Advanced Fault Protection and Stability in PV-Enhanced Urban Power System

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Absztrakt:
This study builds upon the findings of the Budapest Solar-Powered Project, which assessed the maximum feasible photovoltaic (PV) capacity within Budapest's low-voltage distribution network. It is aligned with the European Climate Initiative (EUKI) and the "Budapest Nappal hajtva" programme, both of which aim to map rooftop solar potential and develop strategies for integrating renewable energy sources into urban power systems. By addressing these challenges, the research contributes to advancing climate neutrality and enhancing energy resilience in urban environments. The primary objective of this investigation is to extend the Budapest Load-Flow model to evaluate the impacts of elevated PV penetration levels on power flow dynamics, the recalibration requirements of overcurrent protection devices, and overall grid stability under variable operating conditions. Multiple fault scenarios have been analysed to compare network performance across varying levels of PV integration.

Kulcsszavak: Photovoltaic systems, fault protection, grid stability , low-voltage networks, power flow, analysis, smart grid

1.Photovoltaic Capacity in Budapest

The deployment of photovoltaic (PV) systems in urban environments has become a cornerstone of sustainable energy strategies. In Budapest, multiple initiatives have assessed the technical and spatial potential for rooftop PV installations, resulting in a range of projections and targets for the city's solar energy capacity. The Hungarian Transmission System Operator (MAVIR) has provided official forecasts for PV deployment within Budapest. In MAVIR's 2027 scenario, the pessimistic outlook—denoted as BP1—anticipates approximately 204MW of installed PV capacity. In contrast, the optimistic scenario for 2032, referred to as

BP2, estimates that PV capacity could reach up to 284MW within the capital.[7][9] Complementing these projections, the Budapest City Council conducted an independent assessment of PV deployment potential. Leveraging Light Detection and Ranging (LIDAR) technology, the council surveyed rooftop surfaces across the city to identify technically suitable areas for solar panel installations. This study concluded that Budapest's theoretical rooftop PV capacity could reach as high as 3000~MW.[1] Building upon these findings, prior research has sought to establish a realistic yet ambitious deployment threshold by analysing the voltage rise constraints associated with high levels of distributed PV generation. This network-focused analysis demonstrated that, under worst-case conditions—where all PV systems operate at maximum output while grid consumption remains minimal—the distribution network could accommodate up to 1500~MW of PV capacity without violating voltage limits. This threshold is denoted as BP3 in the subsequent comparative analysis.

Figure 1 illustrates the three deployment scenarios forming the foundation of this study:[1][7]

1. **BP1**: 204~MW — MAVIR 2027 pessimistic forecast
2. **BP2**: 284~MW — MAVIR 2032 optimistic forecast
3. **BP3**: 1500~MW — City Council grid-based deployable target

These scenarios provide a structured framework for assessing the impact of varying PV penetration levels on power flow patterns, fault current characteristics, and protection strategies within Budapest's medium- and low-voltage distribution networks.

