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Increased renewable hosting capacity of a real low-voltage grid based on continuous measurements -- Results from an Actual PV Connection Request

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Abstract. The distributed generation and new load patterns caused by the energy transition are putting strong requirements on the distribution grids. The traditional worst-case planning approaches in the low-voltage grid will lead to excessive grid extensions. Through a digital twin of the low-voltage grid, the true status of the physical grid is used to detect grid bottlenecks and therefore allows to match grid investments to actual needs in the distribution grid. This paper presents preliminary results from a real case study for the novel planning approach which lead to an accurate picture of grid hosting capacity, which is a major step forward from previously used worst case assumptions.

Keywords: Low-voltage grid, hosting capacity, digital twin, grid measurements.

1 Introduction

The PV hosting capacity is the maximum amount of PV that can be added to a distribution grid before the distribution system operator (DSO) needs to upgrade resources like transformers or cables [6, 7]. Knowing the hosting capacity is essential for successful and resource-efficient grid operation. Currently, the industry-standard to determine hosting capacity is a conservative baseline method that performs a simplified grid calculation for the worst-case where all PVs generate with peak power and no consumption is present. In a current real-world scenario at Stadtwerke Landau an der Isar, this worst-case planning method required to exchange the transformer as the total PV capacity installed was exceeding the total transformer capacity. In this paper, we propose a grid planning approach that is based on measurement data and on a digital twin that performs a load-flow analysis to derive non-measured voltages and cable and transformer loadings. The analysis of the historical measurements showed in the given usage scenario, that the transformer loading was not in a critical state during the last year of operation where a maximum loading of 70 % was identified, and that true voltages in operation were quite far from the required boundaries. Performing the novel grid planning based on the digital twin showed a strongly increased hosting capacity. Consequently, the DSO did not have to replace the transformer and cabling. A subsequent continuous monitoring of the grid allows to automatically identify when a new situation arises from significantly changing loading patterns, as e.g., caused by the increased presence of EV charging.

2 Field Trial Setup and PV Connection Case

The case study in this paper is based on a low voltage grid of the Stadtwerke in Landau and der Iar (StwLan) in Germany. In this section, we describe the architecture of this grid, the digital twin built up for this study, as well as the PV connection request of the DSO the case study in this paper is based on.

2.1 Field Trial Architecture: Topology and Measurement Points

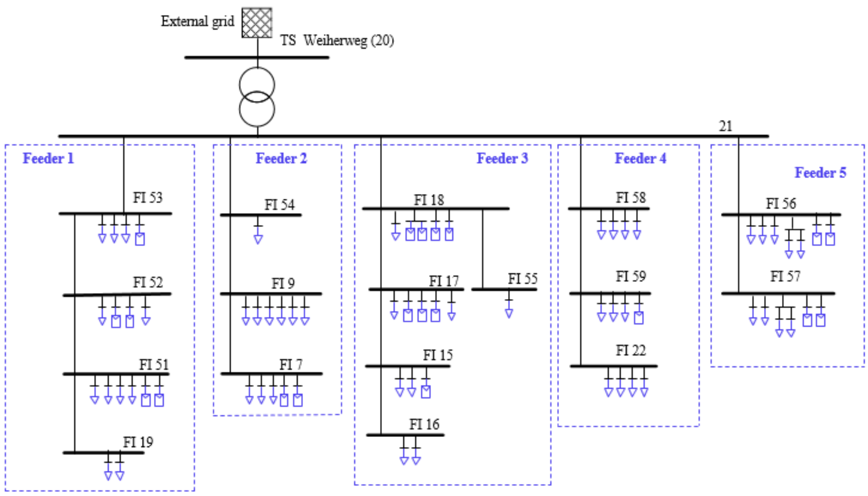

Figure 1: field trial low-voltage grid containing a 250kVA secondary substation serving 5 feeders with loads (triangles) and significant PV generation (rectangles).

Figure 1 shows the low-voltage field trial area from from StwLan. It consists of 28 PV systems (rectangles) with a total capacity of 290.37 kWp, customer connection boxes (triangles) representing customers and small businesses, junction boxes and a secondary substation with a 250 kVA transformer. This substation has 5 feeders, which are visualized in Figure 1. In addition, there are two more feeders that are supplying power to streetlights not shown in the figure.

