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Impact analysis of photovoltaic systems and energy storage systems on a low-voltage distribution grid

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Abstract.

The aim of this paper is to present an impact analysis of photovoltaic systems on a low-voltage distribution grid. It introduces simulation methodology of photovoltaic systems integration and their influence on grid voltage. Simulation results are given for a real low-voltage distribution grid feeder model. Furthermore, the study explores updating photovoltaic systems with energy storage systems, revealing beneficial effects of electricity storage. Although the findings are specific to a particular grid, they hold broader applicability to distribution grids in general. The developed methodology serves as a useful tool for analyzing low-voltage grids universally.

Key words. low-voltage grid, photovoltaic system, energy storage system

1. Introduction

Recent advancements in the development of low-carbon technologies and evolving electricity market dynamics conduct and reinforce energy trends of self-sufficiency and renewable sources. Amidst this progression, photovoltaic (PV) systems have emerged as a driving force in the transition towards sustainable practices. Despite the many beneficial facets of PV systems, their operational volatility cannot be ignored. One of the rudimentary principles of the electric power system is the equalization and simultaneous generation and consumption of electricity. In contrast, the operation of PV systems heavily depends on weather conditions. The widespread integration of these systems into the power grid thus introduces periods of variable grid conditions. Each new system connected to the grid carries the prospect of causing technically and commercially intolerable power quality violations. The proper assessment of new systems' impact is, therefore, essential.

The benefits of distributed power sources within power grids, which encompass reduced loss, enhanced system reliability, and improved power quality, are evident. In contrast, the incapacity of conventional power systems to effectively accommodate distributed electricity sources is also emphasized, alongside the widespread electrification of heating and transportation [1-5]. In response to these challenges, network enhancements are necessary. The Energy Agency in the Slovenian energy market [6] suggests the adoption of energy storage systems as a means of synchronizing electricity generation and consumption. By limiting power flow mostly between self-supply sources and storage systems, the grid experiences reduced load and can accommodate more distributed power sources [6-7]. Furthermore, researchers in [7] propose incentivizing consumers with self-sustaining power systems to incorporate storage systems, thus, alleviating the need for investments by the Distribution Network Operator (DNO).

For the DNO, the most crucial aspect of the PV system planning phase is assessing its impact on the grid. This assessment can involve grid analyses conducted through calculations, measurements, and simulations. The prospect of technical problems in a grid can be a criterion for the operator to accept or reject new systems' connection [3]. The primary constraints for PV system integration arise from thermal limitations and regulations regarding voltage quality [1, 4, 7, 8, 9]. Researchers in [8] present an exemplary grid analysis highlighting that in rural grids, the primary limitation is voltage amplitude, while in urban grids, thermal constraints pose the greatest challenge. Voltage limitations specified in power quality standards typically fall within the range of +/– 10 % of the nominal value. However, some recommendations are even more stringent, namely +/– 5 % voltage deviation at the user level [10].

Approaches for determining the optimal power capacity of PV systems within a grid typically fall into two categories: deterministic and statistical methods. Deterministic methods rely on static models to simulate challenging operating conditions, such as peak electricity production coinciding with minimal consumption. Whereas statistical methods analyze the full spectrum of possible operating scenarios to identify the proportion of cases where grid violations may occur [8]. According to researchers in [9], statistical methods also incorporate deterministic parameters, such as a constant grid topology. Many researchers perform statistical simulations using the Monte Carlo method, which uses random sampling to address mathematical problems [11]. Simulations typically follow an iterative approach, incrementally increasing the total installed power of PV systems by one system at a time or by a few percent with each step. At each level of integration, between 100 and 1000 iterations are conducted, each involving changes in the locations of PV systems. While these simulations represent statistical methods for identifying violations, they commonly focus on the most challenging operating scenarios for the grid rather than simulating all possible states [1, 3, 4, 8]. While some authors use simulations to determine the proportion of iterations with the occurrence of a violation [8], others continue calculations until the first violation arises [5]. A third approach involves recording the proportion of consumer buses where a violation occurs [3].

Studies such as [3, 4, 7] assign consumers random electricity consumption profiles and random PV system sizes from common sets. In [8], electricity production and consumption are determined by distribution functions. In [7], individual PV system sizes are randomly selected from typical values, and in [3], they are statistically distributed between 1 kW and 4 kW.

This paper introduces a simulation methodology designed to assess the effects of integrating PV systems into low-voltage distribution grids. A simulation model of a real grid feeder is introduced, and mathematical models of PV and energy storage systems are described. Voltage is observed as the decisive power quality criterion. The paper is divided into four main chapters: the introduction, methodology (simulation methods, electricity consumption, generation, and storage models), results (impact on grid voltage), and conclusion.

