

Real-time hardware-in-the-loop approach for adaptive centralized protection schemes using clustering algorithms

Meysam Pashaei^{a,*}, Hasan Rastegar^b, Seyed Farhad Zandrazavi^a, Kimmo Kauhaniemi^a, Hannu Laaksonen^a

^a School of Technology and Innovations, University of Vaasa, Wolffintie 34, 65200 Vaasa, Finland

^b Department of Electrical Engineering, Amirkabir University of Technology, Tehran 1591634311, Iran

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ABSTRACT

The main objectives of adaptive protection are isolating only the faulty network section and operating with varying network topologies and levels of generation. To accomplish this, the settings of protective devices may need to modify if, for example, the network topology is changed. Protection relays can have several predefined setting groups (SGs) depending on the number of possible configurations. However, centralized protection and control devices can store a limited number of setting groups, in many cases by far less than the number of possible network topologies. Therefore, in adaptive centralized protection schemes where online setting calculation is not feasible, a proper method should be used to cluster the different possible configurations and reduce their number to match or be fewer than the number of available SGs in relays. The offline calculated settings for each cluster can be stored in the centralized protection and control devices, which continuously monitor the status of circuit breakers (CBs) online. Then, upon detecting a change in the CB status, the corresponding SG will be activated. This paper presents three new methods for clustering network topologies, considering N-1 contingency in adaptive relay coordination. These methods are compared to the one in the literature and each other in terms of operation time delay of relays. Moreover, to mitigate false operations of relays due to unavailability of communication networks, a setting group is dedicated to the robust setting group. Finally, a practical implementation of the proposed method using IEC 61850 standard is illustrated using two schemes step by step. IEEE 14-bus is selected as a test system to evaluate the applicability of the proposed methods. The results, obtained by using MATLAB, DIGSILENT Programming Language, and hardware-in-the-loop setup show the effectiveness of the proposed methods in minimizing operating time delays of overcurrent relays.

1. Introduction

The need for a continuous supply of ever-increasing electricity demand is of paramount importance, which means the implementation of a resilient and intelligent protection system to ensure the continuity of service is imperative (Ghadiri & Mazlumi, 2020). There is a plethora of challenges when it comes to designing such a system. One of the major issues has been the evolution of passive power networks with unidirectional power flow into active ones (Conti, 2009; Aushiq Ali Memon & Kauhaniemi, 2015). Variation in topologies of such networks can cause several problems in protection systems, including but not limited to protection blinding, false tripping, unintentional islanding, electrical device replacement, and relay setting modification due to varying fault

level (El Naily, Saad, Elhaffar, Hussein, & Mohamed, 2017). In traditional protection systems, a fixed setting is determined for all the possible topologies of power networks. Protection systems that are designed by using conventional methods have several drawbacks such as lack of sufficient sensitivity, slow response, extended modification requirement in relay settings, lack of automatic periodic testing features, and inflexible fixed settings (Detjen, 1988). In the conventional relay coordination, it is costly, time-consuming, and sometimes impossible to change settings after any variation in the topologies of power networks (Urdaneta, Restrepo, Márquez, & Sánchez, 1996). Therefore, traditional protection systems are no longer effective to address the problems concerning active networks with different scenarios and varying topologies (Shih, Conde, Leonowicz, & Martirano, 2017).

One viable solution to tackle challenges associated with traditional

* Corresponding author.

E-mail addresses: meysam.pashaei@uwasa.fi (M. Pashaei), rastegar@aut.ac.ir (H. Rastegar), seyed.zandrazavi@uwasa.fi (S.F. Zandrazavi), kimmo.kauhaniemi@uwasa.fi (K. Kauhaniemi), hannu.laaksonen@uwasa.fi (H. Laaksonen).

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Nomenclature		DOCR	Directional Overcurrent Relay
<i>Indices</i>		<i>Acronyms</i>	
k	Number of setting groups	SG	Setting Group
c_i	i^{th} cluster	CB	Circuit Breaker
$d(x, m_i)$	Distance between the input data and centroids	DPL	DIgSILENT Programming Language
$x \in c_i$	Data which belong to clusters	APCS	Adaptive Protection and Control System
d_{st}	Distance between x_s and x_t vectors	PCC	Point of Common Coupling
j	Dimension of vectors	μPMU	Micro-Phasor Measurement Units
R_i	Cohesion and separation indices	PV	Photovoltaic Systems
S_i	Distance between centroid and data in a cluster	PRP	Parallel Redundancy Protocol
d_{ij}	Distance between the centroids of two clusters	HSR	High-availability Seamless Redundancy
m_{ip}	p^{th} dimension of centroid	MU	Merging Unit
m_i	Centroid of the i^{th} cluster	OF	Objective Function
t	Constant for cohesion index (d_{ij})	LAN	Local Area Networks
q	Constant for separation index (S_i)	AI	Artificial Intelligence
N_i	The number of data in the i th cluster	ML	Machine Learning
p	Constant for Minkowski distance calculation	IED	Intelligent Electronic Device
N	The number of main/backup relay pairs	ICD	IED Capability Description
M	Index for main/backup relays in each pair	SCL	Substation Configuration Language
i	Index for relay pairs	PTP	Precision Time Protocol
j	Index for relays in each pair	MAC	Media Access Control
t_{ij}	Time delay of the relays	SV	Sampled Values
t_m, t_b	Operating time for main and backup relays	ASDU	Application Service Data Units
$I_{sc_{ij}}$	Fault current passing through the relay	RIAPS	Reliability Improvement in Adaptive Protection Systems
I_{p_j}	Pickup current of relays	ACPCS	Adaptive Centralized Protection and Control System
A, B	Constant coefficients for the characteristic curves of relays	GOOSE	Generic Object Oriented Substation Event
$TDS_{j,min}$	Lower bounds of TDS t_{ij}	HHO	Harris Hawks Optimization
$TDS_{j,max}$	Upper bounds of TDS t_{ij}	GWO	Grey Wolf Optimizer
$I_{p_j,min}$	Lower bounds of pickup currents	PSO	Particle Swarm Optimization
$I_{p_j,max}$	Upper bounds of pickup currents	GA	Genetic Algorithm
TDS	Time Dial Setting	TLBO	Teaching-Learning-Based Optimization
CTI	Coordination time interval	GA	Genetic Algorithm
OCR	Over Current Relay	MAC	Media Access Control
		AppID	Application Identifier

power system protection with a fixed setting is adaptive protection and control system (APCS), which has been shown in various studies (Abbasi, Karegar, & Aghdam, 2019; Alam, 2019; Ataee-Kachoe, Hashemi-Dezaki, & Ketabi, 2023; Barranco-Carlos, Orozco-Henao, Marín-Quintero, Mora-Florez, & Herrera-Orozco, 2023; Carlos, Henaio, Quintero, Florez, & Orozco, 2022; Chabanloo, Safari, & Roshanagh, 2018; Chattopadhyay, Sachdev, & Sidhu, 1992; Cintuglu, Ma, & Mohammed, 2017; Detjen, 1988; El Naily et al., 2017; Ganoo, Joshi, Valtari, & Niveri, 2022; Ghadiri & Mazlumi, 2020; Karimkhan Zand, Mazlumi, Bagheri, & Abdali, 2023; H Laaksonen, Ishchenko, & Oudalov, 2014; Aushiq Ali Memon & Kauhaniemi, 2015; Ojaghi & Mohammadi, 2018; Piesciorovsky & Schulz, 2017a, 2017b; Rockefeller, Wagner, Linders, Hicks, & Rizy, 1988; Saber, Zeineldin, El-Fouly, & Al-Durra, 2023; Samadi & Mohammadi Chabanloo, 2020; Shih et al., 2017; Singh & Agrawal, 2018; Atul Kumar Soni, Kumar, Panda, Mohapatra, & Singh, 2023; Sorrentino & Rodríguez, 2023; Thorp et al., 1993; J. Wong, Tan, Rahim, & Tan, 2023; Zanjani, Mazlumi, & Kamwa, 2018; Zhang, Guo, & Liang, 2011). These studies show that APCS is not a new idea, but recent developments in technology, communication standards, and affordable communication links have made it feasible to implement and overcome the limitations of traditional protection schemes. APCS can recognize the topologies of networks by monitoring the status of circuit breakers and determines suitable setting groups based on the topologies. (Chattopadhyay et al., 1992) define the devices that are essential for APCS implementation by using a miniature model of the Saskatoon distribution network to change relay setting and pickup current upon detecting any changes in load and generation level. (Thorp et al., 1993)

