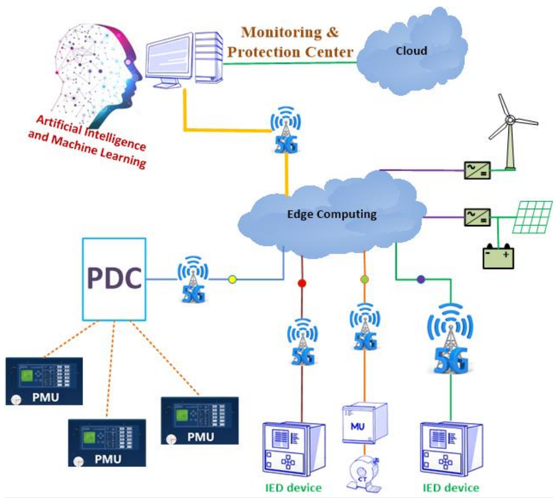

CIRP-5G

CENTRALIZED INTELLIGENT AND RESILIENT PROTECTION SCHEMES FOR FUTURE GRIDS APPLYING 5G

FINAL REPORT

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Vaasan yliopisto
UNIVERSITY OF VAASA

EXECUTIVE SUMMARY

This is the final report of the project "CIRP-5G - Centralized Intelligent and Resilient Protection Schemes for Future Grids Applying 5G" funded by Business Finland (Grant No. 6937/31/2021). The project was a Co-Research project executed between 1.5.2022 and 31.8.2024 as a part of the leading company (Veturi) program of ABB named as "ABB Green Electrification 2035". This final report summarizes the results of the project.

In the CIRP-5G project the aim was to develop new centralized, intelligent, and resilient protection and control methods utilizing cyber secure 5G-based communication, data analytics and AI/ML (artificial intelligence / machine learning) for future active distribution networks. The focus of the project was on the modern electricity distribution systems and in the utilization of the new centralized protection technology and 5G communication. The functionalities studied included the islanding detection, earth fault protection, and wide area monitoring and protection.

As a result of this project an advanced real time simulator -based laboratory environment was developed, and especially the adaptive protection approaches were developed and demonstrated with it. In this environment the latest products by ABB, such as SSC600, REX640 and SMU615 were utilized. Additionally, the capabilities of the 5G communication were tested by applying a private 5G laboratory network created in a parallel project. A monitoring application was developed to study the performance of the communication considering especially the latency and jitter. Beside the experimental parts, the project results include the development of various applications of computational intelligence relating to islanding detection and intermittent earth faults. Additionally, comprehensive reviews of the related emerging technologies, such as edge and cloud computing were made.

ACKNOWLEDGEMENTS

As the project leader, I want to thank all those who have contributed to the CIRP-5G project: Amir Farughian, Aushiq Memon, Enio Costa Resende, Hannu Laaksonen, Hussain Khan, Marcelo Godoy Simoes, Mazaher Karimi, Meysam Pashaei, Nikos Hatziargyriou, Petri Välisuo, and Talal Saleh.

I also want to thank all the members of the project steering group for the active and inspiring collaboration:

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- Mika Niskanen, Business Finland
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And at last special thanks goes to the Business Finland and ST-pool (Sähkötutkimuspooli) for the major financial support to this project.

Vaasa, December 2024

Kimmo Kauhaniemi

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1. INTRODUCTION

In the CIRP-5G project the aim was to develop new centralized, intelligent and resilient protection and control methods utilizing cyber secure 5G-based communication, data analytics and AI/ML for future active distribution networks. The focus of the project was on the modern electricity distribution systems and in the utilization of the new centralized protection technology and 5G communication. The functionalities studied included the islanding detection, earth fault protection, and wide area monitoring and protection.

In this report the main results of the project are summarized utilizing the publications made during the project. Some of the results will be published after the project, but also those are introduced in general level. This report is divided on chapters covering the specific work packages (WPs) of the project.

During this project, 11 scientific papers were published. These publications will be summarized and referred in this report. A complete list of the published papers is available at the end of this report. Additionally, the forthcoming publications still in the pipeline will be mentioned in relevant chapters of this report.

This project was a part of the ABB's leading company (Veturi) program named as "ABB Green Electrification 2035" and thus the project was executed in close collaboration with ABB. A key part of the project was the new laboratory which was enabled by the devices donated by ABB:

- SSC600 (Smart Substation Control and Protection device, 2 pcs)
- SMU615 (Substation Merging Unit, 2 pcs)
- REX640 (Protection and Control relay, 3 pcs)

The other industrial partners of the participating and funding the project were: Helen Sähköverkko, Järvi-Suomen Energia, ST-pool (Sähkötutkimuspooli), and Wapice.

In this project a private 5G network available at our laboratory was utilized. This 5G test environment was created in a parallel project 5G Hub Vaasa jointly executed with VAMK and Novia. In this project the equipment that was used for establishing the 5G connectivity are listed below:

- Amarisoft Base Station
- Amarisoft 5G sim cards
- XR80 5G Router
- Raspberry Pi computers with 5G Hats.

During the project the researchers had wide collaboration with several international partners. Several of the publications were prepared in collaboration with the international partners. The project results were presented in various international forums and the new laboratory facilities developed were introduced to several international visiting groups. As a part of the international collaboration, in total three research visits were realized. There was one longer visit (6 months) from Brazil (Federal University of Uberlândia) and two shorter visits to Portugal (UPTEC) and Croatia (Koncar).

2. SYSTEM ARCHITECTURE

This chapter introduces briefly the created laboratory environment, and the devices used. Furthermore, it summarizes the results from WP1, which included the following tasks:

- T1.1 Technologies and platforms
- T1.2 Utilization of wide area measurements
- T1.3 Comparison of alternative architectures

In this WP suitable technologies and architectures for the centralized protection and control system were reviewed and analysed. Essentially, work done included in-depth review of SSC600 and other devices provided by ABB, 5G communication basics (including introduction to the specific solutions applied in the laboratory environment), and other relevant technologies (such as wide area applications, edge and cloud computing).

2.1. Technologies and platforms

2.1.1. Smart Substation Control and Protection – SSC600

SSC600 device played a pivotal role in CIRP-5G project. This device is capable to replace all bay-level IEDs used to be installed in conventional protection system as well as providing new functionalities that was utilized in the project. One of the key features of this device is covering protection of up to 30 feeders, which increases the scalability of power system protection. Minimizing installation, termination, maintenance, and engineering cost in a centralized protection scheme and approximately 15 percent savings in substation life cycle costs are the other benefits that SSC600 can offer. Figure 1 shows this product of ABB which has been on the market since 2018. A more recently released possibility to reach the same functionalities is to use the virtualized protection and control solution SSC600 SW, which can be installed on any compatible hardware.

Figure 1. Smart Substation Control and Protection SSC600

2.1.2. Substation Merging Unit – SMU 615

Compared to older merging units that were only used for sending current and voltage sampled values, the SMU615 merging unit (Figure 2) offers a broader range of functions such as Disturbance Recorder, Circuit-Breaker Condition Monitoring, Trip Circuit Supervision, Fuse Failure Supervision, Arc Detection, Circuit-Breaker Control, Disconnector Control, and more. It supports communication via both RJ45 and fiber optic connections, providing users with flexibility in their choice of communication medium. Additionally, SMU615 is equipped with high-speed binary output capabilities. In the laboratory setup the SMU615 units can be used for sending IEC61850 sampled values basing on the analog signals originating from the OPAL-RT real-time simulator.

Figure 2. Substation merging unit (SMU615)

2.1.3. Protection and control relay – REX640

REX640 represents the high end IED solution covering basically most of the protection and control needs. For the laboratory setup, initially, one unit with practically all the relevant protection applications was received and at later stage two additional units with specifically line differential protection configuration were added. The REX640 units are equipped with separate display units (Figure 2) that can be mounted at convenient locations.

Figure 3. REX640 protection relay with separate display unit.

2.1.4. 5G communication

5G can be seen as a flexible communication network with reduced cost, high bandwidth, and better reliability. In terms of flexibility, 5G networks are more flexible because they can be quickly deployed and can be easily extended to cover large areas with minimal infrastructure requirements. This makes it easier to implement for power system monitoring, control, protection, and automation applications. In terms of deployment 5G networks are also cost-effective solution compared to wired communication systems, particularly in certain areas or regions where laying cables may be prohibitively expensive. They are designed to be highly reliable, with built-in redundancy and failover mechanisms. This can help ensure uninterrupted communication in the event of network failures or disruptions. Additionally, the repair and maintenance costs for a 5G network are low.

To establish a 5G connection between the protection devices, a wireless link needs to be created between these devices. That wireless link can be provided with the help of a private 5G network or a public 5G network operator. The idea behind the connectivity of private or public 5G network is almost similar in a way that connection is established with the help of a modem (with an NIC supporting 5G connectivity).

2.1.5. Edge computing

Edge computing in power systems refers to the practice of processing and analysing data at or near the edge of the network, closer to where it is generated or consumed. In the context of power systems, edge computing involves deploying computing resources, such as servers, gateways, or data processing devices, at various points within the power grid infrastructure. Power systems relied on centralized data centers for processing and analysing data. However, with the increasing deployment of sensors, smart meters, and other Internet of Things (IoT) devices in power systems, there is a massive influx of data that needs to be processed in real-time or near real-time. Edge computing enables the analysis and decision-making processes to occur closer to the data source, reducing latency, improving efficiency, and enabling faster response times.

Edge computing allows for immediate data processing and analysis, enabling real-time monitoring, protection and control of the power system. This enables faster identification of anomalies, faults, or potential issues, allowing for prompt actions to prevent or mitigate outages. Furthermore, by processing and analysing data at the edge, only relevant information needs to be transmitted to the central control centers or cloud platforms, reducing the volume of data transmitted over the network and minimizing the traffic level of the network. This helps alleviate network congestion and reduces bandwidth requirements. On the other hand, it facilitates localized decision-making, enabling autonomous actions and local control within the power grid. In case of network disruptions or latency issues, critical functions can still be performed at the edge, ensuring the reliability of the power system.

Edge computing in power systems is increasingly being adopted as it provides a distributed and decentralized approach to data processing and analysis, complementing the capabilities of centralized control centers and cloud-based platforms. It enables power system operators to leverage the benefits of real-time analytics, faster response times, and enhanced reliability, ultimately improving the overall efficiency and performance of the power grid.

2.1.6. Cloud computing

Cloud computing in power systems refers to the use of remote servers and computing resources hosted on the Internet to store, process, and analyse data related to power generation, distribution, and consumption. Instead of relying solely on local infrastructure and on-site data centers, cloud computing advantages the capabilities of remote data centers to handle data storage, computational tasks, and software applications.

Cloud computing allows power system operators to scale their computational and storage resources based on demand. They can easily allocate additional resources during peak periods or when handling large volumes of data, and scale back during periods of lower demand. This scalability helps optimize resource utilization and reduces the need for extensive on-site infrastructure. Moreover, cloud computing provides a secure and reliable platform for storing and backing up power system data. Power system operators can upload data from various sources, including sensors, smart meters, and SCADA systems to the cloud, where it can be stored, replicated, and easily accessed from anywhere. This ensures data availability and disaster recovery capabilities in case of on-site failures or outages.