2. Methodology

A. Monte Carlo simulation method

The increase in rooftop PV system integration is evident, yet the decision to install or not to install a PV system is made independently by consumers [7]. The specific location of future systems is hence unknown. If every household can install a PV system, a grid with 36 consumers has 2^{36} possible integration scenarios. Examining all those scenarios is impracticable. Therefore, a random sample of all possible integration scenarios is generated using the Monte Carlo method. Different levels of PV system integration are investigated, beginning with adding one new PV system and incrementally increasing by one on each level. Ten iterations of power flow simulation are performed on every level of integration, with each iteration considering a different scenario of PV systems locations. Simulations are carried out for one data point in given daily time-series data, further discussed in Section 2. *E*. Algorithm 1 presents the described Monte Carlo method employment.

Algorithm 1

```
for i = 1 : number of consumers
      for j = 1 : 10
            1. assign a PV system to i
            randomly selected consumers
            without repetition
            2. perform power flow
            simulation
            3. check for violations of
            operational constraints
      end
end
```

The observed operational limit is the voltage across all consumer buses, roughly following the EN 50160 Power Quality Standard. The permissible range of voltage at any consumer bus is set to + 10 % of the nominal value in anticipation of the overvoltage problem caused by the integration of many PV systems into low-voltage grids.

B. Daily power flow simulation

The electricity production from PV systems and household consumption patterns are subject to temporal variations, leading to fluctuations in the effects on voltage throughout the day. Therefore, a daily power flow simulation is employed to further assess a scenario of PV system locations with a 50 % rate of occurrence for limit violations.

C. Weather conditions

The aim of the simulations is to study the most difficult yet realistic conditions. Two sunniest days were selected, each by a distinct criterion. The first metric was the highest value of the integral of the daily solar radiance curve. The second metric was the highest single measurement of solar radiance at any given time of day. Archival meteorological data spanning three recent years was examined. Both sought extremes occurred in the year 2020. On June 12, 2020, the daily solar irradiance reached 8883 Wh/m^2 and the highest single measurement of solar radiance was 984 W/m^2. On July 18, 2020, the daily solar irradiance reached 5384 Wh/m^2 and the highest single measurement of solar radiance was 1145 W/m^2. Figure 1 shows the daily course of global and diffuse solar radiation on both selected days.

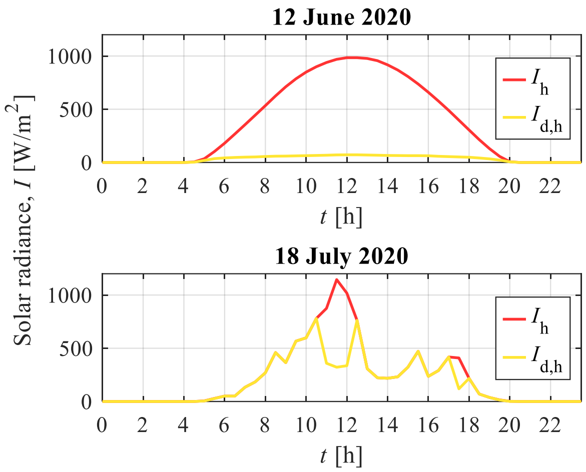

Fig. 1. Daily course of global and diffuse solar radiation on 12. June 2020 and 18. July 2020.

D. Feeder model

A single feeder of a low-voltage distribution grid serves as the case study. The grid is powered by a 250 kVA 20/0,4 kV transformer comprising a total of seven feeders. The considered feeder supplies 32 household consumers and four non-residential buildings. Three households already own operating PV systems. The grid topology of the studied feeder, along with annotations of the locations of existing PV systems, is illustrated in Figure. 2.

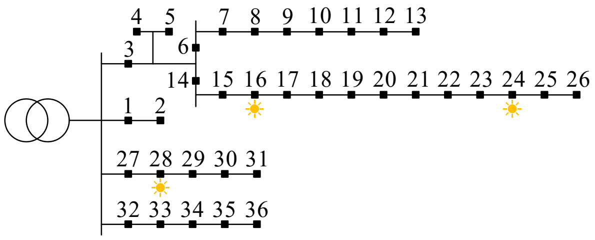
Fig. 2. Grid topology of the studied feeder with annotations of locations of existing PV systems in yellow marks.

E. Household demand profiles

Each consumer is assigned their actual electricity consumption profile obtained from the local DNO, to enhance the accuracy of simulation results. Power exported to the grid is also given in instances where PV systems are already installed. This time-series data was acquired over the course of one year in the highest accessible resolution of 15 minutes. For residential consumers, only active power is measured, hence their load is considered to operate at unity power factor.

F. PV system model

Hypothetical new PV systems to be integrated into the grid are mathematically modelled to simulate electricity production. Solar radiance data recorded by the Slovenian Environment Agency [12] is utilized to calculate irradiance on different slopes and azimuths, representing various roof installations of PV systems. An efficiency of 15 % is assumed for the energy conversion process. No other electricity production related loss is regarded. PV system capacities for individual houses are determined based on the available roof surface area and current state legislation limitations. Production of electricity is estimated by considering respective roof orientation.