in the K8 working group (Substation Protection relaying Subcommittee of the IEEE) have evaluated the feasibility of using adaptive protection for several protective functions from the technical perspectives in 1993, concluding that while protection engineers have a high level of satisfaction with current functions in use, they welcome adaptive functionalities in overcurrent, differential and distance protection. (Rockefeller et al., 1988) present the different methods for APCS in transmission lines such as adapting impedance matrices for fault calculation, adaptive reclosing, and adaptive setting in islanding mode. In that reference, reliability improvement, sensitivity to high impedance fault, and the acceleration in the rate of restoration with monitoring of false trips are mentioned as the adaptive protection advantages. As well as technical aspects, economic one has always been a key factor to put the proposed schemes in use. (Detjen, 1988) conducted the technical evaluation as well as the economic one, and the results show that despite the high initial investment, the benefit-to-cost ratio of adaptive protection varies from 4.3 to 33, which means adaptive protection is expected to be significantly more cost-effective compared to traditional schemes in the long term. Today, the implementation of APCS is in reach thanks to the advances in technology and maturity of IEC 61850, which enables the implementation of a fully modular and scalable protection system.

APCS can be classified from different perspectives. One of them is the communication aspect, which divides the schemes into communication-less or communication-assisted types. (Zanjani et al., 2018) analyze the use of micro-Phasor Measurement Units (μPMUs) for the adaptive communication-based protection of a microgrid. In that reference, by voltage and current phasor estimation in the point of common coupling

(PCC), the Thevenin impedance matrix is calculated so as to monitor the upstream network topology changes and have adaptive relay setting. Adaptive protection of overcurrent relays for radial distribution networks is examined by (A A Memon & Kauhaniemi, 2021) to make better use of IEC 61850 standard and GOOSE protocol to issue a faster trip and alarm decisions. Another relevant study, referenced as (A K Soni, Kumar, Panda, Mohapatra, & Singh, 2023), focuses on adaptive coordination and comprehensively considers various scenarios and the reconfiguration process, while also considering the dual-setting characteristics for each relay using hardware-in-the-loop setup. (J. Wong et al., 2023; J. Y. Wong et al., 2023) employed a communication-less adaptive protection scheme within the reconfiguration process, which is specifically recommended for regions characterized by limited access to communication links and essential infrastructure. In this approach, a microcontroller is utilized to predict the future settings of the relays by continuously monitoring the load flow. When it comes to the section-alizing of a network comprising multiple microgrids, there is a significant potential for protection coordination failure, as observed in a specific case study where it reached 68.4%, as detailed by (Saber et al., 2023). To tackle this issue, a non-communication-based protection scheme is proposed, which incorporates novel relay characteristics.

APCS, from the control system point of view, is divided into centralized, decentralized, and hybrid systems (Ganoo et al., 2022). In central adaptive protection, a central server or monitoring and protection control device is utilized to process data, to detect any changes in topologies of networks, and to send or activate proper settings to relays (H Laaksonen et al., 2014). The need for communication links and strong central servers as well as vulnerability against single point failure, are considered drawbacks of this system, while we believe that by considering full redundancy, single-point failure will be solved. Nevertheless, we put forward another method for networks that do not use full redundancy. (Cintuglu, Ma, & Mohammed, 2017b) proposed a decentralized adaptive protection, which is based on multi-agent systems and the IEC 61850 standard, for addressing the central adaptive protection problems, while structural and operational uncertainties are considered.

APCS from the setting calculation point of view is categorized into the online and offline methods. In the online method, after topology variation, settings of relays are calculated and sent to relays, but in the offline method, the settings of relays are calculated before the identification of topologies (Ojaghi & Mohammadi, 2018). In both methods, the status of network and circuit breakers is monitored online. In this paper, an offline method will be discussed, which offers a solution to the computational burdens associated with online adaptive protection methods. This approach is particularly beneficial for small networks or grids with lower number of scenarios, as it allows them to avoid investing in an online setting calculation. In the offline adaptive protection method, with respect to the limitation of industrial relays in terms of saving different SGs, a proper method should be used to cluster topologies, so that the number of clusters does not violate the limitation of OCRs on storing the setting groups (Abbasi, Karegar, & Aghdam, 2019; Alam, Chakrabarti, & Pradhan, 2022; Atae-Kachoe et al., 2023; Barranco-Carlos et al., 2023; Carlos et al., 2022; Chabanloo, Safari, & Roshanagh, 2018; Chou, Su, & Lai, 2004; Davies & Bouldin, 1979; Karimkhan Zand et al., 2023; Ojaghi & Mohammadi, 2018; Piesciorovsky & Schulz, 2017a, 2017b; Samadi & Mohammadi Chabanloo, 2020; Singh & Agrawal, 2018; Sorrentino & Rodríguez, 2023; Zhang et al., 2011). It is noteworthy that all the references mentioned for adaptive protection, consider N-1 contingency analysis, where each scenario involves the outage of a single device. This type of analysis is commonly employed in power systems. However, (Karimkhan Zand et al., 2023) presents an adaptive protection study incorporating clustering techniques, which considers N-2 contingency analysis, which has rare occurrences in power systems.

Clustering is the task of grouping a set of objects which has many functions in a wide range of scientific subjects such as machine learning, pattern recognition, image processing, data compression, computer

graphics, and classification of scenarios in power system (Chou et al., 2004; Davies & Bouldin, 1979; Zhang et al., 2011). Clustering algorithms have become very popular tools for grouping different scenarios in offline adaptive protection schemes (Abbasi et al., 2019; Atae-Kachoe et al., 2023; Samadi & Mohammadi Chabanloo, 2020). (Ghadiri & Mazlumi, 2020) applied Self-Organizing Map (SOM) clustering algorithm for a new setting group-based adaptive protection coordination scheme that groups the miscoordinated relay pairs based on their similarity. The scheme aims to resolve the mis-coordination between the primary and backup relays. (Chabanloo et al., 2018b) models an offline adaptive protection problem as a multi-objective function and proposes a new method to optimize the number of SGs and time delays of overcurrent relays. However, frequent changes among the SGs in adaptive protection can reduce the reliability and availability of relays in protection systems according to (Piesciorovsky & Schulz, 2017c), which compared programmable logic and setting group methods for adaptive overcurrent protection systems. In the programmable logic method, a setting group is determined by utilizing a programmable logic method and mathematical operators instead of utilizing several different SGs. Clustering and setting group methods for adaptive protection systems, including the voltage-current characteristic curve of relays, are suggested to eliminate the adverse effects of photovoltaic systems (PVs) integration on the coordination of relays (Singh & Agrawal, 2018). (Sorrentino & Rodríguez, 2023) introduces an additional factor in the study to evaluate the probability of topology occurrence in the system. Although this factor may present challenges in certain cases, it yields favorable outcomes even when approximated or based on the expertise of power system operators. (Alam et al., 2022; Carlos et al., 2022; Zhang et al., 2011) suggest clustering-based protection scheme using K-means, while considering merely short circuit current as input in clustering process. This is improved by (Ojaghi & Mohammadi, 2018) considering time delay of relays as an input data for clustering, but the effects of time dial setting on the index calculation (time calculation) during clustering process (not final relay setting) is marginalized; in other words, the value of each TDSs is assumed to be 1. However, the calculation of time delays to be used as clustering input by using unity TDS (TDS=1) is not a precise approach. (Barranco-Carlos et al., 2023) compared several clustering algorithms, namely K-means, K-medoids, and Hierarchical Agglomeration, to each other and it was emphasized that there is minimal disparity among these methods in terms of their clustering performance. This means the index selection to be used as clustering input is more important than merely focusing on the algorithms (Barranco-Carlos et al., 2023; Zhang et al., 2011). In this study, K-means algorithm with Manhattan distance and maximum short circuit current as clustering input yields the best result. The existing literature aims to find a promising solution to address the drawbacks of the conventional system with a fixed setting. However, only some of them consider an acceptable index for clustering the topologies into the number of SGs or fewer. Moreover, communication failure is not considered in the clustering process. In this research, we ensure the clustering process by considering the realistic value of relays operation time and then present two practical schemes that use IEC 61850 sampled values and GOOSE protocol to monitor the system and activate the related SG depending on the changes in the network topology. Therefore, the main contributions of this research are summarized as follows:

