic simulations of the LV grid under stress conditions with high consumption and production are employed to assess network utilization and analyze congestion situations. The study on the AES scenario revealed that the deployed electrical infrastructure of the LV grid is heavily overloaded, affecting both the transformers and the respective power lines.

3 Model description

The grid model comprises a grid section supplied from a Lahmeyer substation featuring a 20/0.4 kV 3-phase transformer (0.63 MVA SGB DTTHL) and seven radial feeders. The underground cables along the roads are of type NAYY 4x150SE 0.6/1 kV with a current rating of 0.27 kA, whereas the residential unit connection cables are of type NAYY 4x35 with a current rating of 0.119 kA (1 kV). The cable and transformer specifications are converted into the per-unit system and dimensioned according to the lengths of the individual cable sections using the GIS information. Each of the 78 grid customers acting as so-called prosumers draws power from the higher-level grid and feeds in PV power. The residual load of each prosumer in the model consists of electricity generation with a maximally expanded PV system, two electric cars, a heat pump, and regular electricity consumption. Details on the data modelling are given in [4]. For the present study, we further refined the residual load data.

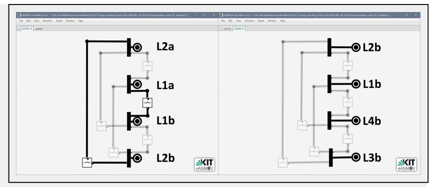
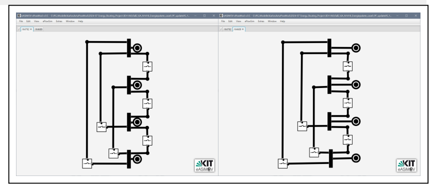
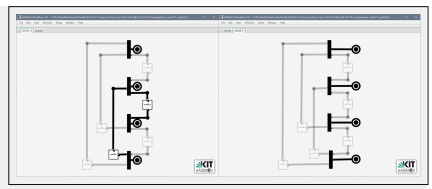
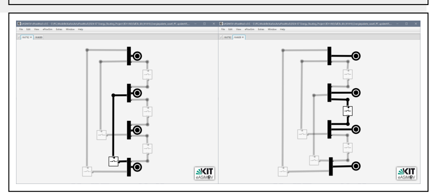
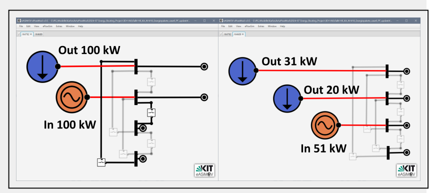
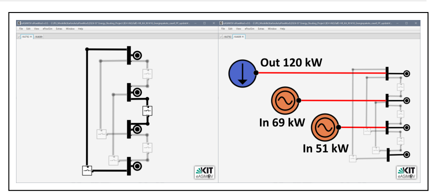
In the selected LV grid portion, we have four switching cabinets (SC), which are referenced by their compass directions. For the Base Scenario, the SCs for East and West are open, allowing us to have a radial LV grid. The switches at the North and South SC are closed, allowing all underground cables from west to east to be interconnected. This means that the cable segments L1a and L1b, as well as L2a and L2b, are passed through. Note that the model contains two underground cables on each street. The structure of the LV grid is shown in Figure 1a, and the two SC for North and East are displayed in Figure 1b, whereas the gray line indicates inactive connections.

4 Methods

Using power electronics devices, we present a method for routing power within a low-voltage (LV) grid. This study examines the potential for mitigating the load on lines by drawing power from overloaded lines and redistributing it to lines with available capacity. In this study, we examine the loading of lines and the voltage values. The aim is to minimize the line loadings and bring the voltage values into the valid range. Starting with the Base Scenario, we experimented with switching the various topology configurations. As a final step, we actively emulated the electronic devices by removing power from the system at the switching cabinets and injecting it into a neighboring cable within the cabinet.