Using cloud computing, the operators can access real-time data, monitor system performance, and remotely control devices and equipment from any location with an internet connection. This facilitates remote operation and control, improving operational efficiency and response times. Cloud computing in power systems offers a flexible, and cost-effective approach to data storage, processing, and analysis. It empowers power system operators with advanced analytics capabilities, remote monitoring, and sustainable power grid operations.

2.1.7. Review of new protection solutions

As a part of task 1.1 a review of the recent development of optimal directional overcurrent protection strategies for sustainable power systems via computational intelligence techniques was made in the publication (Ramli et al., 2022). This paper emphasizes an up-to-date review of the most recent methods for achieving effective optimum protection coordination with the directional overcurrent relays (DOCR). This paper gives a comprehensive overview of the uses of various optimization strategies. The evaluation also examines the benefits and drawbacks of the strategies used to address DOCR coordination problems. Additionally, this paper discusses future lines of inquiry for optimum DOCR coordination.

2.2. Utilization of wide area measurements

The increasing demand for electricity, coupled with the growing number of interconnections, the penetration of variable renewable energy sources, and deregulated energy market conditions, presents significant challenges for the security and reliability of power systems. This section reviews the utilization of wide-area, time-synchronized measurements for control and protection in future power grids, focusing on the development of suitable measurement transfer techniques. The focus is on synchronized measurement technology (SMT) and its applications in wide-area monitoring, protection, and control (WAMPAC) systems, with a particular focus on the role of Phasor Measurement Units (PMUs) and Micro-PMUs.

The ever-increasing demand for electricity and the integration of renewable energy sources necessitate advanced monitoring and protection mechanisms in power systems. Synchronized measurement technology (SMT) is a critical enabler of real-time wide-area monitoring, protection, and control (WAMPAC).

Wide-area measurements are essential for the effective control and protection of power systems. These measurements, which include Routable Sampled Values (SVs) and Generic Object Oriented Substation Events (GOOSE), as well as Micro-Phasor Measurement Units (Micro-PMUs) and Synchrophasors, provide time-synchronized data that is crucial for various applications. The accuracy and standardization of these measurements are paramount for their effective utilization.

SMT has a wide range of applications in power systems. These include real-time visualization, the design of advanced early warning systems, analysis of system blackouts, benchmarking and validation of system models, enhancement in state estimation, real-time congestion management, and improvement of voltage, frequency, and angular stability. Additionally, SMT is used in the design of adaptive protection and control systems, as well as backup protection schemes.

The main components of SMT include Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDCs), application software, and supporting communication networks. PMUs provide synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and current signals. PDCs collect and transmit phasor data, perform quality checks, and align time stamps from multiple PMUs.

The implementation of SMT faces several challenges, including the need for real-time data processing, communication network congestion, optimal placement of PMUs, and accurate time synchronization. Solutions to these challenges include data compression techniques, optimal PMU placement methods, and the use of joint SCADA-PMU data for parameter estimation. The integration of 4G/5G wireless technology is proposed as an economical and efficient choice for future distribution systems.

Micro-PMUs are designed for distribution systems and offer high precision measurements. However, they face challenges such as noise, cost, and resolution. Despite these challenges, Micro-PMUs are valuable for applications like adaptive protection, fault detection, and maintaining system stability. The comparison between PMUs and Micro-PMUs highlights the advantages and limitations of each technology.

Relevant standards for SMT and PMUs include IEC/IEEE and IEEE standards. These standards ensure the accuracy, reliability, and interoperability of SMT components and systems.

The integration of 4G/5G wireless technology for wide-area systems is suggested as a promising solution for future distribution systems. This technology offers cost-effectiveness and efficiency, making it an attractive option for the implementation of SMT in power systems.

In the project a comprehensive review of the current state, challenges, and future directions of synchronized measurement technology and its applications in power systems was made. SMT and PMUs are essential for wide-area monitoring, protection, and control. The increasing importance of Micro-PMUs for distribution networks and microgrids is highlighted, along with the potential of 5G technology to enhance the efficiency and cost-effectiveness of future distribution systems.

2.3. Comparison of alternative architectures

Initially in the project a comparison of different system architectures was targeted. However, it was soon realized that this cannot be fully covered in this project and instead a comprehensive review was made on the emerging technologies and their applications. Essentially the key questions concerning the system architecture is to optimize the measurement, data transfer, data storage and computational resources. It was also recognized that optimal architecture is very much application dependent since different applications do have different requirements relating to the amount of data transferred and processed as well as allowed latencies and reliability in communication links.

As a part of the project a review paper initially titled as "A comprehensive review on emerging technologies and platforms enabling the implementation of intelligent centralized protection and control techniques using 5G and beyond communication" was prepared. This paper is not yet published, but some key points of it are summarized in the following.

Traditionally the power distribution systems have been protected using decentralized protection systems and managed by centralized SCADA system. In the modern power systems with increasing amount of DER new kinds of solutions are needed in order to take advantage of the increasing amount of measured data from different parts of the system. Additionally, the speed requirements of the new functionalities require the use of high-speed communication networks and as well as some emerging technologies to handle the data collection and processing. This means, for example, that the SCADA systems need to be complemented by the advanced wide-area measurement system (WAMS) including time synchronized measurements with high data sampling rate.

The study made in this project focused on virtualized and centralized protection and control where especially the 5G communication could be utilized. 5G communication is the fifth-generation technology standard for broadband cellular networks aiming ambitious maximum download speeds and much lower latency or time delay to transmit a packet of data than the previous generations. 5G also offers a highly reliable communication, strong security mechanisms, malicious intrusion prevention, and high scalability.

The challenges in the deployment of 5G communication in power systems include the lack of standard way to integrate the 5G communication to the distribution protection and automation systems. Essentially the 5G communication should be interoperable and compatible with the existing communication technologies used in power systems for an optimal utilization of existing infrastructure. It also seems that the end-to-end latency of 5G communication does not meet the stringent requirements given for power system protection applications. 5G communication may also mean higher costs, because for achieving higher speeds by using higher frequency bands, like 3.5 GHz and above, 5G requires more base stations. Despite of the challenges, several experimental studies of the application 5G communication in the power systems can be found in the literature. Those are further discussed in the forthcoming review paper mentioned above.

Large number of measurements in the modern power systems require also some efficient methods to handle the collected data. From this point of view also the big data analytics platforms were reviewed in the forthcoming paper. Big data involves handling large volumes of data at high speeds Analysing big data helps uncover hidden relationships within datasets. Efficient big data analysis requires powerful tools, algorithms, and platforms. Big data platforms help to collect and clean the data, which is stored in various databases. Many traditional machine learning tools can't handle big data spread across multiple computers. However, modern analytics platforms are more efficient for big data processing and integrate with edge and cloud environments.

In addition to the above topics the forthcoming review paper briefly discussed the centralized control and protection techniques. The recent development of ICT technology has made centralized applications possible even in the protection applications requiring high speed and high reliability. In the literature several studies relating to specific functionalities can be found while the practical implementation is taking fast steps forward with new products reaching to completely virtualized approaches.

By applying the different emerging technologies mentioned above makes the whole system vulnerable to cyber-attacks. Therefore, the relevant cyber security solutions are actively studied, and some advanced approaches are proposed in scientific literature. These are briefly reviewed in the forthcoming paper as well.

3. CENTRALIZED PROTECTION METHODS FOR FUTURE GRIDS

This chapter summarizes the project results from WP2, which included the following tasks:

- T2.1 Islanding detection
- T2.2 Wide area monitoring and protection
- T2.3 Earth fault management
- T2.4 Connectivity and cyber security

In this WP, new protection and fault management methods utilizing measurements from various locations were developed and partly also demonstrated in the laboratory environment.

3.1. Islanding detection

This section presents the findings from the publication (Karimi et al., 2023), which explores a novel approach to islanding detection. Islanding is a condition where a distributed energy resource (DER) continues to power a local area even when the main grid is down, see Figure 4. Detecting this condition is crucial for the safety and stability of the power grid, especially in microgrids integrated into the 5G network infrastructure, which CIRP-5G focuses on. The primary objective of this research was to develop an efficient islanding detection method that does not rely on communication infrastructure, aligning with the CIRP-5G project's focus on resilient and autonomous microgrid operations. The method proposed in the paper offers a passive detection mechanism based on analysing harmonic signatures from voltage signals at the point of connection (PoC) of DERs.

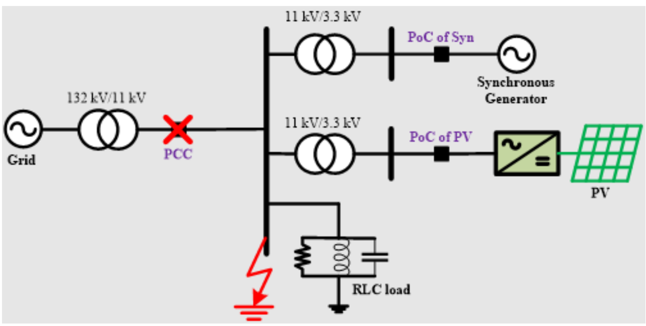

Figure 4. A simple system modelled compliantly with the IEEE 1547 test frame

The study introduces a new method using the full-cycle discrete Fourier transform (DFT) to extract harmonic spectra from voltage signals. These spectra serve as input features for a machine-learning-based one-class classifier, designed to detect islanding events. Unlike traditional methods, this approach eliminates the need for complex threshold settings and operates effectively at lower sampling frequencies (around 1 kHz), making it both cost-effective and practical for real-world applications.

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It is common in power system protection algorithms to apply half-cycle or full-cycle DFT on measured current and voltage signals, depending on the protection requirements like speed and accuracy. The harmonic spectrum in our paper is extracted by applying the full-cycle DFT to the sampled voltage signal. In the real-time application, at each time t, the superimposed spectra are extracted by applying the DFT, as shown in Figure 5, considering two-cycle data-windows of the three-phase voltage signals measured at the PoC. The input pattern (i.e., feature vector) is then formed based on the superimposed voltage harmonic magnitudes of the three phases from 0 Hz to fs/2. For example, with a sampling rate of 1000 samples per second or fs =1 kHz, the extractable harmonics include 0 to 500 Hz.