- 1) In the existing literature, the impact of the TDS during the clustering process has been overlooked. Some researchers have justified this omission by citing the need for simplicity. However, this approach, which involves setting groups, is part of the offline phase. The pursuit of simplicity is not a significant advantage in offline and non-real-time calculations, such as the offline calculation of the setting group presented in this paper. Moreover, such studies including (Ojaghi & Mohammadi, 2018) have typically assumed a TDS value of 1 during the clustering process for all relays. While this assumption simplifies the process and reduces the computational load, which is

not a significant concern in offline calculations, it has been found to yield inaccurate results. By incorporating realistic TDS values into our clustering methodology, we have rectified the inaccuracies inherent in previous approaches. This enhancement ensures that the clustering process considers the unique characteristics of each topology, thereby enabling the calculation of more precise and reliable relay settings. This process employs two clustering methods to tackle the common memory limitation in commercial relays. The first is K-means, where 'K' represents the number of clusters. The second method is Automatic Clustering, which is used to evaluate the impact of clustering without constraining the algorithm to group the 25 topologies into a specific category, which considers both cohesion and separation indices in clustering and compares with traditional methods, adaptive protection based on K-means and the method in previous research in the Table 11. Therefore, Method 1 is based on what presented by (Ojaghi & Mohammadi, 2018) to have comparison, and Method 2, Method 3, and Method 4 is what we have proposed to achieve the mentioned goals.

2) Existing literature, lacks a detailed description of the setting group-based Adaptive Centralized Protection and Control Scheme (ACPCS) using commercial devices and IEC 61850. This includes Scheme 1 and 2, as depicted in Fig. 2 and Fig. 3, which cater to the protection of up to 30 feeders, with or without traditional relays. This paper explores the opportunities and challenges these schemes present. Moreover, these two practical ACPCS implementations address

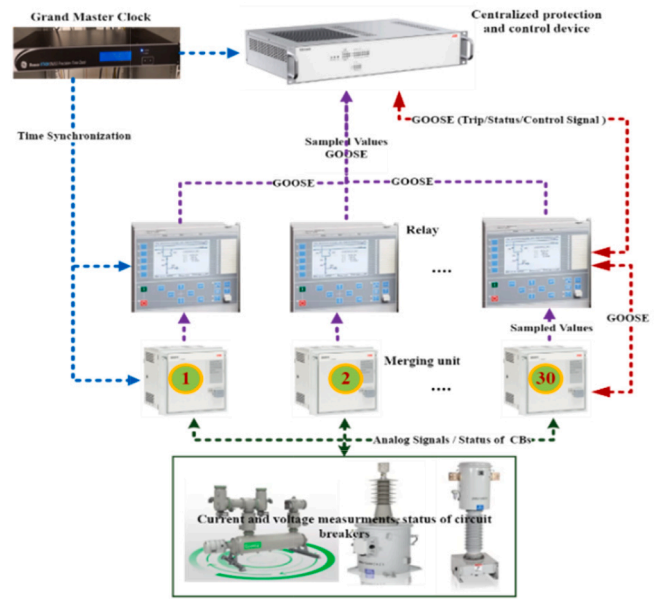


Fig. 2. Proposed centralized adaptive protection scheme 1 which covers the protection of up to 30 feeders combined with traditional relays.

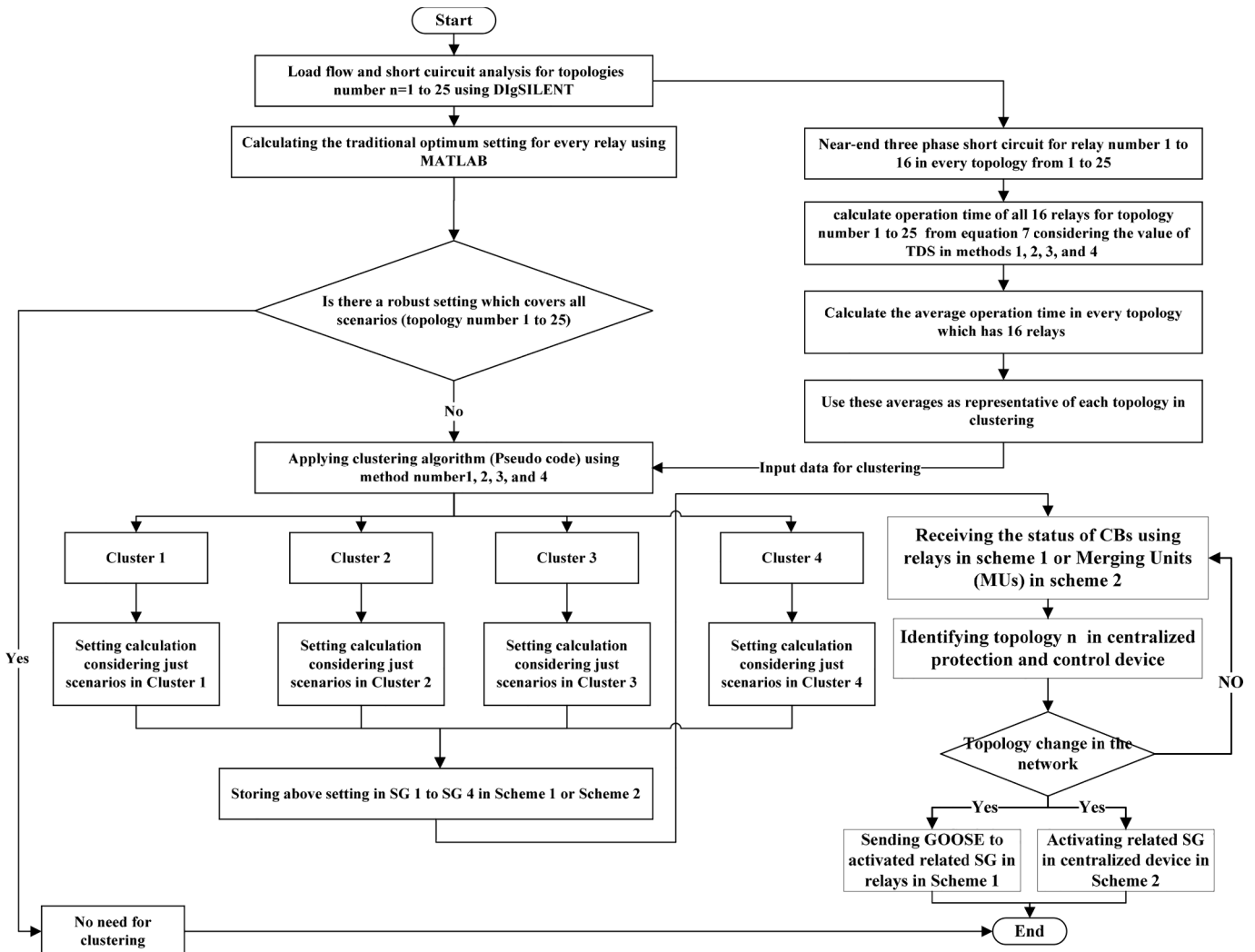


Fig. 1. General overview of the proposed method.