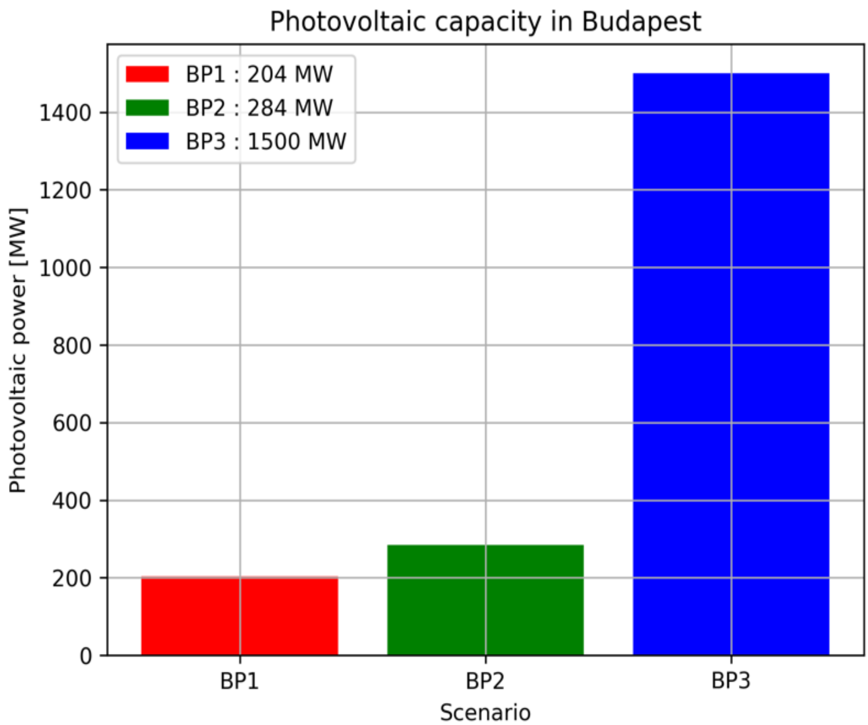

Figure 1 Summary of Budapest PV deployment scenarios (BP1, BP2, BP3).

2. Methodology and Data Preparation

This section outlines the methodology employed to simulate realistic load and generation conditions within Budapest's low-voltage (LV) distribution network. Given the variability of rooftop solar installations and the uncertainties surrounding future deployment scales, the study uses scaled estimations based on historical projections and typical consumption profiles. Three primary datasets were utilised to support the fault current analysis: aggregated household load profiles, outdoor temperature trends, and estimated photovoltaic (PV) generation. These datasets are illustrated in Figure 2.[2]

2.1 Load Profile Aggregation

To replicate representative consumption behaviour, load profiles from 30 individual households were aggregated to form a comprehensive demand curve.

The resulting profile, displayed in the first row of Figure 2, reveals a peak power demand of approximately 70~kW. This value was used to calculate the median load, which subsequently served as the reference for distributing demand across multiple nodes within the LV network model.[2]

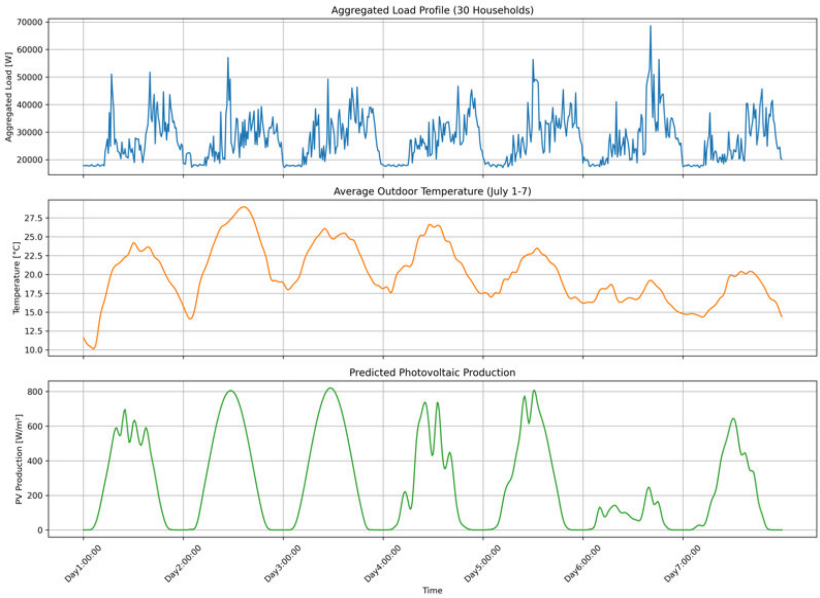

Figure 2. Load profile, outdoor temperature, and PV production estimations for Budapest network simulations.

