Abstract

The subject of this doctoral dissertation is the improvement of the process of supplying electricity generated by a photovoltaic system to the low-voltage power grid, as well as the development of solutions enabling an increase in the power grid's connection capacity while maintaining the required power quality parameters. The starting point for these considerations is the rapid development of renewable energy sources, which is a consequence of the global energy transition and the implementation of climate policy goals, particularly within the European Union. The intensity of the implementation of renewable energy installations, including photovoltaic installations, stems directly from the objectives of the Fit for 55 package, which aims for a significant reduction in greenhouse gas emissions and an increase in the share of renewable energy in the energy balance. At the same time, the power sector is undergoing a process of digitalization, a key element of which is the implementation of the CSIRE system, enabling effective management of metering data, billing, and system flexibility.

This paper presents a comprehensive analysis of the current state of renewable energy development at the global, European, and national level, with particular emphasis on the specific conditions in Poland. It is shown that the development of photovoltaic systems, driven by support mechanisms and growing consumer awareness, is leading to significant changes in the operational structure of the power grid, particularly at the low-voltage level. The transition from a centralised to a distributed system model creates new challenges for distribution system operators, including PGE Dystrybucja S.A., which involve the need to ensure grid operational safety and maintain the required electricity quality parameters.

A key aspect of this work is a detailed analysis of the process of connecting renewable energy installations to the electricity grid. The successive stages of the connection procedure were presented, covering the submission of an application, the determination of connection conditions, the conclusion of a contract and the implementation of the connection, followed by the commencement of energy sales. Particular attention was paid to installations which, due to simplified connection procedures and their widespread nature, place a significant load on the low-voltage grid. The paper analyses both formal and legal aspects as well as technical ones, highlighting the systemic barriers limiting connection possibilities, including limited grid capacity, a lack of operational flexibility, and insufficient capacity to compensate for voltage fluctuations.

In the context of technical conditions, the quality requirements specified in the PN-EN 50160 standard are particularly important, as they define the permissible ranges for voltage, frequency and other indicators of the quality of energy supplied to final consumers. The paper discusses in detail the significance of this standard for both end users and distribution system operators, emphasising the need to comply with it due to the growing share of distributed generation. It also outlines methods for measuring and assessing power quality parameters, providing a basis for identifying operational issues and taking corrective action.

A key part of the thesis is an analysis of actual operational experiences related to the functioning of photovoltaic installations in the low-voltage grid. Based on the measurements and observations, it was demonstrated that the connection of PV installations leads to significant changes in grid operation, particularly in terms of voltage levels and their symmetry.

During periods of high generation, coupled with low energy demand, there is an increase in grid voltage, which may result in the permissible values defined in the standard being exceeded and inverters being tripped. Furthermore, it was shown that a high proportion of single-phase

installations leads to voltage asymmetry between phases, which negatively affects the performance of equipment and degrades power quality.

This paper analyses various connection configurations for photovoltaic systems, covering both single-phase and three-phase systems, as well as their combinations. It was demonstrated that the connection method has a key impact on load distribution in the network and voltage levels, and that an inappropriate connection structure can result in local overloads and a deterioration in quality parameters. The research was supplemented with a detailed measurement analysis, including monitoring of the actual low-voltage network, which enabled identification of characteristic occurrences and their quantitative assessment.

To deepen the analysis, modelling studies were conducted, mapping the actual structure of the low-voltage network and various operational scenarios. As part of the modelling, a number of system operating states were defined, designated as A0–A3 and B1–B3, which corresponds to different connection configurations. The simulations confirmed operational observations, indicating a significant increase in network voltages as the power generation increases, and a growing asymmetry where single-phase installations are dominant. The analysis also showed that, at high levels of grid saturation by PV installations, the permissible voltage parameters are exceeded system-wide, which constitutes a significant constraint on the further development of micro-installations.

Based on the obtained results, a set of measures was developed to reduce the negative impact of photovoltaic installations on the low-voltage grid and to increase connection capacity. The recommended solutions include both technical and administrative measures. Of particular importance are measures aimed at symmetrising the connections of single-phase installations, enabling the reduction of voltage asymmetry and a more balanced phase load. Another significant element is the capability to control the power factor of photovoltaic installations, which enables local voltage adjustment through the generation or consumption of reactive power. The paper also examines the impact of voltage adjustment on the MV/LV transformer, which can serve as an effective tool for limiting voltage overshoots.

Another group of solutions comprises measures to optimise network parameters, including cable lengths and cross-sections, which have a direct impact on voltage drops and the network's transmission capacity. The paper also mentions the possibility of limiting the unit capacity of photovoltaic installations as a tool for managing the growth in generation in areas with limited network capacity.

The conducted analyses clearly indicate that the further development of photovoltaic installations in low-voltage networks requires a systemic approach, encompassing both infrastructure modernisation and the implementation of new operational and regulatory measures. Of key importance is the integration of technical solutions with IT systems and market mechanisms, which will enable effective grid management in conditions of a high share of distributed generation.

This study is an applied research which addresses actual operational challenges encountered in distribution networks. Its findings can be directly implemented by distribution system operators in the course of planning network development, managing grid connections and optimising the performance of the power system. The conclusions and recommendations developed are consistent with the current trends in the energy transition, identifying specific measures to increase the share of renewable energy sources whilst maintaining grid operational safety and the high quality of the electricity supplied.