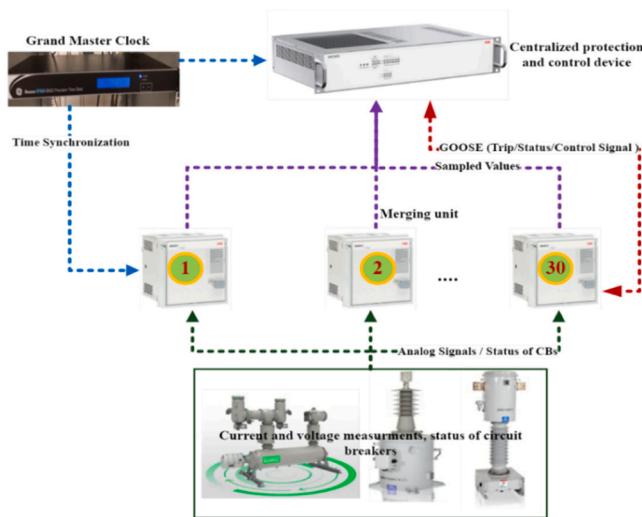


Fig. 3. Proposed centralized adaptive protection scheme 2 which covers the protection up to 30 feeders without traditional relays.

the limitations of conventional methods, such as miscoordination and extended delays. In addition, traditional relay testing, which involves isolating the relay from the power system and injecting current to check the operation time, is also discussed. In this current form of relay testing, engineers are primarily testing the dependability of protection schemes, i.e., issuing a trip when required. However, the security of the protection system, which involves avoiding unnecessary trips for other system zones when testing a specific zone, has been overlooked. This issue, along with other benefits that these two proposed schemes offer, is also addressed in the paper. Furthermore, the paper discusses the use of a disturbance recorder to generate real values from the setup. This allows for a comparison between the Artificial Intelligence (AI) or Machine Learning-based (ML-based) method and the available methods for better judgment.

- 3) Additionally, we proposed the concept of robust setting group, RIAPS method, to cover all or most topologies in scenarios involving failures in networks that lack redundant communication, such as those without PRP (Parallel Redundancy Protocol) or HSR (High-availability Seamless Redundancy).
- 4) Hardware-in-the-loop implementation of the proposed schemes using IEC 61850-9-2 LE (SVs) and IEC 61850-8-1 (GOOSE) along with the challenges and opportunities are also proposed to tackle the problems related to traditional protection schemes.

This paper is structured as follows. Section 2 describes the methodology and algorithms used in this study, including the mathematical formulation of the K-means clustering algorithm, the automatic clustering algorithm, the protection coordination objective function, and the general overview of the proposed method and the practical implementation of ACPCS. Section 3 introduces the test system and the results of the conventional protection coordination in the test system. Section 4 discusses the simulation results for the proposed Methods 1 to 4. Section 5 is intended for hardware-in-the-loop implementation of the proposed method. The final section concludes the paper and suggests directions for future studies.

2. Methodology and algorithms

When it comes to storing SGs in relays, there exist two approaches. The first approach assumes that relays have a limited capacity to store SGs. On the other hand, the second approach involves real-time calculation of settings and allows for multiple settings to be sent and activated

within a single setting group. The primary focus of this paper is on the first approach, which emphasizes the necessity of clustering network topologies and reducing their numbers in situations where networks lack the capability to perform online setting calculations or where implementing a power system with online setting calculation is not cost-effective. This is necessitated by the limited storage capacity of commercial relays. In this approach, the clustering index plays a key role. Among the various indexes used for clustering in power system protection, the time delays of relays have been identified as one of the most effective (Ojaghi & Mohammadi, 2018). This index considers the influence of both short circuit currents and load flow, which contribute to its calculation. It is important to note that during the clustering stage, precise relay operation times for different faults cannot be determined since the exact time can only be determined after the relay settings are calculated, which occurs after the clustering step. Nevertheless, clustering the scenarios based on this approximate index is an effective method of categorization. In contrast to the first method (section 4.1), which assumes a fixed TDS for all relays (TDS=1) (Ojaghi & Mohammadi, 2018) during clustering process, this paper proposes three alternative methods that employ different TDS values based on the topologies and use Equation (11) on page 12 of this paper to generate clustering input. In summary, Methods 1, 2, and 3 utilize both section 2.1 and section 2.3 for the tasks of relay clustering and coordination, respectively. On the other hand, Method 4 employs section 2.2 and section 2.3 for these same tasks. To illustrate the proposed method, a general flowchart is presented in Fig. 1, depicting the various steps involved. In the following subsections, the K-Means (Section 2.1) and automatic clustering (Section 2.2) algorithms, along with the time delay objective function, will be presented in detail.

At a practical level, once all the necessary processes such as clustering, setting calculation, and storing them in different setting groups have been completed, mature standards like IEC 61850 can be implemented. In this implementation, voltage and current values are measured at the process level. These values can be transmitted to centralized protection and control devices using merging units, which digitize the values with a 4 kHz sampling rate. Upon receiving the values and status information from the power system, the centralized protection and control device acts by issuing alarms or initiating trips based on predefined values within the SGs. Additionally, the centralized device is responsible for monitoring the status of the system and implementing control actions as necessary. This includes the ability to modify the setting group based on the current topology of the network, ensuring optimal protection and control measures are in place. It is worth mentioning that merging units can also support the capability of sending circuit breaker status information to monitor the state of the system and activate the relevant setting group as well. Another crucial aspect of the proposed scheme is the utilization of centralized protection and control devices. For instance, the SSC600 (ABB) can be considered as an example of a centralized protection device utilized in both schemes 1 (Fig. 2) and 2 (Fig. 3). Based on the existing relays, networks, and the vendor of the centralized protection and control devices, several schemes can be engineered. Two examples of such schemes are Scheme 1 and Scheme 2, which are illustrated in Fig. 2 and Fig. 3 respectively (field devices shown in both figures are from Hitachi). In scheme 1 (Fig. 2), there is the possibility of using relays as a backup and intelligent merging unit, which can eliminate the need for separate merging units in the centralized protection scheme. However, these relays must support both IEC 61850 and the necessary features of centralized adaptive protection. It is worth noting that this scheme may not be cost-effective if the aim is to design such a system from scratch. In Scheme 2 (Fig. 3), the bay-level relays are eliminated, resulting in reduced system costs. In all schemes based on IEC 61850, time synchronization plays a pivotal role. A grand master clock using IEEE 1588 can be used for this purpose, and in case of failure, any of the other relays with the best performance can act as a master to provide necessary continuity. To gain a more comprehensive understanding of the centralized protection scheme in