In the simulation framework, sub-grids were assigned load values proportionally, reflecting the number of consumers they encompass. For instance, a sub-grid comprising 10 load nodes was allocated approximately one-third of the aggregated load profile. This proportional scaling ensures consistency between the simulated load distribution and actual consumption patterns, thereby providing a realistic foundation for analysing fault current behaviour.[2][3]

2.2 Outdoor Temperature and Seasonal Variability

The second row of Figure 2 illustrates the average outdoor temperature profile over the observation period. While temperature data was not directly utilised in the fault current simulations, it offers essential context for validating seasonal trends in load behaviour. Furthermore, it provides a valuable parameter for potential future enhancements, such as incorporating temperature-dependent load or PV generation adjustments into the simulation model.[3]

2.3 PV Production Estimation

The third subplot in Figure 2 depicts the estimated photovoltaic production profile, expressed in W/m². As granular, rooftop-level production data was unavailable, this study employed generation estimates from the Budapest Solar-Powered Project, which is based on an assumed full deployment of 1500~MW PV capacity.

To accommodate different PV penetration scenarios aligned with MAVIR projections, the base production profile was linearly scaled according to the following scenarios:

1. **BP1 (204 MW):** MAVIR pessimistic forecast for 2027
2. **BP2 (284 MW):** MAVIR optimistic forecast for 2032
3. **BP3 (1500 MW):** Maximum rooftop deployment potential identified by the Budapest City Council using LIDAR assessment

The scaling process applied the following formula to preserve the profile shape while adjusting the amplitude:

$$PVscenario = PV1500[MW]base \times \frac{ScenarioCapacity}{1500} \quad (1)$$

This approach maintains the temporal dynamics of the PV generation curve while accurately reflecting the impact of varying PV capacities. Through this methodology, the simulation captures how different levels of solar deployment influence fault currents and grid protection requirements across each scenario.

3. Grid Modelling and Simulation in Python

To investigate the impact of photovoltaic (PV) penetration on fault behaviour and line loading in Budapest’s distribution network, a comprehensive low-voltage (LV) grid model was developed using the Pandapower Python library. The simulation framework is presented in *Figure 3*, illustrating the network topology, voltage levels, and line loading under varying PV deployment scenarios.[4][8]

3.1 Grid Structure

The simulated grid consists of three medium-voltage (MV) buses operating at 10kV, each connected to the external grid via standard 400kVA transformers. These transformers supply power to the LV side of the network, which operates at 0.4~kV. The network topology is derived from a real-world feeder identified as having a high potential for PV installation, selected from a dataset of approximately 33,000 transformer districts assessed during the Budapest PV deployment study.[1]

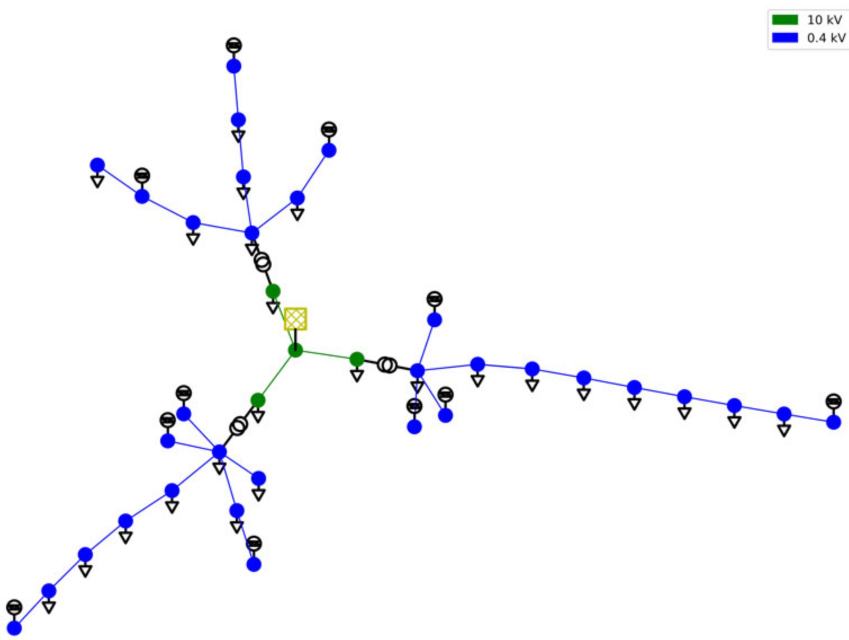

Figure 3a. Network topology and voltage levels of the modelled Budapest MV-LV grid.