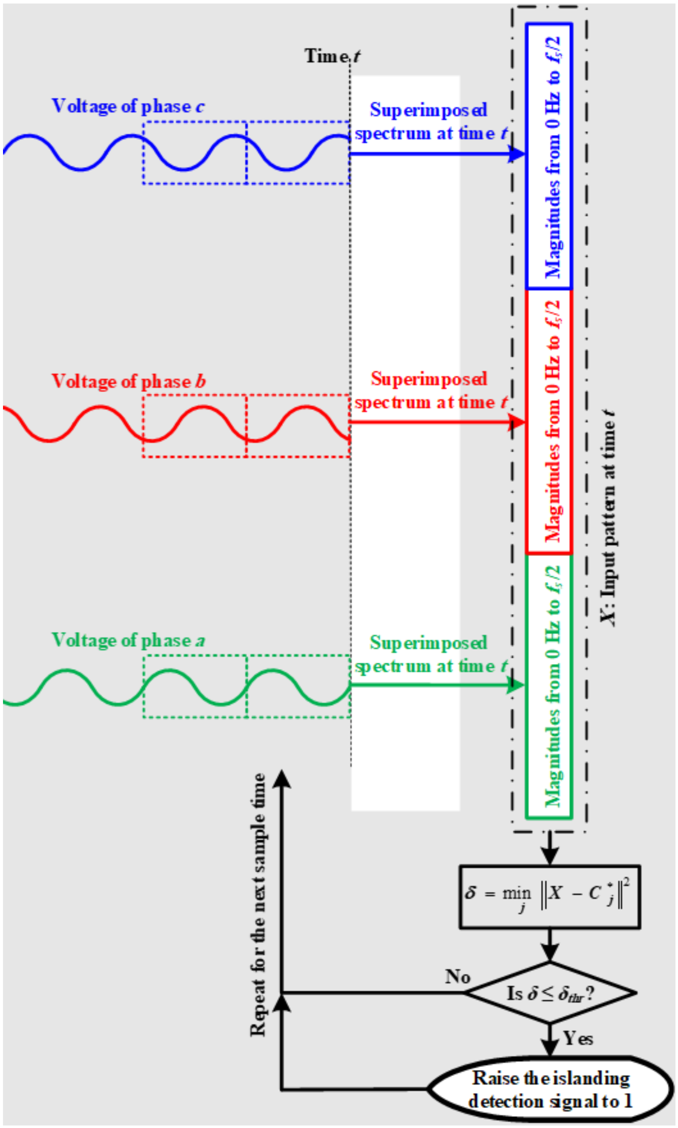


Figure 5. The proposed islanding detection scheme in the real-time application

The proposed method was tested on a microgrid comprising both synchronous and inverter-based DERs. The classifier accurately identified 99.06% of islanding events within the training range. The detection time ranged between 10 to 21 milliseconds, which is significantly faster than the 2-second requirement set by IEEE 1547. The system demonstrated full stability under various conditions, such as load changes, short-circuit faults, and voltage fluctuations. The method exhibited a very small non-detection zone (NDZ), enhancing reliability. These results indicate that the proposed method meets the requirements for fast, reliable, and cost-effective islanding detection, making it suitable for integration into microgrid systems managed within the CIRP-5G framework.

For the CIRP-5G project, the integration of such an approach could enhance the autonomy and resilience of microgrid operations, contributing to the overall objectives of the project. Further research and development may focus on integrating this detection method into the broader 5G network to enhance its application in real-time monitoring and control of distributed energy resources.

3.2. Wide area monitoring and protection

In this task some of the applications of wide area monitoring and protection were studied. A significant part of this task covered the implementation of adaptive centralized protection, monitoring and control scheme shown in the following figures. The key concept behind the proposed adaptive setting group-based scheme, as depicted in Figure 6 and Figure 7, is to capture voltage and current measurements from various feeder and DER connection points of the distribution network. These analogue measurements then are either digitized using merging units (MUs) or OPAL-RT's built-in capability to directly generate IEC 61850 SVs and transmitted to the relays or centralized control and protection devices. After relays operation and opening CBs, the open status of CBs will communicate back to the centralized device for activating predefined setting groups (SGs) to adapt to the present topology of the network. Several scenarios such as different types of faults, islanding and the outage of renewables were applied in the test system and based on the predefined setting and online monitoring of the system, related SGs were activated.

The published works for this task, (Pashaei, Rastegar, et al., 2024) and (Pashaei, Kauhaniemi, et al., 2024), provide a clear implementation guide for preparing an adaptive protection scheme using a Hardware-in-the-Loop (HIL) setup with IEC 61850-9-2 LE (Sampled Values) and IEC 61850-8-1 (GOOSE). Different case studies, including three-phase faults, islanding, and N-2 contingencies, demonstrate the effectiveness of the proposed centralized adaptive protection scheme for future complex grids with a significant percentage of renewable energy sources. These networks require adaptive protection to change protection settings in a timely manner, which our HIL setup achieves with a response time of one to two milliseconds from issuing a trip command to receiving open status of circuit breakers in OPAL-RT and then changing related SG. The test system and result for one case study for a three-phase fault at the end of feeder 1 and feeder 2 (N-2 contingency) is shown in the figures 8 to 11. Information about different scenarios and the implementation can be found in publications (Pashaei, Rastegar, et al., 2024) and (Pashaei, Kauhaniemi, et al., 2024).

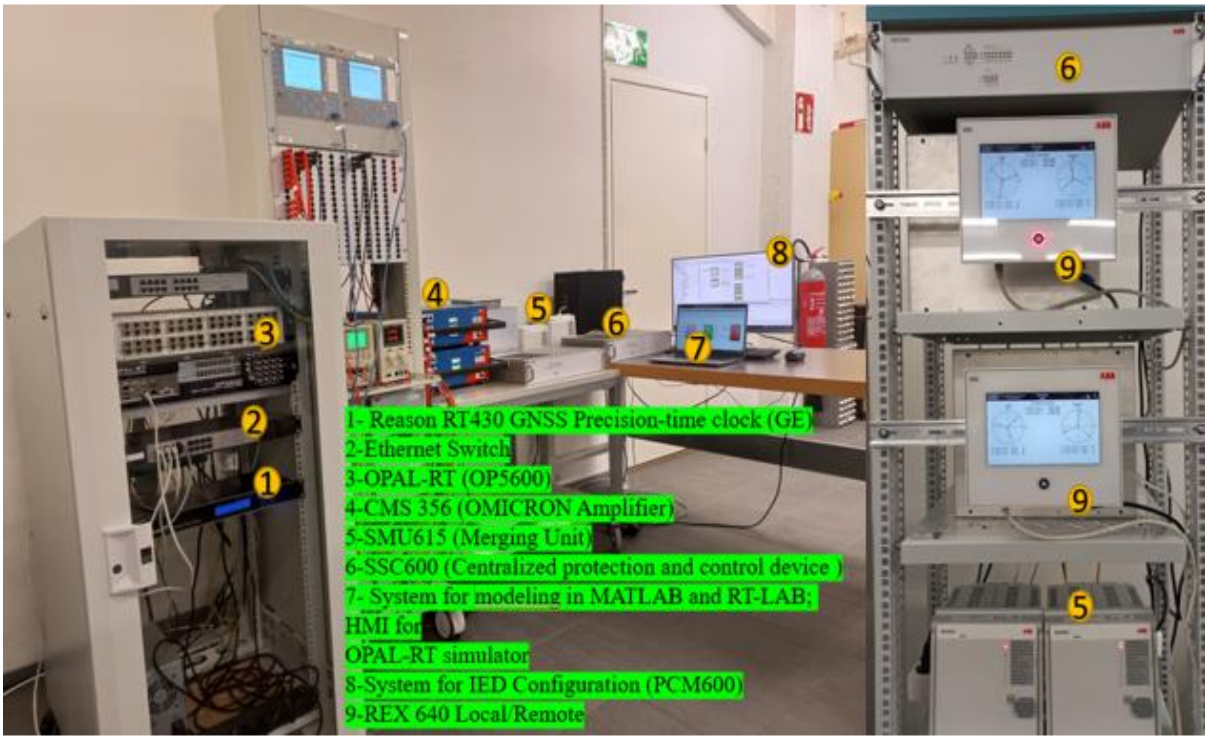


Figure 6. Hardware-in-the-loop setup for centralized adaptive protection scheme.

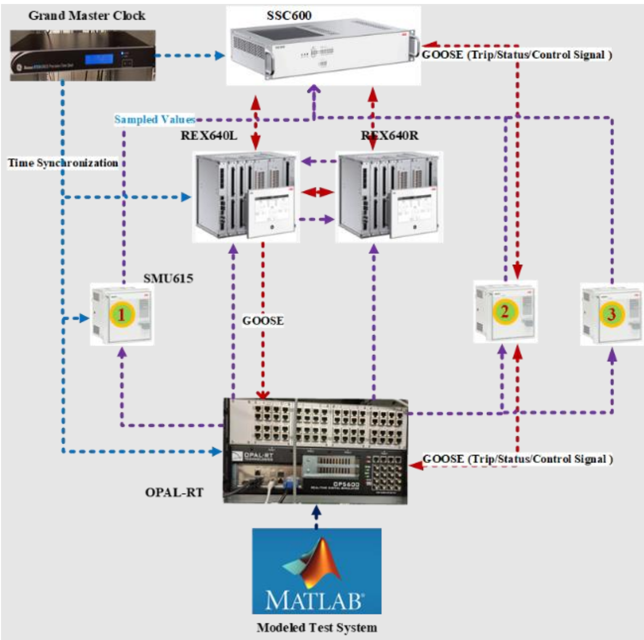


Figure 7. Communication between all devices in the setup.

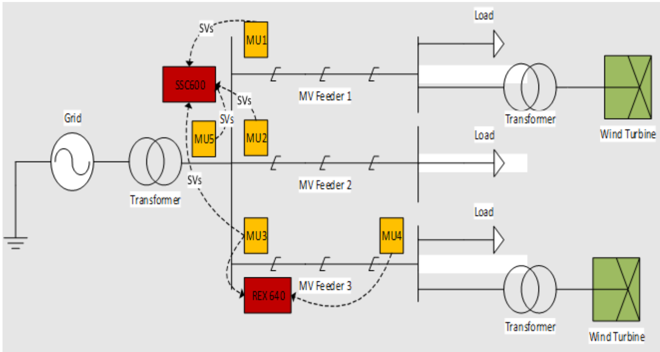


Figure 8. Test system for studying centralized adaptive protection schemes.

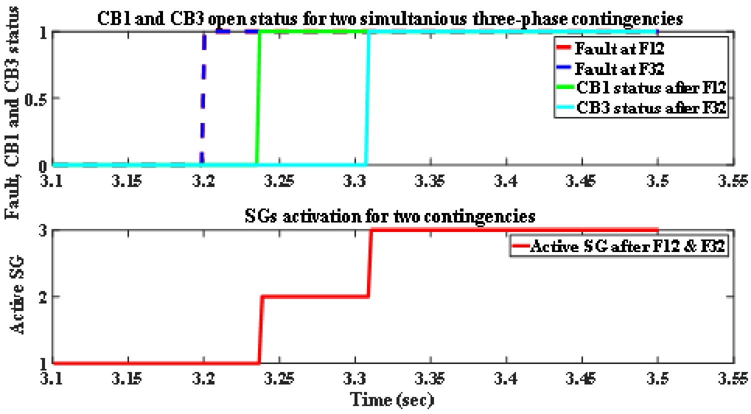


Figure 9. SGs activation considering 2 simultaneous faults at first and third feeders.