the industry extensive investigation was done by (Ganoo et al., 2022). The study investigates various aspects such as requirements, benefits, and challenges associated with the centralized protection scheme, while also acknowledging that the discussion is not limited to these aspects alone. The research highlights the advantages such as centralized data acquisition and future-proof solutions, which significantly reduce the physical footprint of substations and minimize the time required for engineering, commissioning, maintenance, and also real-time testing of relays as discussed by (Piesciarovsky & Schulz, 2017b). These advancements contribute to cost-efficiency benefits in terms of total expenditure, asset management, enhanced protection reliability leading to higher availability, reduced mean time to repair, and efficient spare part management. Additionally, the study reveals unprecedented flexibility in the system, resulting in up to 15% savings in lifecycle costs, alongside other benefits and challenges that are thoroughly explored. The proposed schemes offer several key advantages, one of which is their ability to address traditional relay testing, which involves isolating the relay from the power system and injecting current to verify the operation time. Such relay testing primarily focuses on the dependability of protection schemes, ensuring a trip is issued when necessary. However, the security aspect, which involves avoiding unnecessary trips for other system zones when testing a specific zone, is often overlooked. These issues highlight the benefits of the proposed centralized adaptive protection and control schemes. These schemes consolidate measurements from various points into a centralized protection and control device at the substation level. This centralization also allows for the use of a disturbance recorder to generate a large amount of real values from the setup. Such data can assist Distribution System Operators (DSOs) in developing new functionalities using machine learning techniques and artificial intelligence to develop new functionalities such as prediction of permanent earth faults, thereby preventing intermittent earth faults from developing into permanent ones (Pashaei et al., 2023). This approach also enables a comparison between Artificial Intelligence or Machine Learning-based methods and existing methods, allowing for better judgment of ML-based techniques. Dynamic testing of devices in the IEC 61850-based protection scheme in the proposed setups allows for considering the entire system and devices effect on relays setting. This ensures service continuity and considers the impact of the entire system on relay settings (Valtari, Dominguez, Coggan, Starck, & Pritchard, 2023). Simplicity of testing and running various test procedure in the initial engineering phase brings about many opportunities to improve relays setting at the same time as reducing the cost (Valtari, Dominguez, et al., 2023). In the proposed scheme for setting group-based centralized adaptive protection scheme, SSC600 is a physical device. The scheme can also benefit from virtualized centralized protection and control as a software image to be run at the edge (Kulmala et al., 2023a; Schönborn, Birke, Kozhaya, & Sivanthi, 2023a; Valtari, Kulmala, et al., 2023b). Virtualization decouples software from the underlying hardware and enables deploying applications from different vendors on the same hardware. Virtual Machines (VMs) and containers are among virtualization technologies (Schönborn et al., 2023; Valtari, Kulmala, et al., 2023). Using 5G as a communication medium to improve latency of communication is also an ongoing research and some interesting papers can be found in (Kokkonen-Tarkkanen et al., 2023; Raipala et al., 2023). (Kokkonen-Tarkkanen et al., 2023) make use of wireless 5G-enabled edge computing for fault location and edge-to-edge interstrip to improve communication latency in both 5G Stand Alone (SA) and Non-Stand Alone (NSA) networks. It compares the latency, jitter, and shows that 5G SA reaches closer to the requirements of protection application.

Both Scheme 1 and Scheme 2 employ a Parallel Redundancy Protocol (PRP) with zero-switchover time to improve the reliability of substation communication. This strategy mitigates potential link and switch failures and aligns with the IEC 62439-3:2012 standard. The redundancy scheme, based on the SSC600 technical manual is illustrated in Fig. 4, duplicate all transmitted data across two independent LAN and Ethernet

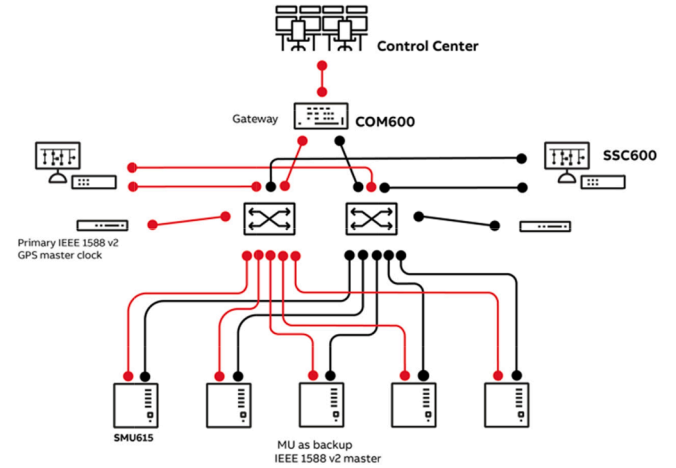


Fig. 4. Parallel redundancy protocol for schemes 1 and 2.

ports. The implementation of these schemes necessitates two SSC600 devices, two switches, and two grand master clocks. Furthermore, the schemes can be extended using the COM600 for monitoring and inter-substation communication, although this extension is not within the purview of this paper. For additional information, please refer to the IEC 62439-3:2012 standard, as well as the technical and engineering manuals of the SSC600 and SMU615.

2.1. K-means clustering algorithm

Clustering algorithms are normally used for grouping different data. Data that belong to the same group (cluster) has the same features. The selection of the K value, which determines the number of clusters, is indeed a significant point of discussion. We acknowledge that the choice of setting groups is influenced by various factors, including but not limited to the specific objectives of the study, the expertise of Distribution System Operators (DSOs), the limitations imposed by relays in terms of the number of setting groups they can accommodate, the reliability and availability index of the relays in the reliability analysis, and the availability of setting groups in the relays themselves. For instance, one scenario where different setting groups may be utilized is in studies involving islanding or the adaptation of setting groups for different seasons, such as winter and summer, where only two setting groups are employed. In our proposed scheme for the IEEE 14 bus test system, we have explored the use of four, three, and two setting groups based on different methods and the availability of setting groups. One of the most popular and useful clustering methods is K-Means algorithm, which is also known as Loid's algorithm. In this algorithm, the objective function (OF) is defined as:

$$OF : \sum_{i=1}^k \sum_{x \in c_i} d(x, m_i) \quad (1)$$

In this method, there are several options for calculating the distances and extracting similarities such as Minkowski. In Minkowski method, the distance between two vectors (x_s, x_t) is calculated by using (2).

$$d_{st} = \sqrt[p]{\sum_{j=1}^n |x_{sj} - x_{tj}|^p} \quad (2)$$

After the clustering, for each cluster, optimum settings based on objective function (7) are computed.

2.2. Automatic clustering algorithm

The clustering of topologies based on fixed or fewer number of setting groups by using K-Means will be analyzed by the objective

function presented in the section 2.1. In this algorithm, the number of clusters, which is fixed through the procedure, is given to the algorithm, but it is not guaranteed that this number is the one that leads to the optimal time delays of the relays. Another drawback of this algorithm is that cohesion is the only index for clustering. In other words, only similarity is important in this method and the differences among input data are neglected. However, considering the separation index or in other words, considering the amount of differences among input data can positively affect the number of clusters, thus the settings. The large number of SGs is also a reason for reducing the availability of relays in protection systems because of multiple changes among the SGs (Ojaghi & Mohammadi, 2018). Therefore, in this paper, automatic clustering algorithm (Davies & Bouldin, 1979), which includes both separation and cohesion indices concurrently, is also used to analyze the effect on clustering topologies of networks. We looked into the employment of the Harris Hawks Optimization (HHO) (Heidari et al., 2019), Grey Wolf Optimizer (GWO) (Faris, Aljarah, Al-Betar, & Mirjalili, 2018), Artificial Bee Colony (ABC) (Karaboga & Basturk, 2007), Particle Swarm Optimization (PSO) (Marini & Walczak, 2015), Genetic Algorithm (GA) (Mirjalili & Mirjalili, 2019), and Teaching-Learning-Based Optimization (TLBO) (Rao, Savsani, & Vakharia, 2011) algorithms to optimize K-means and Automatic clustering objective functions in our research. All of the methods produced similar results, with HHO showing an advantage in the cost function's convergence, which will be discussed. As a result, we focused on HHO in this study. In Algorithm 1, the pseudo code for both K-means clustering and Automatic clustering using using Harris Hawks Optimization (HHO) algorithm is presented. The objective function for automatic clustering, where there is no requirement to determine and enforce the number of setting groups (clusters), is as follows.