The LV network includes both residential loads and distributed PV generation units, spatially arranged based on data from prior LiDAR-based rooftop assessments. Each bus within the model is assigned load and/or generation parameters corresponding to its role in the scenario being simulated.[1]

3.2 Line Lo

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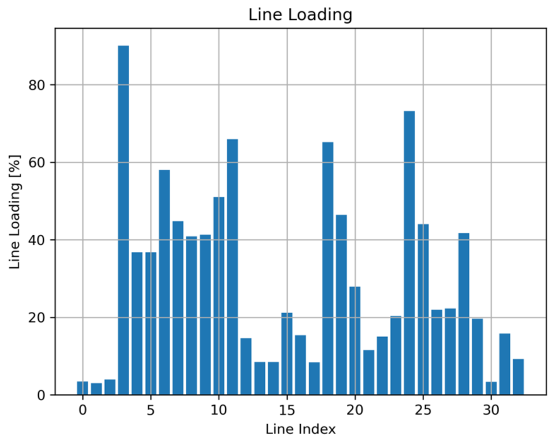

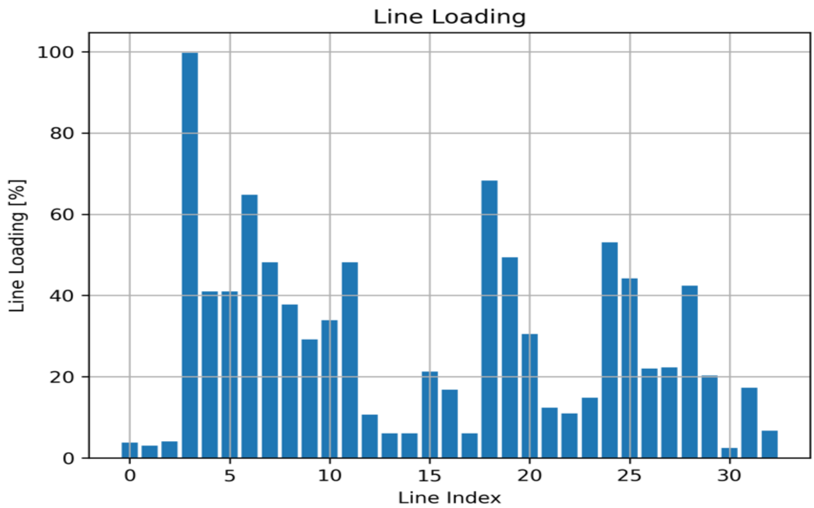

Figure 3b. Line loading under BP1 scenario (204 MW PV penetration).

In the **BP2** scenario, line loading decreases even further as local PV generation offsets consumption, reducing power flows from upstream transformers. This observation confirms that moderate PV deployment can effectively relieve transformer and feeder stress by supplying power closer to consumption points.

Figure 3c. Line loading under BP2 scenario (284 MW PV penetration).

Conversely, under the **BP3** scenario, extensive overloading is observed across nearly all line segments, with loading levels ranging from 200% to 350%. This significant overloading arises from high levels of PV-generated current feeding back into the network, particularly during periods of maximum solar production. The results highlight critical risks associated with high-density rooftop solar deployment, emphasising the need for network reinforcements and advanced protection strategies.

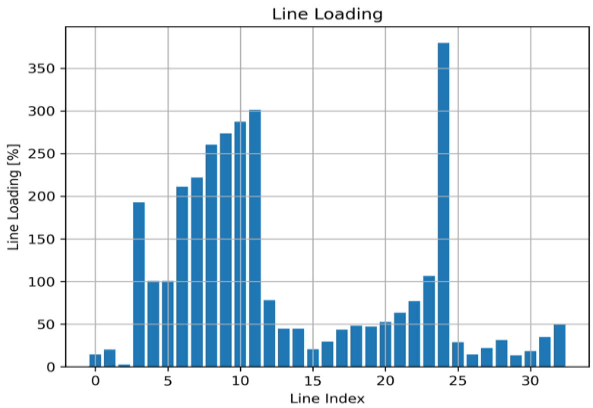

Figure 3d. Line loading under BP3 scenario (1500 MW PV penetration).