G. Energy storage system model

Energy storage systems are integrated in the model as ideal batteries storing exceeding energy in times of high electricity generation and depleting stored energy in times of high electricity consumption. All batteries are uniformly defined by three operating parameters, which were derived from the examination of an existing residential battery. The capacity is set at 8 kWh, the maximum power of charge and discharge is 1,8 kW [13] and the depth of discharge is set to 90 %.

3. Results

Power flow simulations with incremental integration of new PV systems were conducted as described in Section 2. *A*, using MATLAB Simulink. The proposed methodology was applied to the feeder model of a real low-voltage distribution grid presented in Section 2. *D*. Two of the sunniest days were simulated, resulting in overproduction of electricity and consequently overvoltage. The daily average voltage at consumer bus in current grid state is assumed to be at nominal value; thus, no significant undervoltage is observed.

Initially, the moment with the highest solar radiance on a given day is evaluated. The voltage at each consumer bus is observed, and the number of PV systems to be integrated without violating voltage limits is determined. For 32 consumers suitable for integrating a PV system in the studied feeder, a total of 320 different integration cases were analyzed. Figure 3 depicts the rate of overvoltage occurrence at any consumer bus for different levels of PV integration. Generally, as the number of integrated PV systems increases, the rate of overvoltage occurrence rises. As expected, overvoltage occurs slightly more often in relation to higher solar radiance. Considering both days, initial voltage issues arise with 2-4 added PV systems. With 6-7 added systems, violations occur in half of the simulated cases. If eight or more new PV systems are added, voltage violations are expected regardless of the system's locations.

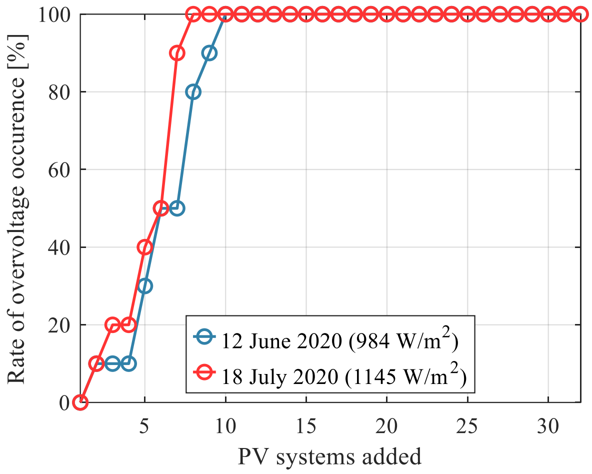

Fig. 3. Rate of overvoltage occurrence at any consumer bus for different numbers of PV systems added.

A combination of six new PV systems locations associated with overvoltage occurrence was used for subsequent simulations. Daily power flow simulations were employed to observe the course of voltage deviation across all consumer buses throughout the day. Figure 4 depicts the course of voltage deviation on 12 June 2020. Slight voltage deviations emerge with sunrise around 6:00 and reach 5 % by 9:00. Deviations across different consumer buses range from approximately 7,5 % to 10 % at noon, then gradually regressing in the afternoon. Around 19:00, the sunset causes the voltage to regain its nominal value. Overall, deviation from the nominal value lasts for approximately twelve hours.

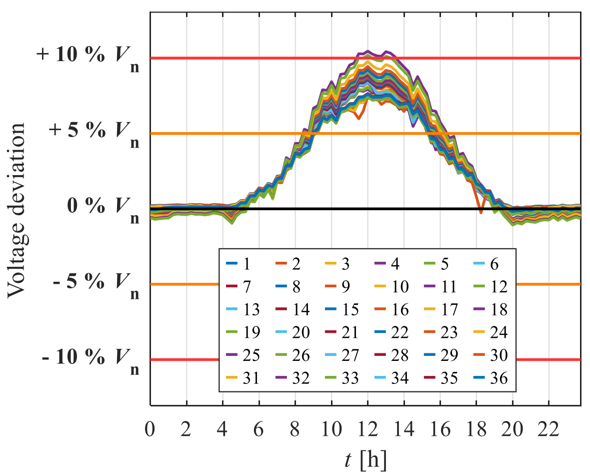

Fig. 4. Voltage deviation for all consumer buses, with six added PV systems, on 12 June 2020.

Subsequently, each installed PV system was improved with a simple energy storage system described in Section 2. *G*. Daily power flow simulations were conducted once again, and the course of voltage deviation was observed. Figure 5 depicts the course of voltage deviation on 12 June 2020, with energy storage systems added to all previously implemented PV systems. Significantly lower overvoltage is observed throughout the day. Initial voltage deviations emerge at 9:00. At noon, deviations across different consumer buses range from approximately 2,5 % to 5 %. Overall, deviation from the nominal value lasts for approximately eight hours.