2.2 Digital Twin and Grid Monitoring Solution

To link the grid topology and measurements, in context of the Net2DG project (www.net2dg.eu), a digital twin [1,2,3] was built up. This digital twin is built up automatically through the grid topology data and heterogeneous measurements as shown in Figure 2: (1) The ICT Gateway responsible for data fusion, (2) HeadEnd Servers responsible for topology and measurement data collection, (3) the observability grid model (OGM) that implements a load flow analysis to calculate non-measured voltages and currents, and (4) applications to monitor the grid and support the digital planning process proposed in this paper based on the digital twin.

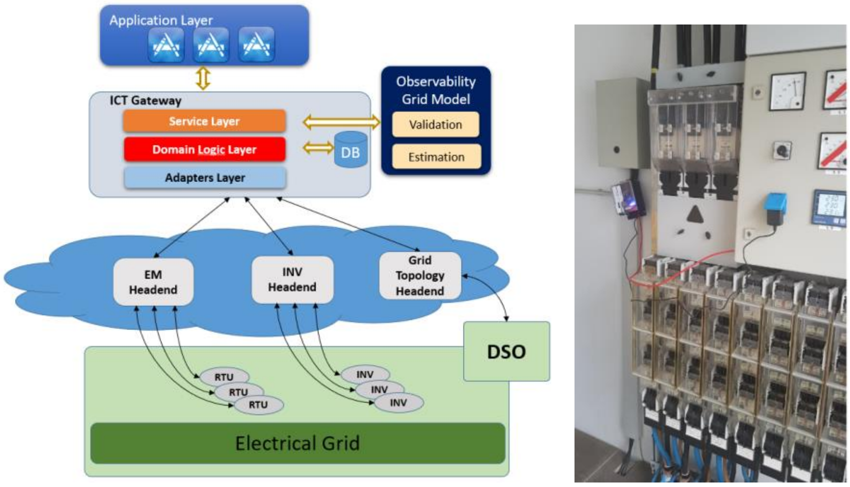

Figure 2. Left: Architecture of the system to obtain the digital twin and run the planning application [1,2,3]. Right: Measurement device and RTU installations at the substation.

The grid topology data is imported by the topology HeadEnd server [5] by parsing an export from the existing geographic information system (GIS) server. The electrical measurements (EM) devices at junction boxes and and the substation are connected through remote terminal units (RTUs) via a cellular network connection to the EM HeadEnd Server. The RTUs are based on Raspberry Pis, the deployment in the substation is in Figure 2 right. Technical details are described in [3]. Two PV inverters have been connected to the Fronius Solar.web portal (solarweb.com). The Inverter (INV) HeadEnd connects to Solar.web to import the measurements. All subsystems are connected via the Internet and via secure VPN tunnels.

2.3 PV Connection Request and Baseline Method

The case study in this paper is based on a DSO request as follows: A new PV system with the size of 19.8 kWp should be added at FI19 node located in Feeder 1 (see Figure 1). The question is whether the additional connection of this PV system exeeds the resource limitations, which are given by: (1) the transformer loadings, (2) the voltages at the customer connection boxes, and (3) the cable loadings.

The baseline method currently used in industry to answer this question is a worst-case analysis: Assessing the existing infrastructure considering a pure infeed PV power production. The result of the worst-case analysis was that Feeder 1 can only carry a total of 78kWp PV, and the additional connection requests with 19kWp would exceed this limit. Limiting resources were the loading of the transformer, and the voltage rise calculated by the worst-case planning approach. Consequently, the worst-case planning method required to exchange the transformer as the total PV capacity installed was exceeding the total transformer capacity. Furthermore, the worst case planning also showed a too high voltage increase and therefore would required a cable replacement or other topology adjustments via additional cabling.
Since this method does not use any measurement data, the worst-case analysis provides a simplified and highly conservative approach for defining the PV hosting capacity.

3 Planning based on a digital twin with real measurement data

The baseline method does not use any measurement data and is therefore highly conservative. In this section, we therefore propose a grid planning approach based on measurement data, that provides realistic results and prevents the DSO from not required purchases and therefore, ultimately, saves costs. To this end, we first present the approach, second present a case study based on this approach, and third discuss the results of the case study and relate them to the baseline worst-case method.

3.1 Grid Planning Approach

To investigate the request by the DSO, only a small subset of measurement data available in the digital twin was required to achieve good accuracy. In fact, only two types measurement locations were used:

1) Voltage as well as active (P) and reactive (Q) energy measured at the substation transformer.
2) Measurements of a reference PV power production profile to model the individual PV systems installed in Feeder 1.