4. Fault Current Analysis under Different PV Scenarios

To assess the impact of varying levels of photovoltaic (PV) penetration on fault behaviour in the distribution network, a short-circuit analysis was performed using the developed Pandapower grid model. By introducing fault conditions at a random node within the low-voltage (LV) network, the simulation aims to capture realistic fault current responses in an urban environment with widespread distributed generation.

4.1 Fault Scenario Configuration

The fault scenario is illustrated in *Figure 4a*, depicting the selected node within the LV grid where a three-phase short-circuit fault was introduced. This random selection represents typical fault conditions and enables a meaningful evaluation of system response in complex urban networks with high PV deployment.

The choice of a three-phase fault scenario reflects one of the most severe fault types, ensuring that protection system adequacy is tested under worst-case conditions. The analysis focuses on observing how distributed PV generation influences the magnitude and distribution of fault currents throughout the network.

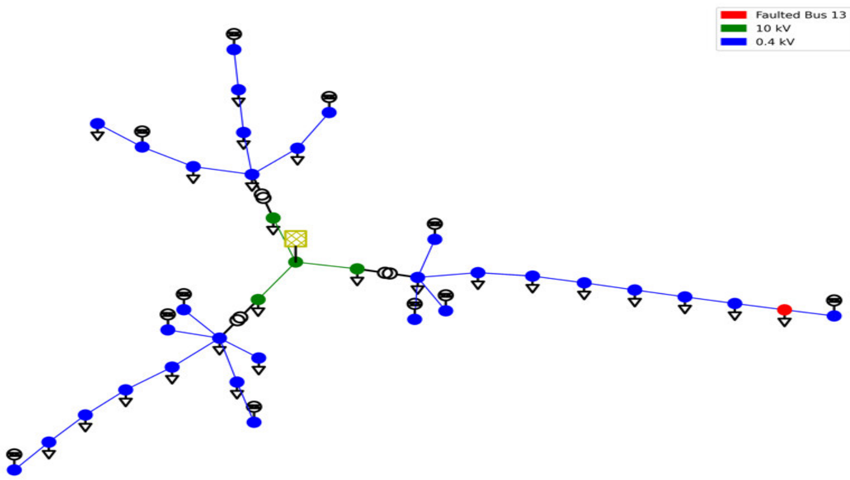

Figure 4a. Simulated fault location in the Budapest LV grid model.

4.2 Influence of PV Penetration on Fault Current Magnitudes

The simulation results, presented in *Figure 4b*, compare line fault current magnitudes between two PV penetration scenarios:

1. **BP1 (204 MW):** MAVIR pessimistic forecast for 2027
2. **BP3 (1500 MW):** Theoretical deployment limit proposed by the Budapest City Council

Under the **BP1** scenario, fault currents remain within expected operational limits, aligning with the design parameters of traditional overcurrent protection systems.