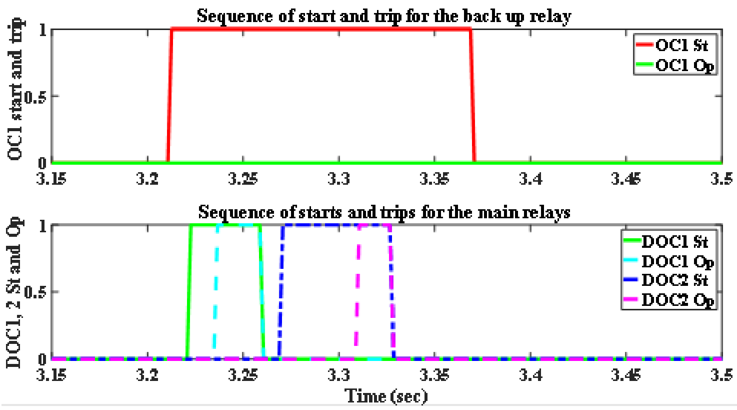


Figure 10. Sequence of starts and operations.

```
-------------------------------------------------
Date                  :   04.04.2024
Time                  :   08:51:45
-------------------------------------------------
Technical key         :   SSC600
IEC 61850 version     :   Edition 2
```

Date	Time	Source	Function	Description	Value
04.04.2024	08:47:57.310	SMU615MU0101	PROTECTION	Active group	
04.04.2024	08:47:57.309	Overcurrent	DPHLPDOC: 2	OPERATE	True
04.04.2024	08:47:57.269	Overcurrent	DPHLPDOC: 2	START	True
04.04.2024	08:47:57.237	SMU615MU0101	PROTECTION	Active group	
04.04.2024	08:47:57.235	Overcurrent	DPHLPDOC: 1	OPERATE	True
04.04.2024	08:47:57.221	Overcurrent	DPHLPDOC: 1	START	True
04.04.2024	08:47:57.213	Overcurrent	PHLPTOC: 1	START	True

Figure 11. Summary of event recorder considering two contingencies in same time and logic mode 1.

In (Pashaei, Rastegar, et al., 2024) hardware-in-the-loop implementation of centralized adaptive protection and control scheme along with the introduction of three novel clustering methods are presented. The primary objective of these methods is to minimize the operating time delays of overcurrent relays. A proper index selection for the clustering of topologies, which have to be equal to or less than the number of setting groups, plays a key role in offline adaptive centralized protection scheme. In this paper, in order to cluster the topologies more effectively and precisely, average time delays of the relays for all the topologies are calculated by considering the realistic TDS values. In other words, in contrast to previous studies, all the TDSs are not assumed to be one. Moreover, a robust setting is suggested for reliability enhancement in adaptive protection systems. In this approach (RIAPS method), a proper setting group is allocated to a robust setting that will be activated using GOOSE (IEC 61850-8-1) message whenever the central server or communication links fail. Results of the optimal setting groups obtained by using this method illustrate that not only will the reliability of the protection system be increased but also the average time delay is improved. The reduced time delay is because of clustering the topologies (25 scenarios in Figure 12) to the number of available SGs or less in relays as shown for one of the methods studied (Method 1) in this publication and shown in Table 1 and Figure 13.

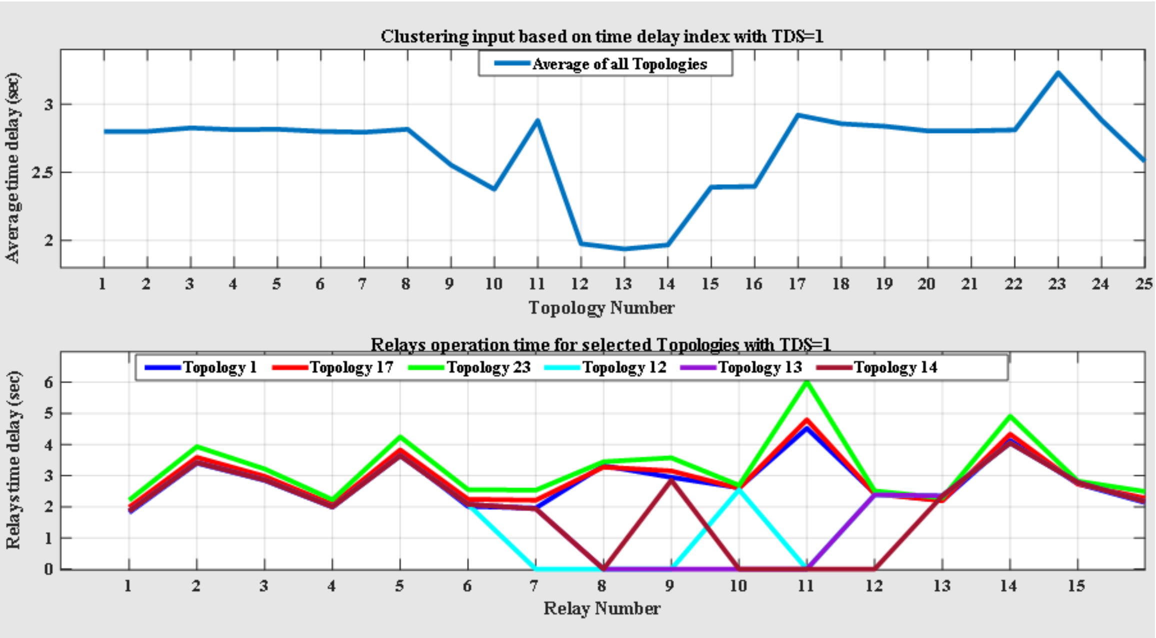


Figure 12. Clustering input for method 1.

Table 1. Topology clusters by using method 1.

Cluster 4	Cluster 3	Cluster 2	Cluster 1
16،15،10	25،9	1-8,11 24-17	14،13،12

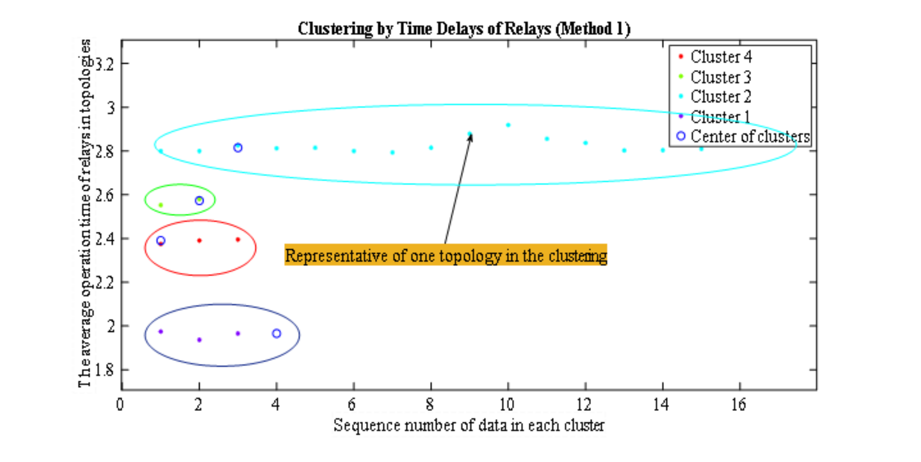
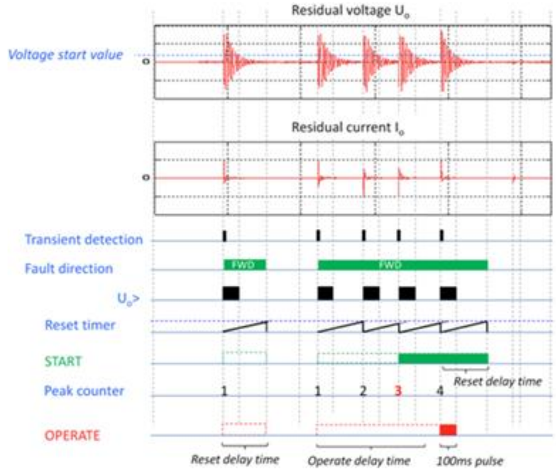


Figure 13. Clustering results and input data.

3.3. Earth fault management

Detection and location of earth faults, which account for approximately 50-80% of faults in Nordic countries, have consistently posed a challenge for Distribution System Operators (DSOs). This is particularly the case in Finland, where close to 80% of the 20kV Medium Voltage (MV) networks are isolated and a fifth of them are compensated. Both these types of networks are characterized by a low level of fault current. These low-level earth fault currents often present difficulties for conventional functions such as the directional earth fault and residual overvoltage. However, the residual overvoltage function has a higher chance of detection due to the more stable behaviour. What deteriorates the situation is intermittent earth faults, which often go unnoticed by traditional protection relays. Traditional phasor-based relaying algorithms typically either dismiss high-frequency sampled signals of intermittent earth fault as noise or continually cycle between starting and resetting. These faults can potentially lead to permanent ones and can be attributed to a variety of factors including the natural aging process of the equipment, electrical overstress, mechanical deficiencies, unfavourable environmental conditions, chemical pollution, moisture ingress, poor insulation, and loose connections. Condition monitoring and early detection of such faults are crucial, especially with the increasing use of underground cabling to enhance the security of electricity supply. These measures can enable DSOs to carry out preventative maintenance, which in turn can reduce system interruptions and improve the delivery of MV electricity.

In this task, first we have implemented intermittent earth fault functionality using SSC600 and the setup shown in Figure 6 and Figure 7. This functionality makes use of residual voltage and current as setting parameters. The number of peaks in residual current resulting from intermittent earth fault is also set between 2 and 20, which is set to 3 in our case study. If the number of spikes in residual current exceeds the set value, the function will operate. These parameters are shown in Figure 14.



Parameter Setting

Parameter Name	IED Value	New Value	Unit	Min.	Max.	Step
Operation	on	on				
Operation mode	Intermittent EF	Intermittent EF				
Directional mode	Forward	Forward				
Operate delay time	500	500	ms	40	1200000	10
Reset delay time	1000	1000	ms	40	60000	1
Peak counter limit	3	3		2	20	1
Voltage start value	0.20	0.20	xUn	0.05	0.50	0.01
Min operate current	0.20	0.20	xIn	0.01	1.00	0.01

Figure 14. Setting of parameters for intermittent earth fault detection

The result for the simulated intermittent earth fault (Figure 15) in phase C of the first feeder in the test system is shown in Figure 16, with the operation time being 0.449 sec.

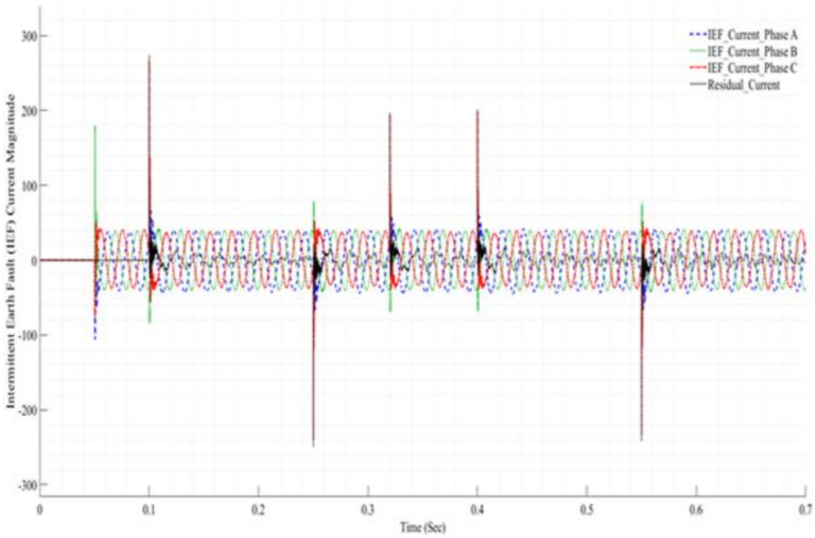


Figure 15. Simulated intermittent earth fault

```
Product identifiers
----------------------------------------------
Type                     :    SSC600
Product version          :    1.0 FP3
-----------------------------------------------------------------------------------------------
Fault record 905
Parameter name           IED value             Unit           Min            Max
-----------------------------------------------------------------------------------------------
Fault number             905                                  0              999999
Time and date            2023.09.08 19:12:40:856
Protection               INTRPTEF
Protection instance      1                                    1              999999
Start duration           100.00                %              0.00           100.00
Operate time             0.449                 s              0.000          1000000.000
Breaker clear time       (3.000)               s              0.000          3.000
Active group             1                                    1              6
-----------------------------------------------------------------------------------------------
Fault record 902
Parameter name           IED value             Unit           Min            Max
-----------------------------------------------------------------------------------------------
Fault number             902                                  0              999999
Time and date            2023.09.08 19:09:46:844
Protection               INTRPTEF
Protection instance      3                                    1              999999
Start duration           77.00                 %              0.00           100.00
Operate time             0.300                 s              0.000          1000000.000
-----------------------------------------------------------------------------------------------
Fault record 901
Parameter name           IED value             Unit           Min            Max
-----------------------------------------------------------------------------------------------
Fault number             901                                  0              999999
Time and date            2023.09.08 19:09:44:533
Protection               INTRPTEF
Protection instance      1                                    1              999999
Start duration           99.99                 %              0.00           100.00
Operate time             0.395                 s              0.000          1000000.000
-----------------------------------------------------------------------------------------------
```