The approach involved the following steps, implemented by a digital planning application on top of the digital twin:

1) Process the historic voltage measurements at the secondary substation to obtain the historic worst case (maximum voltage at substation in the measured period).
2) Use the reference PV system to extrapolate the generation of each PV plant using the information about is peak power.
3) Sum up all PV generation to obtain the total generation in the low-voltage grid area, see blue curve in Figure 3 for the example.
4) Use the measurement of P and Q at the substation, correct it by removing the generation to obtain the total consumption in the grid (red curve in Figure 3).
5) Equally distribute the total consumption over all loads connected to the LV grid area. In the used case-study, there were no larger industrial loads in the

LV grid area. However, the information about the special types of consumers can also be included for a proportional and also time-of-day dependent splitting of the total load across all consumers in the LV grid area.

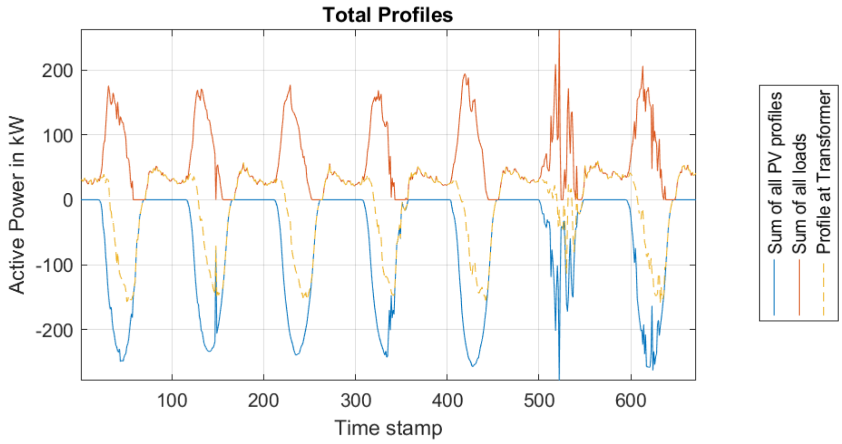

Figure 3: Approach to determine load and generation profiles.

Based on the obtained consumption and generation profiles and the historic worst-case voltage at the substation, the digital twin uses the observability grid model to calculate the following parameters:

(1) Transformer loadings
(2) Cable loading for all cables
(3) Voltage at all customer connection boxes

We define that the hosting capacity is not exceeded, if the transformer and cable loadings are below 90%, and the voltages of all nodes is maximum 10% over the nominal voltage (400V). Thus, the voltage at all CCBs should stay within the boundary of 440V.

3.2 Case Study

The grid planning approach proposed in Section 3.1 was implemented as a new application and used to assess the grid integration of a new PV system at junction box FI 19 in StwLan field trial. One spring week with maximum PV generation of the reference PV was selected by the planning application based on processing of the historic data. This week with maximum PV generation is shown in Figure 3 and the corresponding measured active power at the transformer and resulting extrapolated PV generation and calculated total loads are shown in the figure. As voltage at the LV busbar of the secondary substation, the maximum measured voltage at the secondary side of the substation transformer is used, which is 410.6 V between August 2020 and April 2021.

Using these measurements and the grid topology in the digital twin as basis, studies are performed to calculate the maximum PV hosting capacity through the OGM. To this end, the planning application incrementally connected PV systems in 3 kWp steps at all existing nodes in Feeder 1 in a round-robin fashion. In each iteration, the grid parameters stated in Section 3.1, i.e., the transformer and cable loading as well as the voltage at all customer connection boxes in Feeder 1, were assessed. Figure 4 illustrates the transformer loading with additionally 123 kWp PV connected at Feeder 1 assessed for seven days. As shown the 90% loading limit is just reach but not exceeded by installing that much additional PV capacity in Feeder 1. Therefore, the hosting capacity until reaching the transformer loading limit is obtained here as by additional 123kWp. Figure 5 shows the situation for voltages at all customer connection boxes: The limit of 10% over nominal is reached for the shown case of additional 24kWp connected to Feeder 1. For the concrete DSO request described in Section 2.3, the results showed that there are no transformer loading challenges and the voltage will stay within admissible limits when connecting the new PV installation at node FI 19.