$$OF = DB_{ind} : \frac{1}{k} \sum_{i=1}^k R_i \quad (3)$$

$$R_i = \max_{j \neq i} (S_i + S_j / d_{i,j}) \quad (4)$$

$$d_{i,j} = \sqrt{\sum_{p=1}^d |m_{ip} - m_{jp}|^t} \quad (5)$$

$$S_i = \sqrt[q]{\frac{1}{N_i} \sum_{x \in c_i} d(x, m_i)^q} \quad (6)$$

2.3. Optimization algorithm for time delays of relays

The main objective in time delays of relays optimization is to determine the optimal coordination between overcurrent relays in different scenarios while minimizing the sum of operating times of the primary and backup relays for near-end faults (forward current). To calculate settings of relays, it is essential to calculate time dial settings (TDS) and pickup currents (I_p) firstly. TDSs and I_p s are obtained by optimizing the following objective function (7), while all the technical constraints (8)-(10) are satisfied.

$$OF : \sum_{i=1}^N \sum_{j=1}^M t_{ij} = \sum_{i=1}^N \sum_{j=1}^M A \times TDS_j / (I_{sc_{ij}} / I_{p_j})^B - 1 \quad (7)$$

$$t_b - t_m \geq CTI \quad (8)$$

$$TDS_{j,min} \leq TDS_j \leq TDS_{j,max} \quad (9)$$

$$I_{p_j,min} \leq I_{p_j} \leq I_{p_j,max} \quad (10)$$

Pseudo code for both K-means and Automatic clustering using Harris

hawks optimization (HHO) algorithm is presented as follows.

Algorithm 1: Pseudo code for clustering using HHO

Begin Clustering using the Harris hawks optimization

Input parameters: MaxIterations, PopulationSize, Data x , Number of Clusters k (only for K-Means method)

Initialize Population: Let $M = \text{PopulationSize}$

Generate M initial possible solutions (hawks positions) randomly within the data bounds

Evaluate fitness values according to Eq (1) for **K-Means clustering** and according to Eq (3) for **Automatic clustering**

While (not reached MaxIterations):

For each hawk in the population:

Generate a random number q in the range [0, 1]

If $q \geq 0.5$ (Exploration phase):

Generate a random number r in the range [0, 1]

If $r < 0.5$:

Update hawk's position using Levy Flight Strategy relative to GlobalBest

Else:

Update hawk's position using Random Exploration relative to another randomly selected hawk

Else (Exploitation phase):

Generate a random number r in the range [0, 1]

If $r < 0.5$:

Update hawk's position using Soft Besiege strategy towards GlobalBest

Else:

Update hawk's position using Hard Besiege with rapid dives towards GlobalBest

Apply bound constraints to hawk's position

Evaluate the new position's fitness

If the new fitness is better than the hawk's current fitness:

Update hawk's position and fitness

If the hawk's fitness is better than GlobalBest's fitness:

Update GlobalBest with hawk's position and fitness

End For

Termination Criteria:

Check if termination criteria are met, such as reaching a maximum number of iterations or achieving convergence

Update Best Solution:

Keep track of the best solution found so far in terms of fitness

End while

Report the population as the final set of cluster centroids

End Clustering using Harris hawks optimization

3. Case Study: IEEE 14-Bus test system

In Fig. 5, IEEE 14-bus test system that is available in Power Factory 15 (Examples Section) is illustrated. Relays in this test system must be directional in order to provide a selective protection system due to the bidirectional flow of current. Relays' coordination is done for the 33 kV sector of the test system, considering N-1 contingency, which can be modeled as a line outage, a generation unit outage or a transformer outage. The purpose of this study is to examine the coordination of overcurrent relays in power systems by modelling these changes through equipment outages, which can also be planned for maintenance purposes, to minimize power losses, or to balance loads among feeders. While the IEEE 14 Bus system does not explicitly include DGs in its distribution part, we incorporated the impact of DGs through the consideration of various resource outages. Specifically, we considered five generators (G1, G2, G3, G4, G5) and their outages as five different scenarios in the active network. This approach allowed us to assess the coordination of all relays in the distribution part under different outage conditions. The topologies 1–16, represent the outage of lines 1–16 (L_1, L_2, \dots, L_{16}), respectively. The transformers 1–3 (T_1, T_2, T_3) outages create the topologies 17–19; the topologies 20–24 are related to the G_1 - G_5 outages. The main topology of the network (without any outage) is considered as the topology 25. The characteristic curves of the relays are standard inverse. In addition, $A, B, CTI, TDS_{j,min}$, and $TDS_{j,max}$, are 0.14, 0.02, 0.2, 0.05, and 2, respectively. Moreover, $I_{p_j,min}$ and $I_{p_j,max}$ are considered to be 1.2 and 1.5 times as large as the maximum load current, respectively. In conventional relay coordination for networks, the goal is to determine a robust setting that ensures coordinated operation of relays for all topologies, which means the robust setting that covers topology number 1 to 25. To compare the result of proposed methods, a conventional relay coordination problem is solved for all 25 topologies