Figure 16. Relay operation time for an intermittent earth fault in phase C

The second and third part of this task was the use of machine learning-based (ML-based) techniques to detect and classify intermittent earth fault and permanent earth fault. In (Pashaei et al., 2023) we proposed an intermittent earth fault detection approach for monitoring the condition of MV distribution networks based on the voting classification (VC) methodology, which benefits from several classifiers, thus increasing reliability of the algorithm compared to the use of single classifier. Comparison between the results, based on various criteria such as Precision, Recall, F1, and Accuracy of VC technique and that of KNN, GNB, MLP, and Dtree shows the effectiveness of the VC method in the prediction of the existing and future faults of the system. This is why aggregated information displayed to human grid operators can help them schedule maintenance to avoid evolving intermittent faults into permanent ones.

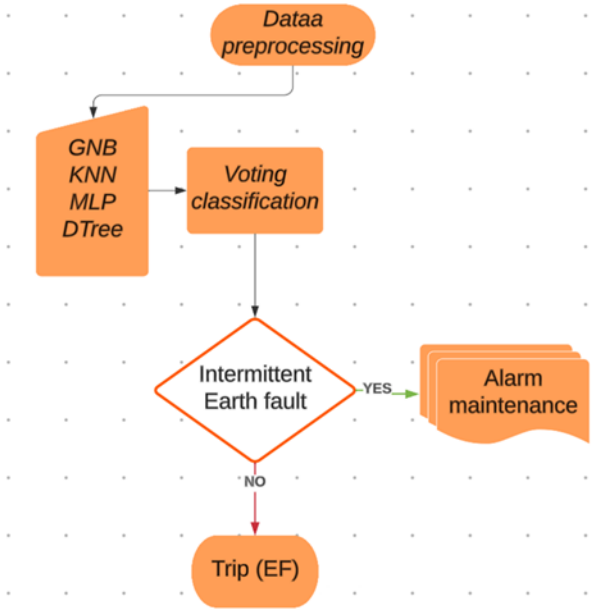


Figure 17. Proposed flowchart for the intermittent fault detection

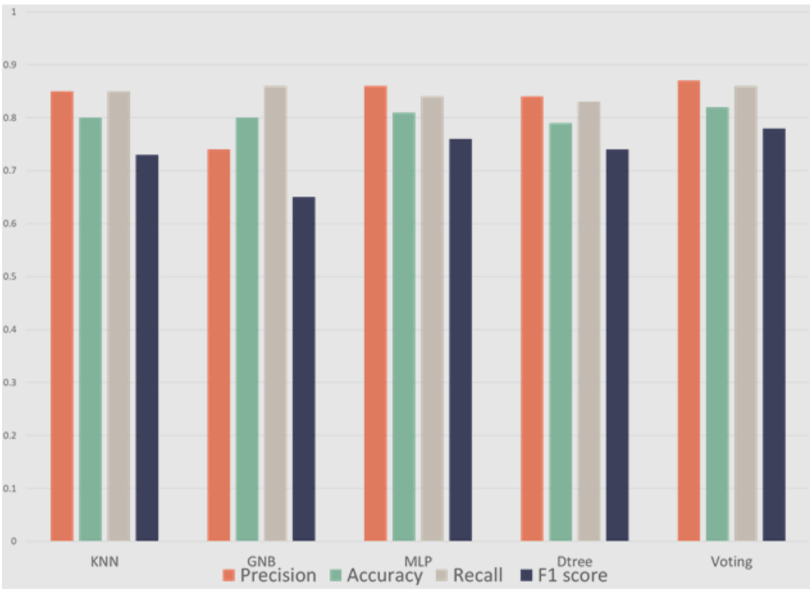


Figure 18. Comparative results for the applied methods

The results in Figure 18 shows the better performance of VC compared to each of the methods. It is worth noting that in the figure metrics are calculated using the following formulas and Figure 19. The confusion matrix in the figure, for example, for True Positive (TP) shows the number of predicted intermittent earth fault by model that are intermittent earth faults in reality. However, FP is the instances that are normal earth fault, but the model predicted them as intermittent one.

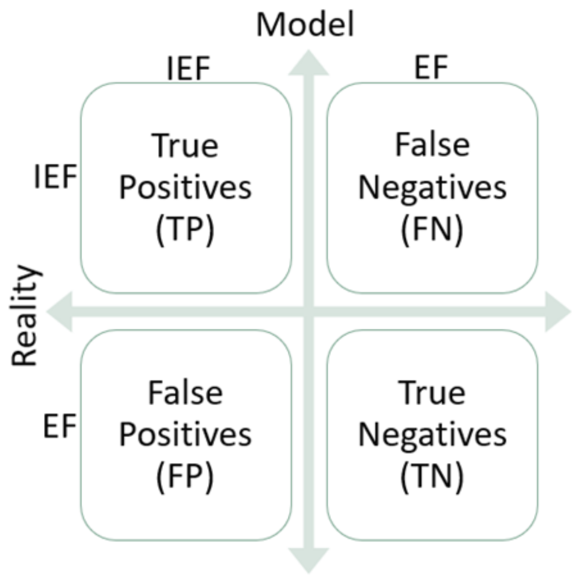


Figure 19. Confusion matrix for the assessment of proposed method

The performance of ML methods can be evaluated with the following metrics:

- Accuracy = (TP+TN)/(TP+TN+FP+FN)
- Precision = TP/(TP+FP)
- F1 score = 2*(Precision*Recall)/(Precision+Recall)
- Recall = TP/(TP+FN)

We also explored the ML-based techniques and supervised learning namely multilayer perceptron (MLP), support vector machines (SVM), Long short-term memory (LSTM) and Decision Tree algorithms in classification of intermittent earth fault in an MV 20kV distribution system in the publication (Razmi et al., 2024). The sporadic nature and short duration of these faults make them difficult to detect using traditional methods like phasor-based algorithms. This study explored the application of machine learning techniques, specifically MLP, SVM, and Dtree, for classifying intermittent earth faults and normal ones. The outcomes of the study validated the effectiveness of the employed methods, especially emphasizing that the Support Vector Machine (SVM) and Decision Tree algorithms demonstrated a classification accuracy surpassing 98%. This level of accuracy significantly outperformed the Long Short-Term Memory (LSTM), Recurrent Neural Network (RNN), and Multilayer Perceptron (MLP) models, which were prone to higher rates of classification errors. These findings emphasize the significance of employing machine learning approaches for accurate intermittent earth fault detection. The summary of this study and confusion matrix are shown in below table and Figures.

Table 2. Accuracies of different algorithms

Algorithm	Validation		Testing	
	Accuracy	Recall	Accuracy	Recall
SVM	98.5 %	98.6 %	98.9 %	98.9 %
DT	99.1 %	98.4 %	98.8 %	98.7 %
LSTM	76.4 %	75.6 %	74.6 %	75.3 %
RNN	75.5 %	75.1 %	74.4 %	74.9 %
MLP	69.6 %	69.8 %	68.2 %	68.4 %

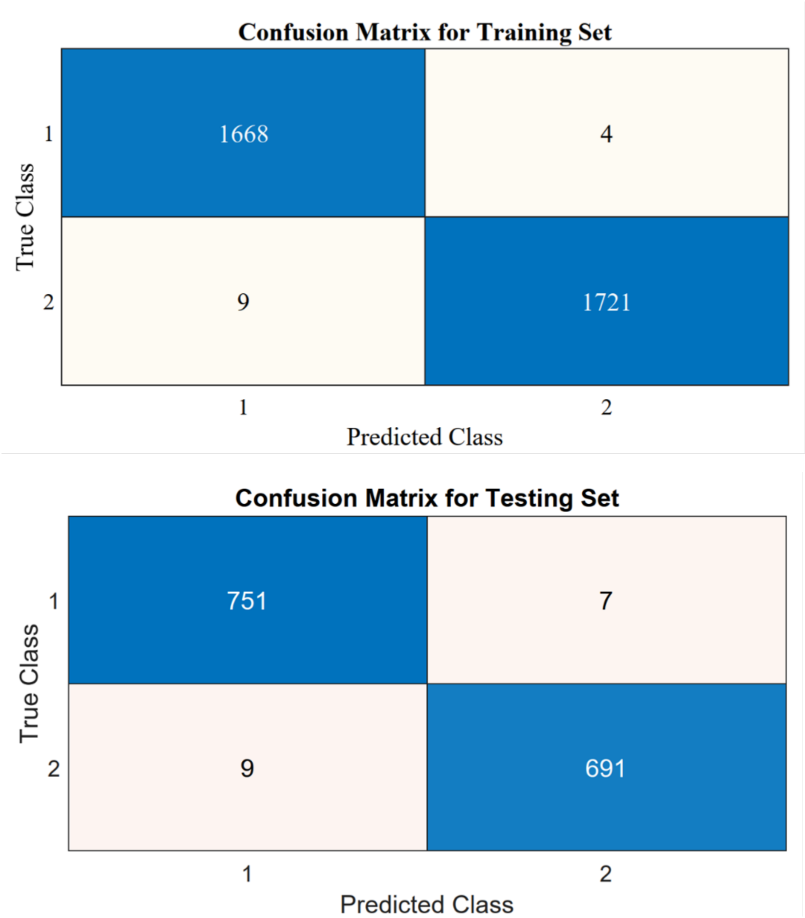


Figure 20. Confusion matrix for SVM as the best method of classification

3.4. Connectivity and cyber security

In this task various tests and experiments were conducted using the private 5G communication setup at the laboratory. The aim was to get knowledge and hands on experience of the capabilities of 5G communication and various setting affecting its performance. Additionally, the possibilities to implement AI based solutions at edge level and effects of basic cyber security attacks were studied.

3.4.1. Testing the 5G connectivity

This section gives an overview of the results obtained regarding the 5G connectivity and a test case for intelligent protection applying 5G (Saleh et al., 2024). The first step was to establish a 5G connectivity. In our laboratory we have our 5G base station (Amarisoft Base Station) which can generate cellular signals and provides a 5G communication network as per 3GPP standard release 17. To connect with our 5G network we have our own sim cards which can be inserted into any user device (5G router or Raspberry PI Hats) which supports 5G connectivity. Once the sim cards are inserted and the access point network (APN) is configured, we get easily access to our 5G network.