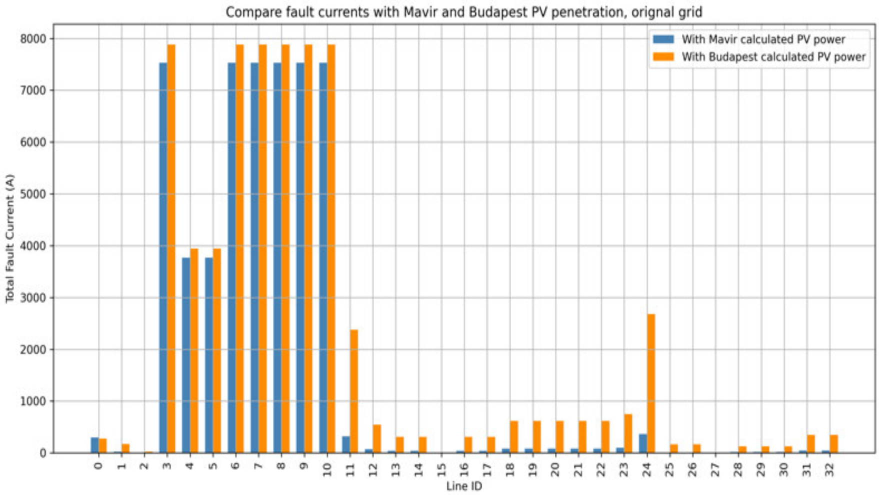

Figure 4b. Comparison of fault current magnitudes across network lines under BP1 and BP3 scenarios.

Conversely, the **BP3** scenario exhibits a substantial increase in fault current magnitudes. The elevated contribution of fault current from distributed PV installations significantly raises fault levels, particularly along lines electrically closer to major PV clusters. This amplification of fault current flow is a direct consequence of bidirectional current injection by decentralised PV systems during fault conditions.

The findings underscore a pivotal challenge for future grid operation: conventional overcurrent protection devices, calibrated for networks with unidirectional power flow and lower fault contributions, may become insufficient in high PV penetration environments. Without recalibration or the implementation of adaptive protection strategies, these devices risk miss-operation, either failing to detect actual faults or triggering unnecessary disconnections, both of which threaten the reliability and safety of the urban power grid.

5. Grid Topology Modification: From Radial to Looped Structure

To evaluate strategies for mitigating elevated fault currents in urban grids with high photovoltaic (PV) penetration, the original radial network design was modified to a looped (meshed) configuration. By enabling bidirectional power flows at both the medium-voltage (MV) and low-voltage (LV) levels, the modified topology aims to improve fault current distribution and overall system resilience.

5.1 Modified Grid Configuration

The reconfigured network is presented in *Figure 5a*. In this design, additional lines were introduced to interconnect buses, forming closed loops. Such meshed topologies are widely adopted in urban environments to increase operational flexibility, enhance reliability, and provide redundancy during fault conditions.

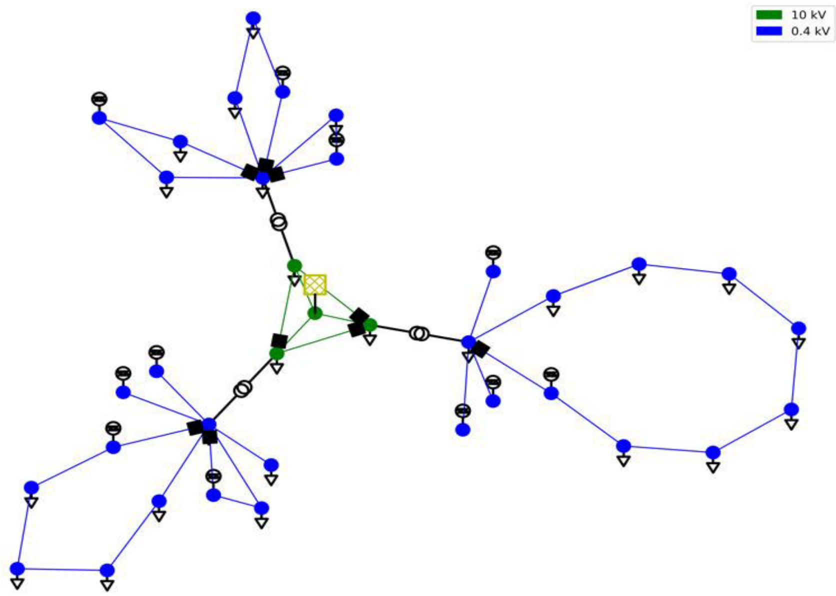

Figure 5a. Modified looped topology of the Budapest MV-LV grid.