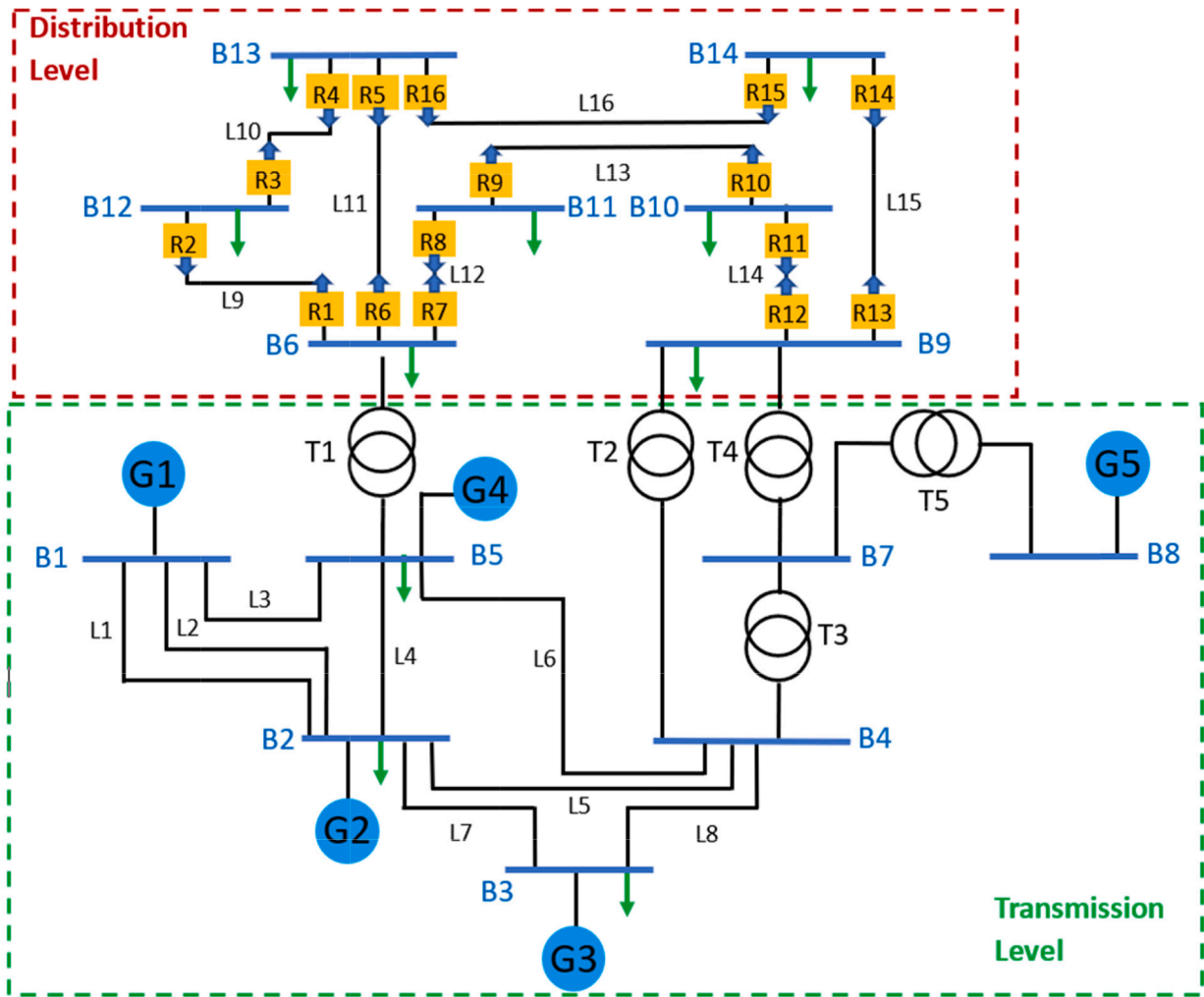


Fig. 5. Single-line diagram of the IEEE 14-bus test system.

by analyzing the three-phase maximum near-end fault in this section. The load currents passing through the relays are calculated for each line, generation unit, or transformer outage. The quantities of $I_{p_{min}}$, $I_{p_{max}}$ are assumed to be 1.2 and 1.5 times larger than the maximum load current, respectively. The optimization algorithm is applied to the data generated by short circuit and load flow analysis using the DiGSILENT Programming Language (DPL). It determines the values of TDS and I_p for the conventional setting and main topology setting, considering worst-case scenario among all possible topologies. Table 1 presents the results of solving the relay coordination problem for 22 relay pairs, aiming to minimize the operating times of the main and backup relays.

4. Proposed methods relay for coordination

Table 1 indicates that the average operating time of the relays is substantial due to the need for their settings to be compatible with all topologies. The conventional method of coordination, which relies on a single robust setting to address all scenarios, can result in instances where coordination between specific main and backup relays is insufficient. Even when proper coordination is achieved, the operation delay time may not meet the desired level of satisfaction. Therefore, employing adaptive protection mechanisms is a more sensible approach to tackle such issues and avoid miscoordination between relays. It is important to note that the selection of an appropriate index for topology clustering has a profound impact on the effectiveness of adaptive coordination. Hence, in this section, we analyze the effects of index selection

Table 1
Optimal setting for the OCRs.

Main Relays	Optimal settings for the OCRs				Backup Relays
	Main Topology Setting		Conventional Setting		
	TDS	I_p (kA)	TDS	I_p (kA)	
1	0.28	0.190	0.29	0.292	5,8
2	0.05	0.200	0.05	0.292	4
3	0.33	0.041	0.27	0.199	1
4	0.16	0.044	0.12	0.160	6,15
5	0.05	0.379	0.08	0.382	3,15
6	0.22	0.460	0.23	0.396	2,8
7	0.30	0.200	0.22	0.342	2,5
8	0.18	0.195	0.15	0.342	10
9	0.27	0.102	0.15	0.373	7
10	0.31	0.098	0.20	0.373	12
11	0.17	0.168	0.10	0.477	9
12	0.36	0.160	0.24	0.477	14
13	0.16	0.251	0.17	0.388	11
14	0.16	0.249	0.12	0.388	16
15	0.13	0.147	0.15	0.239	13
16	0.26	0.144	0.20	0.239	3,6
$\sum t$	23.76		26.40		
$t_{average}$	0.540		0.614		

on the operating times of the relays within the context of clustering.

4.1. Time delay-based clustering of the relays (Method 1)

One of the clustering indices is time delays of the relays, which includes pick-up and short-circuit current. For simplification purposes, the quantity of TDS for each relay is suggested to be 1 (Ojaghi & Mohammedi, 2018). By knowing the quantities of I_{sc} and I_p and using (11), the time delays of the relays for all topologies are determined as Fig. 6, which is only used for clustering process. The average operating times for all 16 relays in each of the 25 topologies, for three-phase close-in faults (Singh & Agrawal, 2018), which is the worst-case scenario and the most severe type of fault that can occur in the test system, are utilized as input data for the clustering algorithm. These averages, representative of each topology in clustering which is shown in Fig. 6, are calculated based on the operating times of relays R1 to R16 within each topology. For instance, the outage of line 1 results in topology 1. In this topology the time delay for the short circuit current for R1 to R16 is calculated and their average is the representative of topology 1 in the clustering. This is repeated for all other 24 topologies.

$$t = (0.14 \times TDS) / ((I_{sc} / I_p)^{0.02} - 1) \tag{11}$$

Fig. 6 shows the variation in average time delays used for clustering process across topologies 1 to 25. Notably, Topology 23 indicates the highest value and is related to a generation contingency (G4), followed by Topology 17 representing a transformer contingency. These variations stem not only from the type of equipment involved but also from the network configuration, installation location etc. The figure further presents the impact of selected topologies representing different scenarios on relays 1 to 16 in clustering process. These scenarios include line contingencies in cluster 1 (topologies 12, 13, and 14), generation contingency (topology 23), transformer contingency (topology 17), and a line in transmission level contingency (topology 1). In Fig. 6, we can observe zero-time delays for relays 7, 8, 9, and 11 in Topology 12. This is because, after the outage of line 12, these relays are not part of the relevant topology for the three-phase close-in fault scenario in coordination process for main and backup pairs. Similar observations can be made for other topologies where relays are not involved in the specific fault scenario being analyzed.

After applying K-means clustering algorithm, optimizing the objective function (1), topologies are categorized into four different clusters

Table 2
Topology clusters by using Method 1.

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

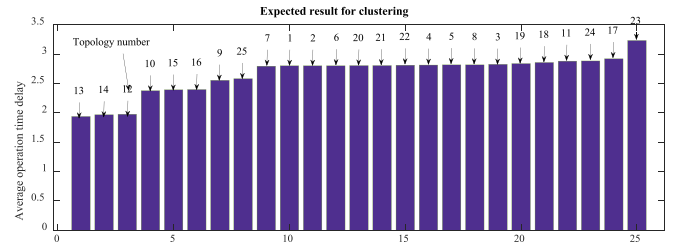


Fig. 7. Bar diagram of clustering input based on time delay index considering only the effect of load flow and short-circuit.

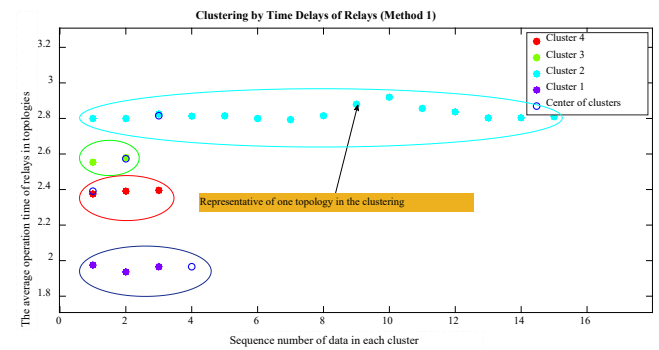


Fig. 8. Clustering result and input data.

based on Table 2, Fig. 7, and Fig. 8.

The depicted figure serves as a valuable means of validating the clustering results, as it clearly demonstrates that the selected topologies for each cluster must adhere to a specific order. This order ensures that topology 13, for instance, cannot be grouped within the same cluster as topology 23.

