Application of a demand-response-optimized electrical load profile to a plant supplying an energy micro-community

Abstract

Demand response (DR) strategies play a crucial role in balancing energy supply and demand in both grid-connected and islanded microgrids. By integrating renewable energy sources (RES) and storage systems, DR programs help optimize energy consumption and increase self-sufficiency. This study investigates the application of a DR-optimized electrical load profile to a plant supplying an energy micro-community. The experimental setup involved the S.A.P.I.EN.T.E. hybrid system, which was tested under real operational conditions. The study compared the performance of a non-optimized electrical load profile with a DR-optimized load profile in terms of self-consumption and self-sufficiency. Furthermore, the research was extended to a larger energy community using a simulation platform based on Matlab/Simulink models to assess the energetic indices and economic profitability of DR logics.

Introduction

The transition towards renewable energy is essential to address climate change and energy security concerns. However, the intermittent nature of RES poses challenges to grid stability and reliability. The increasing variability in consumer demand and growing peak loads further complicate grid management. DR programs provide a solution by adapting end-user demand profiles to grid requirements, thereby reducing peak loads and enhancing load factor efficiency. While DR has been successfully implemented in industrial settings, residential applications are gaining attention due to the proliferation of smart appliances and energy management technologies. Energy communities, as promoted by the European Directive 2009/28/EC, offer an ideal environment for DR participation, given their inherent flexibility in energy generation and storage. This study examines the impact of a DR-optimized electrical load profile on an energy micro-community, assessing its effectiveness in improving self-consumption and self-sufficiency.

Methodology

System Description The investigated energy micro-community consists of a building equipped with a heat pump (HP) having a maximum heating capacity of 30.4 kW and a nominal input electrical power of 13.3 kW. The system also includes a 1500-liter thermal storage unit and a 12 kW photovoltaic (PV) system. A Programmable Logic Controller (PLC) was employed to manage the production, storage, and utilization of electrical and thermal energy. The system, known as S.A.P.I.EN.T.E., is installed at the ENEA Casaccia Research Center.

Experimental Electrical Load Profiles A Monte Carlo method was utilized to generate electrical load profiles, distinguishing between flexible and non-flexible loads. A simulation tool was employed to shift flexible loads to periods of peak PV power availability. These adjustments were made to ensure optimal energy use, reducing the dependency on grid electricity while maximizing self-consumption.

Experimental Thermal Load Profile A dry cooler was used to emulate the residential thermal load. The load profile exhibited peak demand in the morning and late afternoon through the evening. The dynamic response of thermal loads was analyzed to evaluate how DR optimization could further enhance efficiency in heating and cooling operations.

Experimental Parameters The experiment spanned 17 hours, from 05:30 to 00:30, with the PID controller maintaining the storage temperature within a set range (45°C to 50°C). The PV system produced 71.04 kWh/day, while the building's total electrical consumption was 31.19 kWh/day.

Simulation Scenarios The study extended to a larger residential building with eight apartments across four floors. Several configurations were tested, including traditional heating systems, PV integration, collective self-consumption, and DR-optimized load management. The ODESSE simulation platform was utilized to analyze energy performance and economic outcomes. Each scenario was assessed to determine the extent to which DR strategies could be applied to improve grid interaction and reduce overall costs.

Results and Discussion

Experimental Findings The DR-optimized load profile demonstrated significant improvements in energy self-consumption and self-sufficiency. The HP successfully tracked PV power availability, reducing energy exchange with the grid. Compared to the non-optimized profile, the DR strategy reduced excess PV energy fed into the grid and increased local consumption. The ability to control peak demand through DR strategies highlights their importance in modern energy systems.

Energy Coefficients and Economic Analysis The DR-optimized load profile improved self-consumption from 62% to 77% and increased self-sufficiency from 34% to 41%. The application of DR logics resulted in greater economic savings by reducing reliance on grid electricity and enhancing PV utilization. Simulation results confirmed that DR integration improved net present value (NPV) and overall economic benefits for the energy community. Further analysis suggests that DR strategies can be effectively scaled to larger residential complexes.

Extended Analysis and Future Prospects Further examination of the DR-optimized strategy in a broader context reveals potential applications in larger residential complexes and mixed-use developments. Future enhancements could include real-time adaptive algorithms that adjust load profiles dynamically in response to grid fluctuations. Additionally, integrating machine learning techniques could improve predictive accuracy for demand patterns, optimizing DR strategies even further. The expansion of DR strategies into commercial and industrial settings presents an opportunity to further increase energy efficiency and sustainability. A holistic approach integrating policy incentives and advanced metering infrastructure could accelerate the adoption of DR technologies.

Moreover, further research should explore the long-term effects of DR implementation on grid stability and renewable energy integration. Simulation models should be refined to incorporate seasonal variations and evolving consumption behaviors. Policy frameworks could also play a role in ensuring the economic viability of DR strategies, fostering a collaborative approach among stakeholders. The inclusion of energy storage solutions, such as advanced battery technologies, could further optimize DR efficiency by smoothing load variations and improving grid resilience.

Additionally, the integration of decentralized energy management systems could enhance demand-side flexibility. Future research should investigate how blockchain technology and distributed ledger systems could facilitate transparent and efficient energy trading within microgrids. The application of smart contracts could automate DR participation, creating a more interactive and self-regulating energy ecosystem.

Conclusion The study highlights the advantages of integrating DR-optimized electrical load profiles in micro-communities. By enhancing self-consumption and self-sufficiency, such strategies contribute to a more sustainable and economically viable energy system. Future research could explore additional optimization techniques and expand the analysis to different climatic conditions and community sizes. This work establishes a foundation for advancing DR strategies, ultimately promoting a resilient and efficient energy future. By bridging the gap between theoretical models and practical implementation, the findings support the continuous evolution of smart grid technologies and sustainable energy solutions. As energy markets continue to evolve, DR strategies will play an increasingly pivotal role in creating flexible and decentralized energy systems. The widespread adoption of DR-enhanced systems will be instrumental in achieving long-term sustainability goals, ensuring a reliable and resilient energy network.