With our 5G setup we tested a novel method of protecting power lines by predicting faults using AI algorithms and 5G to communicate information between two sections of a power network. The idea was to test the proposed method with a hardware-in-loop setup, 5G communication, and an edge server running intelligent algorithm. A power grid model was built on Simulink and dataset was generated using that model. The dataset consisted of voltage and current measurements of the grid taken during normal operation and during faults. Using these datasets a model was trained using Python language and a script was created which allows the trained machine learning model to run in real-time.

For testing in real-time the application of 5G communications and the AI algorithm for protection of power system, a hardware-in-loop setup was designed as shown in Figure 21 and with devices shown in Figure 22. A power grid model running in OPAL-RT would send real-time voltage and current measurements over the 5G network to the AI algorithm running at an edge server of the 5G base station. So, the 5G base station acts as a cellular signal generator and can run AI algorithms in real-time.

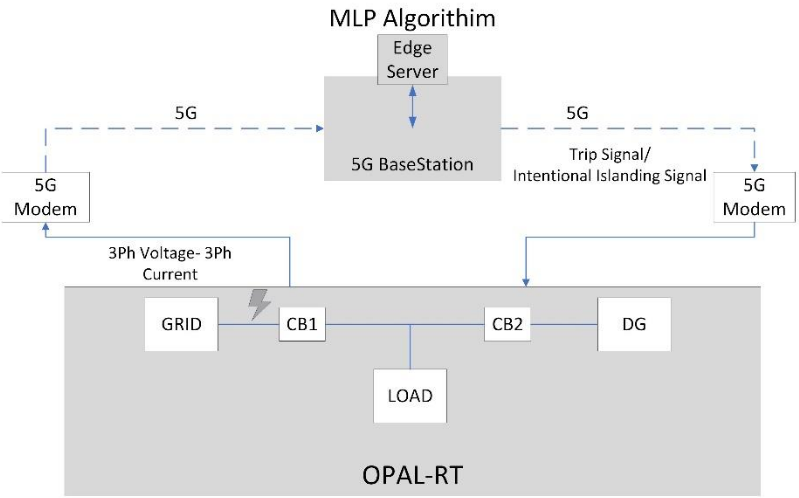


Figure 21. Test Setup for Virtualized Intelligent Relaying over 5G

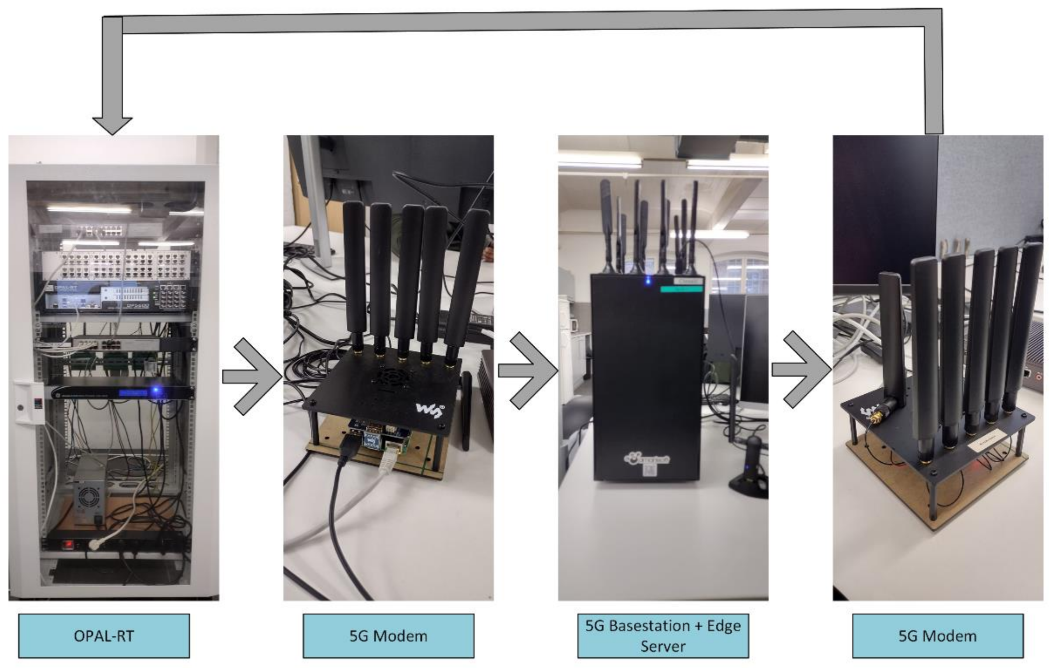


Figure 22. Devices involved in implementation

The next step involved testing the applicability of the proposed concept. Since 5G communication introduces latency into the system, AI algorithms were employed to predict faults before they actually occurred, thereby overcoming the latency barrier. Multiple sets of tests were conducted, yielding varying results. However, in all cases, the AI algorithm successfully predicted the fault before it occurred. Two specific results highlighted in the paper demonstrate that the fault was predicted and isolated within 90 ms and 200 ms after a pre-fault event. This time frame includes both the 5G communication latency and the time required for the AI algorithm to make its predictions.

3.4.2. Experiments with the monitoring application

The monitoring application developed was experimented with the line differential protection setup connected to the 5G devices as described in a forthcoming publication "Monitoring Application For Line Differential Protection Applying 5G". Line differential protection (LDP) works on the principle of Kirchhoff's circuital law which compares node currents and protect lines by resulted differential current. Differential current more than zero or threshold value highlights a presence of a fault in a power line. The line differential protection can be developed by utilizing wide area measurements. IEC61850 standards provides a way to communicate the wide area measurements using Sampled Values (SV) and allows entities to perform control & protection functionalities using Generic Object Oriented Substation Events (GOOSE). The protection methods can be developed by utilizing wireless communication, such as 5G, to perform distributed or centralized protection & control functions over wider areas. 5G communication network are economical solution but the latency (delay) of the communication is a challenge for its implementation. In this paper a line differential protection setup is established which allows ABB REX640 devices to communicate with each other by sending the traffic over private 5G network. To monitor the communication performance of 5G, a monitoring application was developed using TShark packet analyzer, Python, and MQTT protocol.

GOOSE messages and SV used in line differential protection can be communicated over the 5G network and monitored using the monitoring application (see the figure below). In this paper we developed the application to monitor GOOSE messages. Monitoring the performance of GOOSE messages help us evaluate the effect of changing configuration of 5G network on the GOOSE latency, jitter, and packet loss. It also helps in studying and analysing the behaviour of REX640 relays when they are communicating over a wireless 5G network.

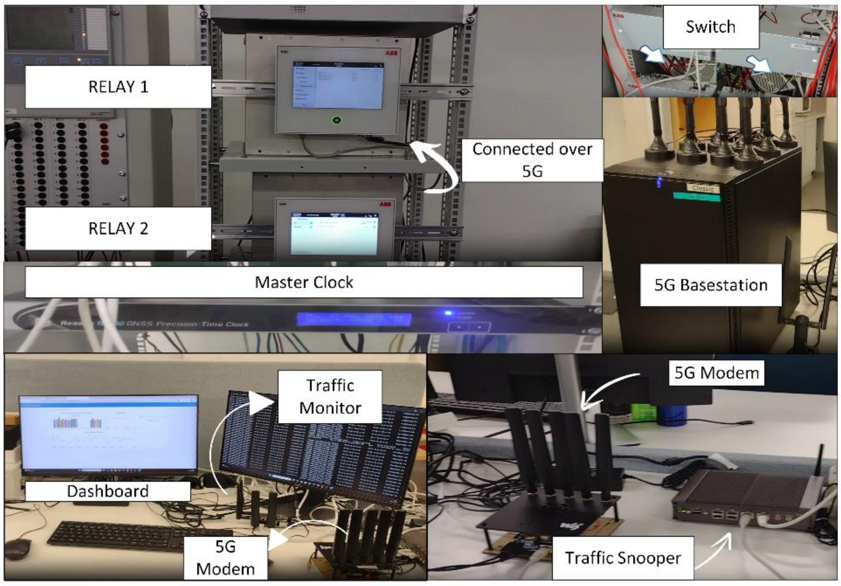


Figure 23. LDP monitoring setup over 5G network

The 5G network created with Amarisoft base station can be configured with n-number of possible configuration combinations. We observed that changing some of the configuration parameters contributed in either decreasing or increasing the latency of the GOOSE messages. One such configuration parameter is defining the uplink (UL) and downlink (DL) slot configuration and associated period with it. However, it is important to mention that a 5G network can be configured as frequency division duplex (FDD) or time division duplex (TDD). In this paper we have studied the TDD configuration settings. The figure and table below show the effect of changing configurations on the latency and jitter. Some of the parameters such as frequency, subcarrier spacing, antenna setting, and similar other parameters were kept same for both the settings.

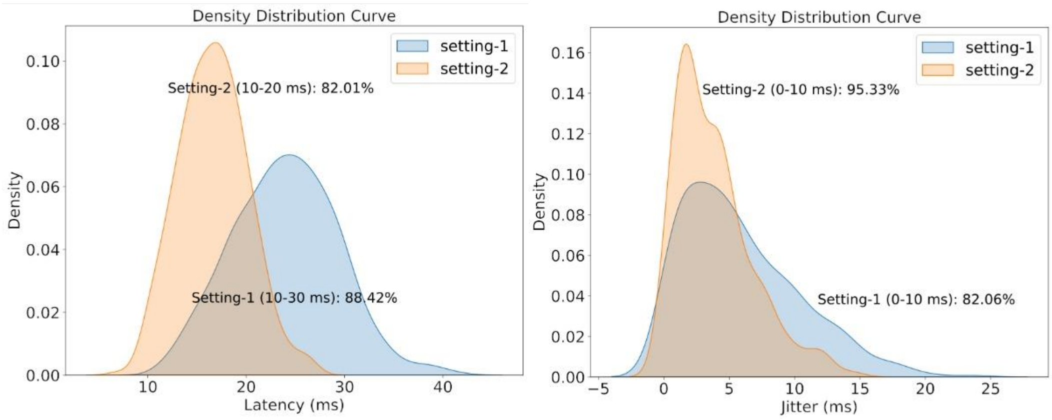


Figure 24. Latency and Jitter results for two different settings

Table 3. Latency and Jitter Packet Distribution.

Majority Packets	**Latency**			**Jitter**	
	0-10 ms	**10-20 ms**	**20-30 ms**	**0-5 ms**	**5-10 ms**
SA Setting 1	0%	24.88%	63.55%	51.60%	30.47%
SA Setting 2	1.4%	82.01%	16.59%	72.66%	22.90%

3.4.3. Cybersecurity in 5G and beyond networks

5G and beyond wireless network provides opportunity for developing innovative methods to protect the electrical grid but this process of digitalizing the grid also brings cybersecurity related challenges. Digitalized power system protection is a critical infrastructure which protects the electrical grid, but it is also vulnerable to cyberattacks. A poorly developed protection system can provide an attacker a way to listen to critical information, inject false information, congest the network of protection system, or even cause maloperation of the protection system.

Time sensitive protection methods, such as line differential protection, needs time synchronization to ensure the current measurement are received and compared at exact same time. In such methods the relays or other protection devices are time synchronized with a master clock. Time based cyberattacks can disturb the time synchronization of the system and it can cause protection devices to go either into blocking state or false operation.