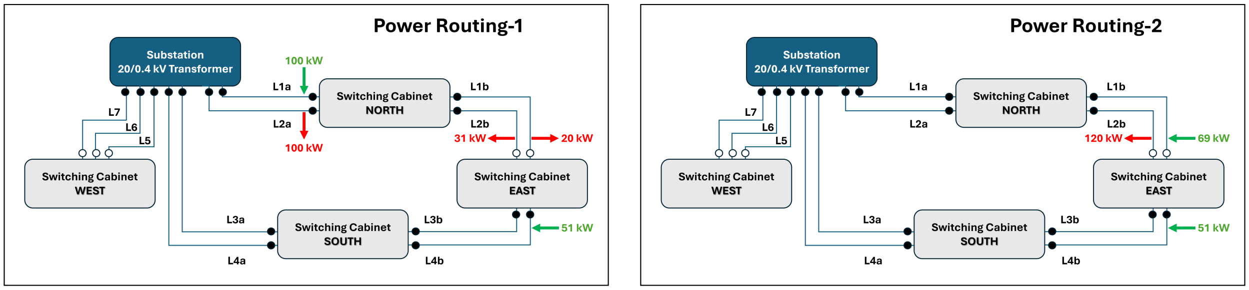
Starting from the Base Scenario in case 1, we conducted heuristic experiments for cases 2, 3, and 4 to reduce the line loadings. For power routing cases 5 and 6, we conducted an in-depth analysis of power flows on the lines to determine the necessary power amount and the specific locations for redirecting the power flows to mitigate line loadings. In detail, we conducted the experiments given in Table 1.

Table 1: All studied cases with description and the switching state in SC North and East. The Base Scenario in case 1 shows the assignment of the line names to the switching ports, as also shown in Figure 1b.

Id	Case Name	Description	SC North and SC East Switching States
1	Base Scenario	The grid is operated in radial mode, which is accomplished by opening the switches in SC East and West. The SC North is passing through the cables L1 and L2 by interconnecting the segments L1a/L1b and L2a/L2b. SC South passes the cables L3 and L4 (see Figure 1a).	
2	FullMesh	All switches are closed, and the grid is operated in full meshed mode.	
3	Cable-Isolation	We isolate L2a; for this, L1b and L2b were connected to L1a.	
4	Cable-Isolation & Crossed	Isolation of L2a with additional crossed interlinking at SC East.	
5	Power Routing-1	The switching states are as in case 1: Base Scenario. Power is drawn and injected into other lines at two SCs. In detail, within the SC North, we draw 100 kW from L2a and inject the same amount into L1a. Additionally, we draw 31 kW from L2b and 20 kW from L1b, and inject 51 kW into L4b at SC East. See Figure 2a for a schematic representation and Appendix Figure 4 for the full grid model.	
6	Power Routing-2	The switching states are as in case 1: Base Scenario. Power is drawn and injected into other lines only at SC East. Here, we draw 120 kW from L2b and inject 69 kW into L1b and 51 kW into L4b. See Figure 2b for the schematic representation and Appendix Figure 5 for the full grid model.	

5 Results

Figure 3 shows the comparison of line loadings for selected cases. To enable comparability of different color scales, we uniformly set the colormap range to 0%-160%. The most problematic cable segment is L2a. In the base scenario, we have a maximum line loading of 153,07%. With the fully meshed operation, the line loading can be reduced to 135,09%. In case 3 we isolate Line L2a, to disable additional loading from the power injection or power load from the prosumers at L2b, which results in further reduction of the loading. The goal of reducing the line loading below 100%



(a) Case 5: Power Routing method at two SCs.

(b) Case 6: Power Routing method at one SC.

Figure 2: Power Routing is accomplished by drawing power from the line using a load element, and injecting it on another line using a generator element.

is accomplished with active power routing in case 5 and 6, where we draw power from the system and inject it into another cable.