Key characteristics of the looped configuration include:

1. **Multiple power flow pathways** that reduce voltage drops and alleviate line loading during normal operation.
2. **Alternative fault current paths** that redistribute fault currents, potentially decreasing thermal and mechanical stress on specific components.

5.2 Comparison of Fault Currents: Radial vs. Looped Networks

Figure 5b compares fault current magnitudes between the original radial grid and the modified looped topology, under the high PV deployment scenario defined by the Budapest City Council (1500 MW).

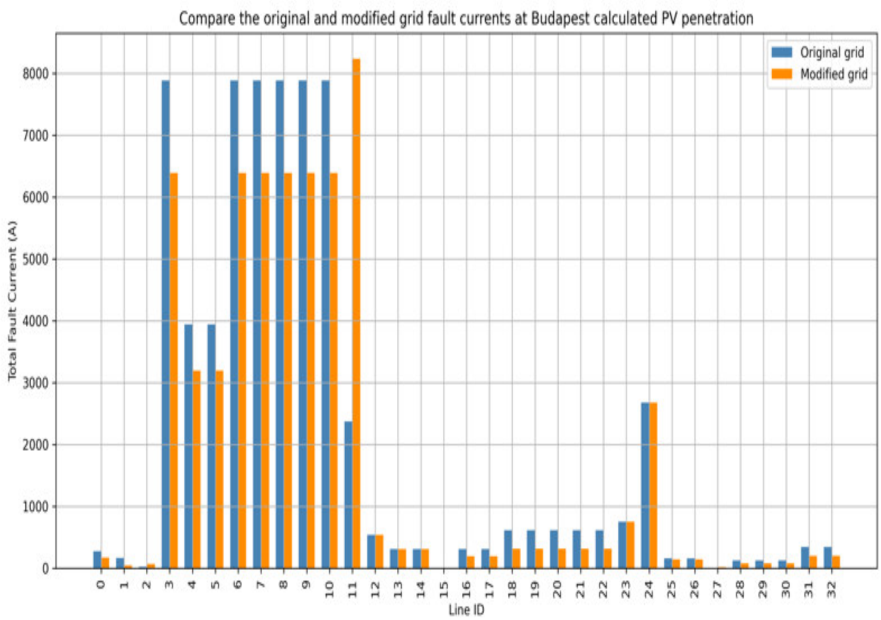

Figure 5b. Fault current comparison between radial and looped grids at 1500 MW PV penetration.

Key observations:

1. In most parts of the network, the looped configuration resulted in **significantly lower fault currents** compared to the radial design. The redistribution of currents across multiple paths helped mitigate localised overcurrent risks.
2. However, the **faulted line experienced an approximately 3.5-fold increase** in fault current relative to the radial scenario. This surge is explained by converging fault contributions from multiple feeding paths in the meshed network.
3. Although the looped design enhances fault tolerance in general, it simultaneously concentrates current at the fault location, emphasising the need for careful protection system coordination.

5.3 Protection Implications

The results highlight critical considerations for protection system design in looped urban networks with high PV penetration. Conventional overcurrent protection, typically calibrated for radial systems, may prove insufficient under these conditions.

Recommendations for protection system adaptation include:

1. **Directional protection schemes** to accurately detect the direction of fault currents and prevent malfunctions caused by bidirectional power flows.
2. **Adaptive protection settings**, which dynamically adjust tripping thresholds in response to real-time changes in generation and load conditions.
3. **Selective coordination**, ensuring that protection devices isolate only the faulted section without unnecessarily disconnecting healthy parts of the network.

By implementing these advanced protection strategies, grid operators can harness the benefits of looped network topologies while maintaining fault resilience and operational reliability in the face of growing renewable energy integration.[6]

6. Conclusion

This study examined the influence of increasing photovoltaic (PV) penetration on fault behaviour within Budapest’s medium- and low-voltage (MV-LV) distribution network. The results confirm that, beyond their impact on voltage profiles, high levels of distributed PV generation substantially increase fault currents across the grid. These elevated fault levels challenge the adequacy of existing protection schemes, particularly in urban LV networks originally designed for unidirectional power flows and lower short-circuit currents.