In the forthcoming paper "Cybersecurity challenges and solutions for B5G integrated protection methods" we aim to study challenges and solutions related to cyberattacks on time sensitive protection methods. IEEE 1588 PTP protocol is used as per the IEC61850 standard to allow protection devices to time synchronize with a master clock. However, it is possible to manipulate the network time synchronization by introducing fake master clock which uses fake PTP messages. Therefore, the possible solution could be to improve PTP algorithm, use encryption methods, or other possible concepts to prevent cyberattacks.

3.4.4. Aspects of IT/OT cyber security

As utilities increasingly integrate Information Technology (IT) and Operational Technology (OT) systems, cybersecurity has become a critical concern. This integration, while improving operational efficiency, introduces complex vulnerabilities and cyber threats. A forthcoming paper "IT/OT challenges and opportunities to improve cyber resiliency for utilities: a review paper" is prepared jointly with REDISET project, which evaluates strategies based on the National Institute of Standards and Technology (NIST) cybersecurity framework to address these challenges, noting the need for alignment between IT and OT practices. Key threats include malware, phishing, advanced persistent threats (APTs), denial of service attacks, zero-day exploits, insider threats, and supply chain attacks. Each presents unique risks that necessitate a unified cybersecurity approach.

The paper suggests leveraging advanced technologies such as automated monitoring tools, blockchain for data integrity, AI-driven supply chain management, machine learning for predictive analytics, quantum-resistant encryption, and advanced network segmentation to enhance security.

By comparing the proposed strategies with existing literature, the report identifies strengths and areas for further research, emphasizing the need for empirical validation. It aims to provide a comprehensive framework to help utilities strengthen their defences against cyber threats through improved IT/OT collaboration and adherence to established cybersecurity standards.

In this regard, research has been carried out to delve into these issues, offering a comprehensive exploration of the challenges and opportunities that arise from the IT-/T integration in utilities. It seeks to understand the underlying causes of friction between IT and OT cultures, identify the cybersecurity risks specific to the utility sector, and propose actionable strategies for enhancing collaboration and cyber resilience. By examining successful models of IT/OT integration and drawing lessons from sectors that have effectively managed similar transformations, this forthcoming paper aims to provide utility companies with a roadmap to strengthen their defences against cyber threats.

4. CONTROL OF DER UNITS

This chapter summarizes the project results from WP3, which included the following tasks:

- T3.1: DER control behaviour during grid faults
- T3.2: Development of centralized control methods

4.1. DER control behaviour during grid faults

4.1.1. Grid-following converters in low inertia systems

The integration of renewable energy sources (RESs) such as solar and wind into power systems is accelerating to achieve cleaner and more sustainable energy production. However, transitioning from conventional systems to those with high RES penetration presents significant challenges, particularly in low-inertia systems. This issue is discussed in paper (Aljarrah, Fawaz, et al., 2024), which is summarized here.

In power grids, inertia is crucial for maintaining stability and is traditionally provided by synchronous generators (SGs). Low-inertia systems and weak grids, characterized by low short circuit ratios (SCR), are more sensitive to disturbances. High penetration of RESs reduces system inertia, leading to issues such as voltage and frequency instability and the malfunction of protection systems. This reduction in system strength exacerbates these challenges, making weak grids even more vulnerable.

Grid-Following Converters (GFL) are commonly used to interface RESs with the grid. These converters rely on the grid for stable operation, which becomes problematic in low-inertia systems. The performance of GFL converters is affected by grid strength, control topologies, and tuning parameters. In weak grids, issues such as phase-locked loop (PLL) problems and high-frequency stability concerns are prevalent.

Key challenges in low-inertia systems include:

- Voltage and Frequency Stability: Ensuring stable voltage and frequency under all operating conditions is critical.
- System Strength Reduction: Reduced system strength impacts the operation of other grid components and devices.

- Control and Synchronization: Effective control and synchronization of GFL converters are challenging in weak grids.

Addressing these challenges in low-inertia systems is essential for the successful integration of RESs. Future research should focus on enhancing GFL functionality, improving control mechanisms, and updating grid codes to support scenarios with high RES penetration.

4.1.2. ANN based tool for short circuit currents estimation

The increasing integration of Power Electronics (PE)-based renewable energy sources (RESs), such as wind and photovoltaic (PV) systems, is significantly altering the dynamics and characteristics of power systems traditionally dominated by synchronous generators (SGs). Specifically, the presence of PE-based renewables affects the short circuit (SC) currents, which are crucial for the secure operation of the power grid. Traditional methods of estimating SC currents, which rely on detailed and complex time-domain simulations, can be computationally intensive. In (Aljarrah et al., 2023) a method has been proposed for faster and more efficient alternative by utilizing an Artificial Neural Network (ANN)-based tool for estimating SC currents in systems with high renewable penetration.

The proposed ANN-based tool is designed to estimate the characteristics of SC currents, including sub-transient, transient, and peak currents, based on the level of renewable penetration. The methodology involves several key steps:

- Modeling and Simulation: The power system is modeled using DIgSILENT PowerFactory software, where various scenarios of renewable penetration are simulated. The scenarios range from 0% to 100% penetration of PV systems.
- Data Collection: The SC currents are calculated using the IEC 60909 standards, which account for the fault contributions from both SGs and PE-based renewables. The dataset generated includes the SC current components for each penetration level.
- ANN Development: An ANN is trained using the collected data to map the relationship between renewable penetration levels and SC current characteristics.
- Validation: The trained ANN is validated against additional scenarios to ensure its accuracy in estimating SC currents.

The application of the ANN-based tool on a modified IEEE 9-bus test system demonstrated its effectiveness. The tool accurately estimated the SC current components across various scenarios of renewable penetration. The ANN was able to provide quick and accurate estimations without the need for detailed modeling or repetitive fault calculations, making it a valuable tool for system operators and planning engineers.

The study successfully developed and validated an ANN-based tool for estimating SC currents in power systems with high penetration of PE-based renewables. The tool offers a fast and efficient alternative to traditional methods, providing accurate estimations based on renewable penetration levels. This approach enhances the understanding of SC characteristics in future power systems and supports the secure and stable operation of grids with significant renewable integration.

The paper discusses the development and application of an ANN-based tool for estimating short circuit currents in power systems with high penetration of power electronics-based renewable energy sources. The tool addresses the challenges posed by the changing dynamics of SC currents due to the increased use of renewable energy, providing a faster and efficient alternative to traditional estimation methods. The study's results validate the tool's accuracy, making it a valuable asset for grid operators and engineers in managing future power systems.

4.1.3. Grid inverter behaviour under low voltage ride through events

One essential requirement for the grid connected inverters is the ability tolerate grid faults. In the grid codes this is usually referred as low voltage ride through (LVTR) capability. During the project, simulation models were developed for studying the behaviour of inverters during the specified grid faults. As a basis the existing model for the Sundom Smart Grid was utilized. For the control of inverter some novel approaches were tried. The challenging part in this kind of events is to have the inverter operating properly even in severe voltage dips. Furthermore, the maximum current feeding capacity of the inverter must not be exceeded. The newest grid code standards specify some additional requirements for the current fed during the fault. This part of the research is expected to be finalized later and the work is partly continued in a parallel project Smart Grid 2.0 and further extended in a new project “Grid Code Certification by Simulation”.

4.2. Development of centralized control methods

4.2.1. Direct power control method

The integration of renewable energy sources into the utility grid has led to the development of microgrids (MGs). These systems require advanced control methods to manage power flow between the MG and the main grid, ensuring stability and high power quality. Traditional control methods often rely on PLL, which can introduce delays and instability.

The paper (Ahmad et al., 2022) proposes a direct power control (DPC) approach for grid-tied AC microgrid (MG) photovoltaic (PV) voltage source inverters (VSIs). This method regulates active and reactive power by modulating the point of common coupling (PCC) voltage, eliminating the need for phase-locked loop (PLL) technology. This approach simplifies the control system and improves dynamic performance. The method includes:

- Nonlinear PCC Voltage Modulation: Directly controlling real and reactive power.
- Feedforward and Feedback PI Controllers: Ensure accurate power tracking and stability.

In the paper real-time simulations are presented validating performance of the proposed control method. The results indicate faster convergence and lower power oscillations compared to traditional control method:

- Faster Power Tracking: Achieved in 0.055 seconds compared to 0.23 seconds with traditional methods.
- Lower Power Oscillations: Nearly zero steady-state power oscillations.
- Reduced Harmonic Distortion: Total harmonic distortion (THD) of 1.697% at VSI output current.

4.2.2. Impacts of grid forming converters

The impact of high penetration of renewable energy sources (RESs), particularly those utilizing grid-forming (GFM) converters, on the propagation of voltage dips in power systems has been investigated. As the integration of converter-interfaced RESs like wind and photovoltaic (PV) systems increases, conventional synchronous generators (SGs) are being displaced. This transition leads to reduced system inertia and fault levels, thereby weakening the overall grid strength and resilience.

The diminished system strength in renewable-rich power systems poses significant challenges, particularly in the event of short circuit (SC) faults. Traditional Grid-Following (GFL) converters, widely used in RESs, have limited capabilities to support the grid during such disturbances, exacerbating the propagation of voltage dips. The research presented in (Aljarrah, Karimi, et al., 2024) addresses the potential of GFM converters to mitigate these issues by emulating the dynamic behaviour of traditional SGs.

The study utilizes the IEEE 9-BUS test system implemented in DIgSILENT PowerFactory software that has been presented in Figure 25. The research begins by comparing the SC response of GFM converters with that of GFL converters and SGs. Various penetration scenarios of RESs, based on GFL and GFM converters, are simulated to assess their impact on voltage dip propagation. The focus is on droop-based GFM converters, which are modelled and controlled to adjust their output frequency and voltage in response to grid conditions.