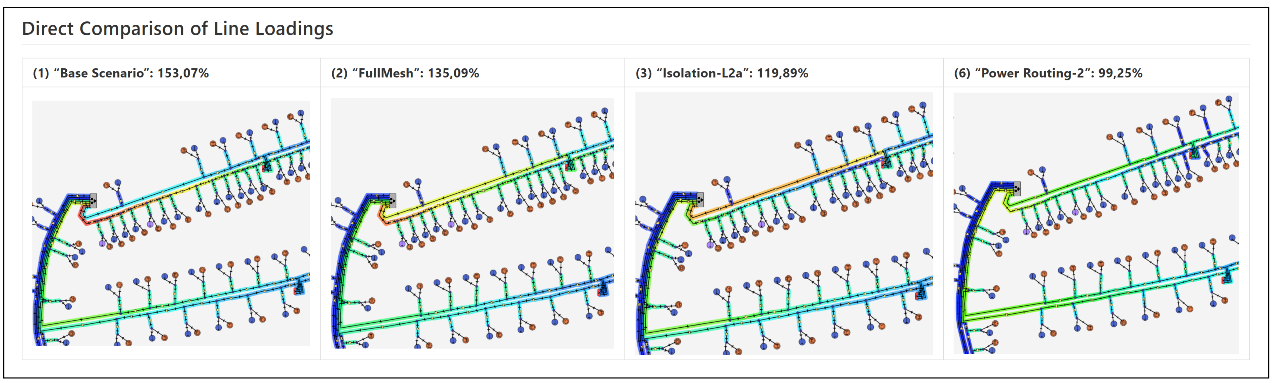


Figure 3: A direct comparison of line loadings for selected cases 1, 2, 3, and 6. With the power routing method, the reduction of the maximum line loading from 153 % to 99 % could be achieved.

The Table 2 summarizes all cases with the resulting maximum line loadings and maximum voltage values in pu. A graphical display of the results for each case is given in Appendix A, showing switching states in the SCs, along with the resulting loadings and voltages. Note that we set fixed colormap limits for comparability.

Table 2: All cases and with the resulting maximum line loadings in % and maximum voltage values in pu.

Id	Case Name	Max. Line Loading	Max. Bus Voltage
1	Base Scenario	153.07 %	1.087 pu
2	FullMesh	135.09 %	1.001 pu
3	Cable-Isolation	119.89 %	1.087 pu
4	Cable-Isolation & Crossed	106.25 %	1.133 pu
5	Power Routing-1	99.24 %	1.10 pu
6	Power Routing-2	99.25 %	1.10 pu

6 Discussion

The results in the previous section compare various options for mitigating the overload on sections of a power cable. Switching the network from a radial to a fully meshed configuration (case 2) was unable to reduce the overload to within the nominal rated value of the cable. Isolating a section of the feeder and connecting it to another feeder (cases 3 and 4) was more successful in reducing the load at the bottleneck, although not within the rated value. Case 4 resulted in an increase in voltage to values exceeding those compliant with the standard DIN EN 50160:2020-11, as published in [5]. Two different possibilities for power routing (cases 5 and 6) were able to bring the loading to within the rated cable value, and the voltage was just within the compliance limits of the standard mentioned above.

Moving from a radial configuration to a meshed one has drawbacks from a network operations perspective. Network protection systems become more complicated due to the presence of parallel paths for short-circuit currents. This could mean an outage at the station, since all feeders are meshed and not just a single feeder, as in a radial configuration. Cases 5 and 6 need to be compared from an economic perspective (single entity with greater power vs. smaller power from multiple components), but this was not the focus of our investigation. Further work will be conducted on how the PFC determines its setpoints. A possible scenario could a master controller at substation level which distributes setpoint to its slave PFCs. Another interesting possibility would be the possible estimation of network state using only the local electrical variables at the coupling points of a PFC.

7 Conclusion

For an "All Electrical Society" scenario with a high number of prosumers in a future 100 % renewables-based low-voltage (LV) grid, our analysis revealed significant overloading of the LV grid's electrical infrastructure, affecting transformers and power lines, underscoring a key challenge for future electrified distribution networks.

This paper presents a method for routing power within a LV grid to mitigate load on lines by drawing power from overloaded lines and redistributing it to lines with available capacity, utilizing power electronics devices. The methodology presented is superior to the heuristic methods employed by experts. For the analyzed LV grid, the registered maximum line overloading of 153.07 % for the reference Base Scenario with a radial-operated grid was successfully reduced to 99.25 % with valid voltage ranges using active power routing with power electronics. In contrast, heuristic methods only achieve line loading values above 100 %, but these usually cause voltage problems.