A principal finding is that transitioning the network from a conventional radial design to a looped (meshed) topology effectively alleviates the widespread increase in fault currents associated with high PV integration. By providing multiple current pathways, the looped configuration redistributes fault currents, thereby reducing thermal and mechanical stress on individual lines and enhancing overall network resilience.Nevertheless, the analysis also identified a critical trade-off. While fault currents across most parts of the looped network are reduced, the faulted line itself experiences a significant rise in current magnitude—approximately 3.5 times higher than in the radial configuration. This concentration of fault energy underscores the need for advanced, adaptive protection systems that can dynamically respond to evolving fault conditions.

The findings validate the initial hypothesis that the challenges introduced by high levels of distributed renewable generation can be addressed through a combination of network reconfiguration and intelligent protection coordination. Specifically, protection strategies incorporating real-time data from Phasor Measurement Units (PMUs) and dynamic network sectionalisation can minimise the adverse effects of fault currents. Such adaptive systems can isolate faulted sections during disturbances and promptly restore normal operation following fault clearance, ensuring reliable grid performance even under extreme renewable integration scenarios.By providing actionable insights into fault management and protection design, this research contributes to the development of more robust and sustainable urban energy systems. These findings support the broader goals of climate neutrality while maintaining the safety and reliability of power distribution infrastructure.

REFERENCES

1. J. Bencsik and V. Becsó, ‘Load-Flow Model Optimized for the Solar Capacity of Cities’, in *2024 IEEE 7th International Conference and Workshop Óbuda*

on Electrical and Power Engineering (CANDO-EPE), Oct. 2024, pp. 237–242. doi: 10.1109/CANDO-EPE65072.2024.10772879.

2. J. Muehlenpfordt, 'Time series'. Open Power System Data, Oct. 06, 2020. doi: 10.25832/TIME_SERIES/2020-10-06.
3. V. G. Kurbatsky and N. V. Tomin, 'Smart system of monitoring and forecasting for electric power systems', in *2012 IEEE International Conference on Power System Technology (POWERCON)*, Oct. 2012, pp. 1–6. doi: 10.1109/PowerCon.2012.6401289.
4. Sarhan, V. K. Ramachandaramurthy, T. Sieh Kiong, and J. Ekanayake, 'Simulation and Validation of a New IEEE Reliability Test System (RTS-GMLC) using PyPSA', in *2020 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, Oct. 2020, pp. 77–82. doi: 10.1109/ICSGCE49177.2020.9275636.
5. Pál, Ľ. Beňa, and Z. Čonka, 'Optimization algorithms for calculation of selected network parameters', in *2021 IEEE 4th International Conference and Workshop Óbuda on Electrical and Power Engineering (CANDO-EPE)*, Nov. 2021, pp. 167–172. doi: 10.1109/CANDO-EPE54223.2021.9667922.
6. Q. Wang, Y. Li, and R. Li, 'Integrating artificial intelligence in energy transition: A comprehensive review', *Energy Strategy Reviews*, vol. 57, p. 101600, Jan. 2025, doi: 10.1016/j.esr.2024.101600.
7. 'Hálózatfejlesztési tervek 2021-től - MAVIR - Magyar Villamosenergia-ipari Átviteli Rendszerirányító Zrt.' Accessed: Mar. 10, 2025. [Online]. Available: https://www.mavir.hu/web/mavir/halozatfejlesztesi-tervek-2021-tol
8. T. Phongtrakul, Y. Kongjeen, and K. Bhumkittipich, 'Analysis of Power Load Flow for Power Distribution System based on PyPSA Toolbox', in *2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Jul. 2018, pp. 764–767. doi: 10.1109/ECTICon.2018.8619954.
9. R. Segurado, G. Krajačić, N. Duić, and L. Alves, 'Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde', *Applied Energy*, vol. 88, no. 2, pp. 466–472, Feb. 2011, doi: 10.1016/j.apenergy.2010.07.005.