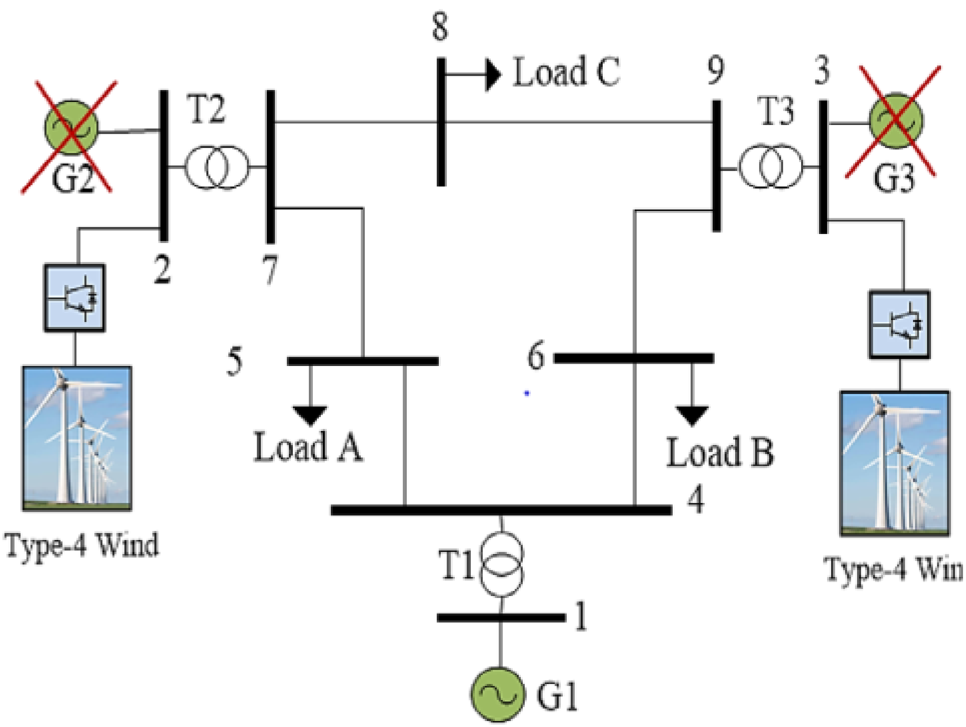


Figure 25. The adjusted IEEE 9-bus system with RESs

The findings of the research are as follows:

- Short-Circuit Behavior: GFM converters demonstrated a distinct advantage over GFL converters during SC events. GFM converters provided a higher transient current contribution, which helps in stabilizing the grid voltage more effectively during faults.
- Voltage Dip Propagation: The study shows that systems with high penetration of GFL-based RESs suffer from extensive voltage dip propagation due to the limited dynamic support offered by these converters. In contrast, GFM converters significantly reduced the severity of voltage dips, thereby enhancing the overall system stability.
- Control Strategy: Droop-based GFM converters were found to be particularly effective in maintaining stable voltage and frequency outputs, even under high penetration of RESs. This control strategy allows GFM converters to actively regulate the grid, mitigating voltage dip propagation.

It is noted that the GFL-based RESs fails to support the dynamic voltage as intended. For instance, bus 2 which is directly connected to the RESs at G2 has shown the minimum voltage during the fault with a value of 0.366 p.u, as shown Figure 26.

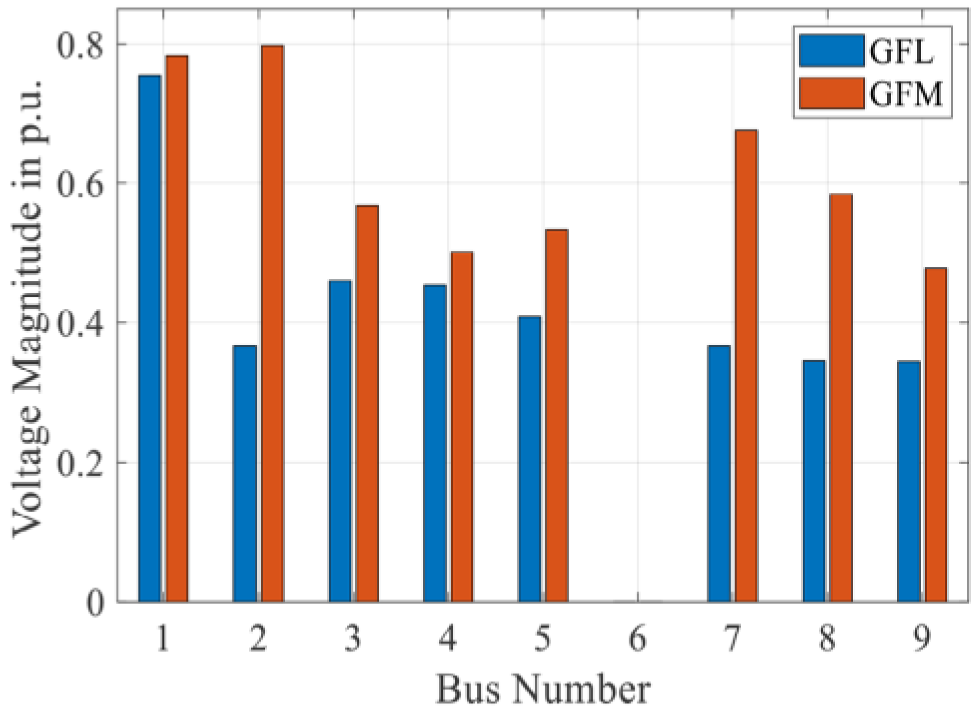


Figure 26. Minimum bus voltages during the fault

The research concludes that GFM converters, particularly those employing droop-based control, are a promising solution to the challenges posed by high penetration of RESs in power systems. By improving dynamic voltage support and reducing voltage dip propagation, GFM converters can enhance grid stability and resilience in renewable-rich environments.

This study highlights the importance of transitioning from GFL to GFM converters in renewable-rich power systems to address the challenges of reduced system inertia and fault levels. Through extensive simulations, the research demonstrates that GFM converters can, in most cases, effectively mitigate voltage dip propagation, making them a vital component in the future of power systems with high RES penetration.

5. SUMMARY AND CONCLUSIONS

In the CIRP-5G project, the aim was to develop new centralized, intelligent, and resilient protection and control methods utilizing cyber-secure 5G-based communication, data analytics, and AI/ML for future active distribution networks. The focus was on modern electricity distribution systems and the utilization of new centralized protection technology and 5G communication. The functionalities studied included islanding detection, earth fault protection, and wide-area monitoring and protection.

As a result of this project, an advanced real-time simulator-based laboratory environment was developed, with a particular emphasis on adaptive protection approaches. In this environment, the latest products by ABB, such as SSC600 and REX640, were utilized. The adaptive protection schemes created were based on activating different setting groups of the relays depending on events in the grid. Furthermore, new clustering methods were developed to achieve the required number of robust setting groups considering different possible network topologies. The development of the laboratory environment, combining the latest centralized protection solutions and a real-time simulation platform, can be considered one of the main outcomes of the project. This environment, together with the gained knowledge and expertise, provides good potential for further studies.

The capabilities of 5G communication were tested by applying a private 5G laboratory network created in a parallel project. In the laboratory setup, 5G communication was applied in a differential protection use case. An integral part of the laboratory setup was a monitoring application developed to study the performance of the communication, especially considering latency and jitter. Furthermore, cybersecurity aspects were briefly studied. Significant steps were achieved in this project concerning the capabilities to experiment with 5G technology in the context of power system protection. Further steps are expected to be achieved in subsequent projects with expanded facilities and potentially with 6G communication in the future.

Besides the experimental parts, the project results include the development of several applications of computational intelligence related to islanding detection and intermittent earth faults, among others. The machine learning and AI methods are particularly useful for analysing the large amount of data available from modern distribution systems. For practical implementation, the availability of data processing capability should be considered. Some data processing can be done at the edge level, while part of the processing may be most beneficial at the cloud level. In this project, a comprehensive review of related emerging technologies, such as edge and cloud computing, was conducted. Based on that, it became obvious that the system architecture for data processing and computing should always be designed based on the application's needs, considering specific requirements related to speed and security.

Since inverter-based DER units are an essential part of the modern grid, this project also involved studies related to them. Due to the lack of personnel resources and the major resources needed for the experimental parts of the project, this part of the studies was mainly based on international collaboration and several jointly made research papers. A special focus was on the behaviour of the DER controllers, especially considering the newest approaches utilizing grid-forming and grid-following controllers.

In conclusion, the CIRP-5G project successfully reached its targets by providing a large amount of useful knowledge on the topic. In total, 11 scientific papers were published, and several more will be published in the near future. Additionally, the developed laboratory facilities and the gained knowledge form a good basis for potential future projects.

6. LIST OF PUBLICATIONS

The publications listed below are or will be available also at the Osuva, open archive of UVA: https://osuva.uwasa.fi/.

Ahmad, S., Jhuma, U. K., Karimi, M., Pourdaryaei, A., Mekhilef, S., Mokhlis, H., & Kauhaniemi, K. (2022). Direct Power Control based on Point of Common Coupling Voltage Modulation for Grid-Tied AC Microgrid PV Inverter. *IEEE Access*, 1–1. https://doi.org/10.1109/ACCESS.2022.3213939

Aljarrah, R., Al-Omary, M., Alshabi, D., Salem, Q., Alnaser, S., Ćetenović, D., & Karimi, M. (2023). Application of Artificial Neural Network-Based Tool for Short Circuit Currents Estimation in Power Systems With High Penetration of Power Electronics-Based Renewables. *IEEE Access*, *11*, 20051–20062. https://doi.org/10.1109/ACCESS.2023.3249296

Aljarrah, R., Fawaz, B. B., Salem, Q., Karimi, M., Marzooghi, H., & Azizipanah-Abarghooee, R. (2024). Issues and Challenges of Grid-Following Converters Interfacing Renewable Energy Sources in Low Inertia Systems: A Review. *IEEE Access*, *12*, 5534–5561. https://doi.org/10.1109/ACCESS.2024.3349630

Aljarrah, R., Karimi, M., Azizipanah-Abarghooee, R., Salem, Q., & Alnaser, S. (2024). Voltage dip propagation in renewable-rich power systems utilizing grid-forming converters. *IET Renewable Power Generation*, *18*(5), 753–763. https://doi.org/10.1049/rpg2.12939

Karimi, M., Farshad, M., Azizipanah-Abarghooee, R., & Kauhaniemi, K. (2023). Harmonic Signature-Based One-Class Classifier for Islanding Detection in Microgrids. *IEEE Systems Journal*, 1–10. https://doi.org/10.1109/JSYST.2023.3279389

Pashaei, M., Karimi, M., Kauhaniemi, K., Asadi, A., Pil Ramli, S., & Pourdaryaei, A. (2023). Intermittent earth fault detection in distribution network based on the voting classification technique. *27th International Conference on Electricity Distribution (CIRED 2023)*, 3759–3763. https://doi.org/10.1049/icp.2023.0726

Pashaei, M., Kauhaniemi, K., & Laaksonen, H. (2024, September 10). *Implementation of Adaptive Centralized Protection Scheme in Active Networks with a HIL Setup*. 7th International

Conference on Smart Energy Systems and Technologies (SEST 2024), Turin, Italy. https://doi.org/10.1109/SEST61601.2024.10694251

Pashaei, M., Rastegar, H., Zandrazavi, S. F., Kauhaniemi, K., & Laaksonen, H. (2024). Real-time hardware-in-the-loop approach for adaptive centralized protection schemes using clustering algorithms. *Expert Systems with Applications*, *255*, 124707. https://doi.org/10.1016/j.eswa.2024.124707

Ramli, S. P., Pashaei, M., Karimi, M., Kauhaniemi, K., Pourdaryaei, A., Daryaei, M., & Zarei, M. (2022). The Recent Development of Optimal DOCR Protection Strategies for Sustainable Power Systems via Computational Intelligence Techniques. *IEEE Access*, *10*, 134277–134291. https://doi.org/10.1109/ACCESS.2022.3231603

Razmi, P., Pashaei, M., Karimi, M., Kauhaniemi, K., & Simoes, M. G. (2024). Data-Driven Intermittent Earth Fault Detection in Compensated and Isolated MV Networks. *2024 International Workshop on Artificial Intelligence and Machine Learning for Energy Transformation (AIE)*, 1–6. https://doi.org/10.1109/AIE61866.2024.10561426

Saleh, T., Anwar, A., Elmusrati, M., Kauhaniemi, K., & Välisuo, P. (2024). Virtualized Intelligent Relaying of Smart Grid Over 5G Network. *2024 International Workshop on Artificial Intelligence and Machine Learning for Energy Transformation (AIE)*, 1–6. https://doi.org/10.1109/AIE61866.2024.10561295