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A Appendix

The following images show the power flow simulation results for the presented power routing method.

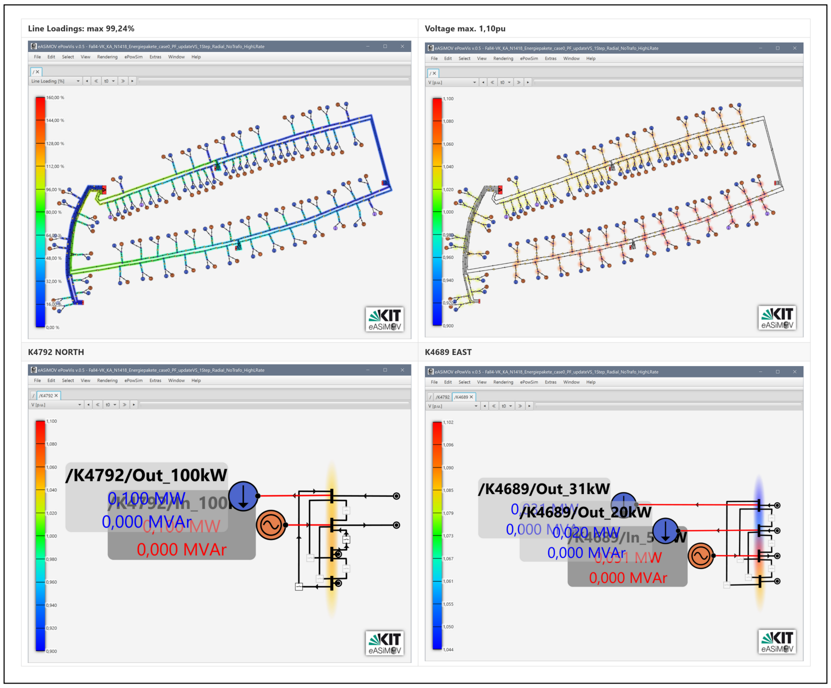

Figure 4: Case 5 - Power Routing-1: Power is drawn and injected into other cables at *two* SCs.

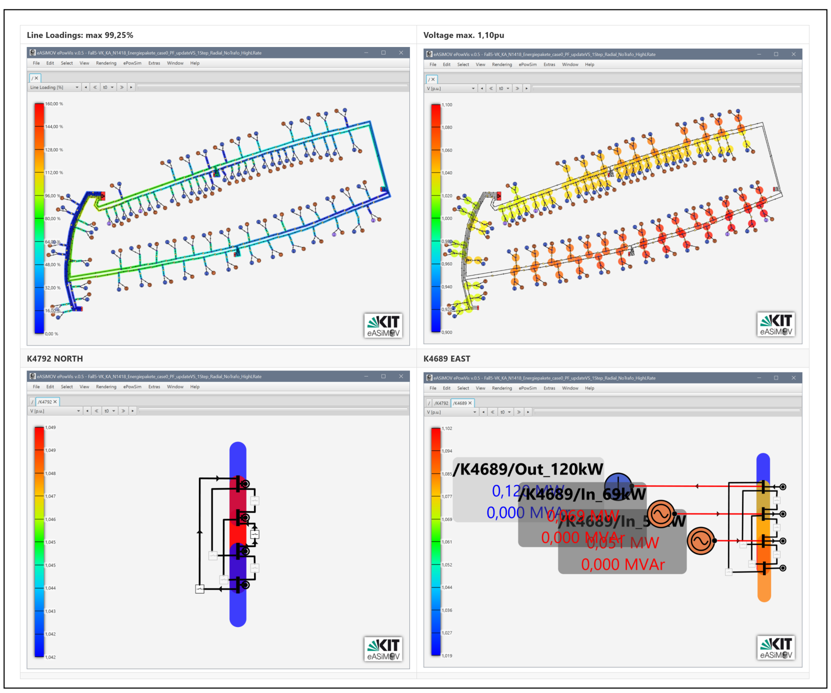

Figure 5: Case 6 - Power Routing-2: Power is drawn and injected into other cables at *one* SC.