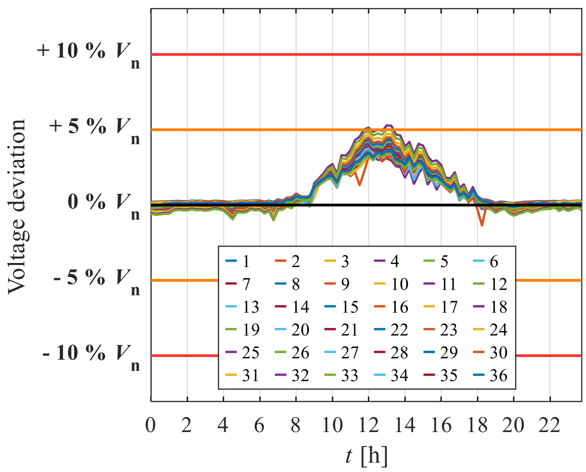

Fig. 5. Voltage deviation for all consumer buses, with added energy storage systems to all PV systems, on 12 June 2020.

Figure 6 depicts the course of voltage deviation on 18 July 2020. Initial voltage deviations emerge around 7:00 and reach 5 % by 10:00. Deviations continue to increase until noon, exceeding 10 % across most consumer buses. In the afternoon, voltage follows the shape of the solar radiation curve, with the deviation dropping to approximately 2 % at 14:00. The sun reemerges around 16:00 and 17:00, causing voltage deviation to rise to approximately 4 %.

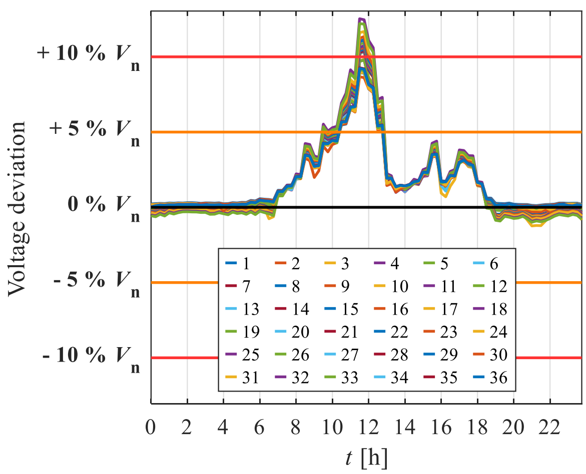

Fig. 6. Voltage deviation for all consumer buses, with six added PV systems, on 18 July 2020.

Figure 7 depicts the course of voltage deviation on 18 July 2020, with energy storage systems added to all previously implemented PV systems. Once again, lower overvoltage is observed throughout the day. Initial voltage deviations emerge after 10:00. By noon, deviations across different consumer buses reach around 5 %.

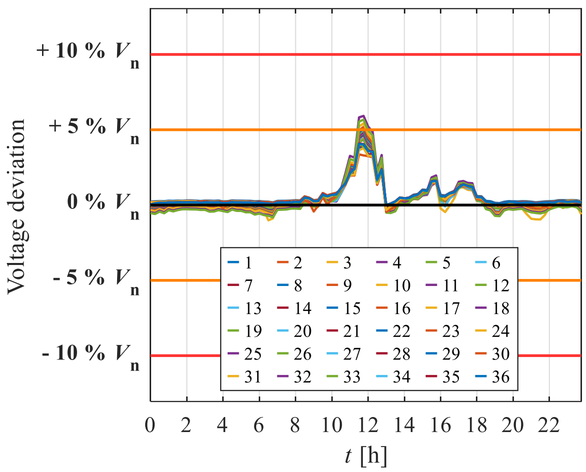

Fig. 7. Voltage deviation for all consumer buses, with added energy storage systems to all PV systems, on 18 July 2020.

4. Conclusion

This paper introduces a stochastic approach for assessing the impact of integrating residential rooftop PV systems into distribution grids, alongside the associated effect of energy storage systems. The Monte Carlo method illustrates the random placement of PV systems, generating a sample of scenarios used for power flow simulations in MATLAB Simulink. Demonstrated on a real low-voltage distribution grid feeder, the method incorporates consumer load time series data and grid topology for modelling purposes. Results from power flow simulations highlight overvoltage issues emerging from widespread PV system deployment. However, integrating energy storage systems with PV systems shows promising outcomes in mitigating overvoltage. The proposed methodology holds potential as an evaluation tool for DNOs assessing new system integrations. Future research may explore the impact of other emerging residential low-carbon technologies on distribution grids, and extended simulation periods to capture the time-dependent behaviours of energy storage systems. Improving computational efficiency is essential for further advancements of the proposed methodology.

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