ABSTRACT

The doctoral project is Focus on the integration of prosumer photovoltaic (PV) micro-installations with low-voltage (LV) distribution networks and focuses on examining their impact on selected parameters characterising network operation by simulating the system over a defined time horizon. The OpenDSS software was used to perform the simulations. First of all, the research was conducted on a test LV network model, which is a part of the CIGRE benchmark network. Simulations were carried out over a 24-hour time horizon with hourly resolution. The impact of photovoltaic generation on, among other things, voltage levels, current flows and energy losses was analysed. It was found that the presence of PV sources changes the operating conditions of the network, in some cases leading to exceedances of permissible operating parameters, which adversely affects both the network and the consumers supplied by it.

For the same network model, the next stage of work simulations were carried out over a one-year time horizon, also with hourly resolution, the results of which likewise confirmed the periodic negative impact of PV sources. The simulation results were used to develop a method enabling quantitative assessment of the degree of adverse impact of PV micro-installations on LV network operation, by determining the risk level of exceeding permissible network parameters over the assumed period. The final stage of the scientific part was to examine the impact of atmospheric conditions on the risk levels occurring in the network. Simulations were carried out on the existing network model, with input data modified to reflect different weather conditions. The results made it possible to determine the influence of weather conditions on the risk of exceeding permissible network parameters and, additionally, to determine the maximum saturation level of the CIGRE test network with PV sources at which no disturbances in its operation were observed. This concluded the scientific part.

The developed method for determining the risk of exceeding permissible network parameters was then applied to real distribution systems, forming the implementation part of the project. Technical data of actual LV distribution networks provided by the Distribution System Operator (DSO) were used to prepare their models in OpenDSS. Due to the planned very large number of simulations, a tool was first developed to automate the simulation process, which significantly reduced the time required for a single analysis.

Three different LV networks were selected for the study. For each of them, the impact of PV sources on network operation was analysed by determining the annual risk of exceeding permissible network parameters for various degrees of PV penetration level. Simulations were carried out over a one-year time horizon with hourly resolution. They confirmed, as shown in the scientific part, the negative impact of PV sources on network operation during certain periods. As a result of the research, the network with the worst operating parameters was identified and subjected to a detailed analysis focusing mainly on voltage levels and on proposing technical solutions to mitigate the negative impact of PV micro-installations. By performing daily simulations with minute level resolution, ten possible options were examined, and the results allowed a technical solution minimising the adverse effect of PV sources on the studied network to be recommended to the DSO. Consequently, the DSO included the proposed, research validated solution in its investment plan. The analysis of the simulation results also showed a positive effect of installing battery energy storage systems at selected prosumer sites on grid voltage levels, with the first stage of research assuming infinite capacity and a relatively simple operating programme.

The final stage of the work included simulations assuming finite capacity of prosumer storage units and an alternative control strategy reflecting the realities of frequent electricity price changes on the Polish market. Two control strategies were considered, for which appropriate operating profiles were prepared: the first aimed at minimising energy costs and the second at maximising the financial neutrality of prosumers. To determine these profiles, a Particle Swarm Optimisation (PSO) algorithm was applied and daily simulations were performed using energy price profiles for two different days of 2024. Annual simulations covering electricity prices prevailing on the Polish market throughout 2024 were also carried out. In the daily simulations, the impact of storage operating programmes on network voltage levels and the duration of overvoltages compared to a system without storage was examined. In the annual simulations, the risk of exceeding the voltage above the permissible value i.e. 1,1 U_n at customer connection points was assessed and the amount of potentially ungenerated energy resulting from PV micro-installation shutdowns due to excessive network voltage was estimated. The analysis showed that better results were achieved when the storage units operated under programmes maximising prosumers financial neutrality. In this case, the duration of overvoltages was further reduced and the amount of potentially ungenerated energy was also lower compared to the situation where the storage was controlled according to cost minimising profiles.

The most important practical conclusion from the research is that the application of appropriately controlled distributed energy storage systems installed at prosumers premises mitigates overvoltages in the network and reduces the frequency of PV installation shutdowns by inverter protection devices which translates into lower financial losses for prosumers and longer service life of the devices themselves, particularly inverters. This conclusion is important for the design of energy management systems for residential consumers equipped with PV micro-installations and energy storages, and it should also be taken into account in any future development of regulatory frameworks in this area.