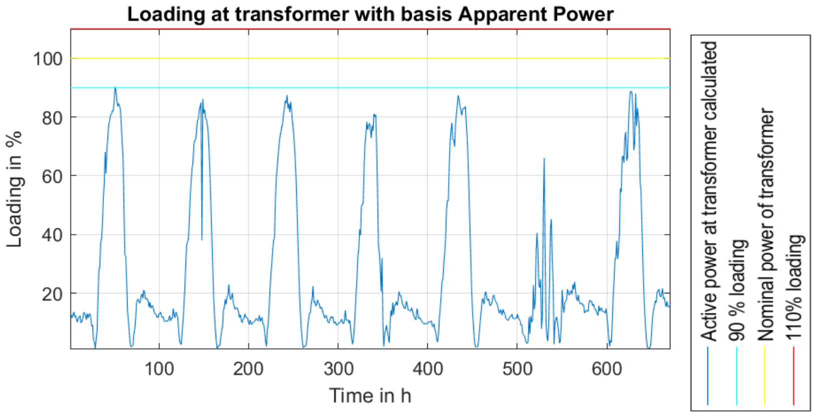

Figure 4: Transformer loading with additionally 123 kWp PV capacity in Feeder 1.

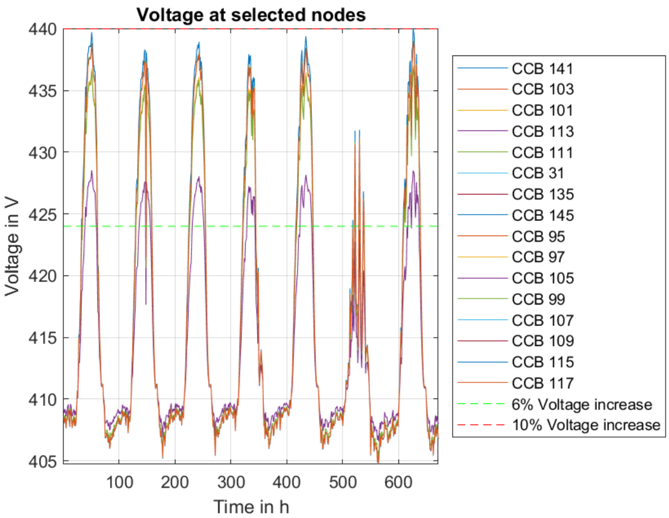

Figure 5: Voltage at nodes with additional 24 kWp PV installations distributed in Feeder 1.

3.3 Summary of Results

A summary of the resulting hosting capacity when considering different grid limitations and the improvement compared to the current planning approach for determining the PV hosting capacity for the StwLan field trial feeder is given in Table 4. Note that the previous section specified *additional* PV peak power connected to the grid while the table now considers the total connected PV peak power as the hosting capacity.

	Main Constraints on Resources	**Other Constraints on Resources**	**PV hosting capacity Feeder 1**	**Increase compared to baseline**
Baseline Worst-Case Approach	*Transformer Loading reached limit ; Voltage at last junction box reached limit;*	*Cable loading below limits*	*78 kWp*	*Baseline*
Grid Planning Approach using digital twin	Voltage at CCBs 440 V (+10% of nominal)	Max trafo loading 64.9% Max cable loading 34.9%	102 kWp	**31 %**
Grid Planning Approach using digital twin and additional voltage regulation measures	Max Transformer Loading 90%	Cable loading	201 kWp	**158%**
Grid Planning Approach using digital twin only considering cable loading	Max Cable Loading 90%		234 kWp	**200%**

Table 1. Summary of PV hosting capacity results for the field-trial Feeder 1.

The results in Table 1 show that the considered StwLan field trial feeder can accommodate 31% more PV when using the proposed grid planning approach based on measurement data and the digital twin, and then voltage limitations are reached. When instead considering transformer loading or cable loading as the limiting factors, the hosting capacity is even much higher. Specifically, the feeder can accommodate 158% more PV when the transformer loading is the only constraint, and 200% when the cable loadings are the only constraints.

Therefore, there is a substantial benefit of using the proposed approach that is supported by historic measurement data and load flow analysis.

4 Discussion and Outlook

The maximum hosting capacity of a grid is an important variable for a DSO to know whether he needs to buy new transformers and cables with higher capacity in case new PV systems should be connected. This paper proposes a grid planning approach that determines the maximum hosting capacity of a distribution grid by using a digital twin. Compared to the currently used conservative baseline method, the digital twin allows to use measurement data and load flow analysis in the grid planning approach. To evaluate the approach, a case study with a real German was performed. The study proves that the proposed grid planning approach reveals that the actual hosting capacity is up to 200% higher than determined by the baseline. Compared to the baseline method, using the proposed grid planning approach saves cost for the DSO, as it prevents him from buying new transformers and cables if there is no need.

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