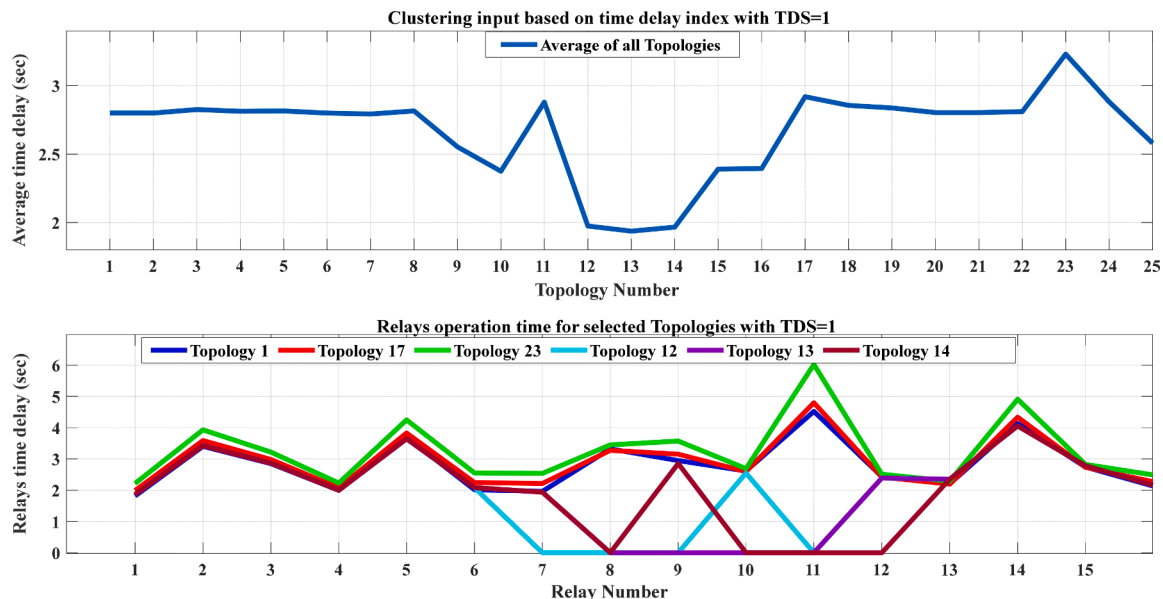


Fig. 6. Clustering input for Method 1.

The index of topologies in each cluster is presented in Table 2. The settings of relays for each cluster are determined by optimizing the objective function (7). The results for settings of relays are presented in Tables 3 and 4. The bar diagram of the time delays of the relays in different topologies that is illustrated in Fig. 7 shows that similar topologies (in terms of time delay) belong to the same clusters, which verifies the accuracy of the clustering algorithm. The convergence of K-means clustering is depicted in Fig. 9.

The average of time delays of the relays, which is obtained using the conventional method is 0.614 s. According to Tables 3 and 4, the average of time delays of the relays in clusters 1 and 2, which includes 80% of the topologies, decline by 30.78% and 7.49% in comparison with the conventional method, respectively. In addition, the total average of time delays of the relays decreases to 0.576 (about 6% in comparison with conventional method). In cluster 3, accounting for only 8% of the topologies, an increase in time delay is observed. Despite satisfying the coordination problem, this increase is undesirable. To cluster the topologies more efficiently, the effects of TDSs must be included in the clustering algorithm. This aspect is further investigated in Method 2.

4.2. Time delay-based clustering of the relays by considering TDSs effects (Method 2)

In Method 1, the clustering process only considers the impacts of fault and load flow (pickup) currents. Furthermore, all Time Dial Settings (TDSs) are assumed to be 1 during the clustering process. While this approach is simple and requires fewer calculations, it has been found to be inaccurate. It is worth noting that simplicity is not a significant advantage in an offline and non-real-time calculation like the one described in this paper. By incorporating the realistic TDS values into our clustering methodology, we can overcome the inaccuracies of the previous approach. This enhancement ensures that the clustering process takes into consideration the specific characteristics of each topology and enables us to calculate more precise and reliable relay settings. To elaborate further, our methodology places emphasis on gathering the average time delays of 16 relays for each of the 25 topologies, which are used as inputs for the clustering algorithm as shown in Fig. 10. The setting and time delays in this stage (TDS and I_p to calculate the t for all 16 relays in all 25 network topologies) are just for clustering. To calculate the average time delay of 16 relays for each topology to be used in clustering process, the setting calculation does not require considering other topologies and scenarios, unlike the next stage in which we consider all topologies in each cluster for the final relay

Table 3
Optimal settings for the OCRs at the cluster 1 & 2 by using Method 1.

Main Relays	Optimal settings for the OCRs				Backup Relays
	Cluster 1		Cluster 2		
	TDS	I_p (kA)	TDS	I_p (kA)	
1	0.29	0.123	0.27	0.292	5,8
2	0.05	0.117	0.05	0.292	4
3	0.30	0.033	0.24	0.199	1
4	0.19	0.033	0.11	0.160	6,15
5	0.09	0.302	0.08	0.324	3,15
6	0.22	0.302	0.21	0.335	2,8
7	0.12	0.215	0.20	0.342	2,5
8	1.16	0.194	0.15	0.342	10
9	0.05	0.127	0.14	0.373	7
10	0.05	0.127	0.19	0.373	12
11	1.16	0.192	0.09	0.477	9
12	0.13	0.214	0.24	0.477	14
13	0.23	0.156	0.16	0.388	11
14	0.12	0.174	0.11	0.388	16
15	0.17	0.124	0.15	0.207	13
16	0.22	0.124	0.18	0.207	3,6
$\sum t$	14.47		24.43		
$t_{average}$	0.425		0.568		

Table 4
Optimal settings for the OCRs at the cluster 3 & 4 by using Method 1.

Main relays	Optimal settings for the OCRs				Backup relays
	Cluster 3		Cluster 4		
	TDS	I_p (kA)	TDS	I_p (kA)	
1	0.38	0.116	0.32	0.148	5,8
2	0.05	0.105	0.05	0.118	4
3	0.31	0.093	0.32	0.057	1
4	0.14	0.093	0.16	0.057	6,15
5	0.09	0.374	0.07	0.396	3,15
6	0.33	0.374	0.26	0.396	2,8
7	0.46	0.122	0.39	0.152	2,5
8	0.30	0.122	0.24	0.152	10
9	0.43	0.065	0.35	0.097	7
10	0.47	0.065	0.38	0.097	12
11	0.29	0.097	0.22	0.154	9
12	0.53	0.097	0.43	0.154	14
13	0.31	0.162	0.23	0.234	11
14	0.26	0.162	0.18	0.234	16
15	0.29	0.085	0.16	0.239	13
16	0.42	0.085	0.24	0.239	3,6
$\sum t$	32.74		25.06		
$t_{average}$	0.744		0.659		

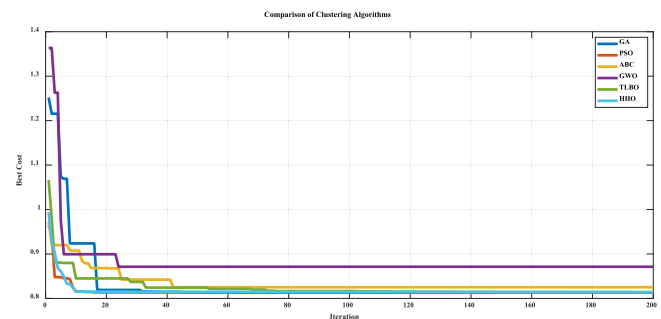


Fig. 9. Convergence of K-means clustering algorithms.

settings to cover all possible topologies within each cluster. In this case, the results of clustering are shown in Table 5, and the results of optimum relay settings are demonstrated in Table 6. The results for cluster 1 and cluster 2 are same as Table 3. In Fig. 11, the bar diagram of the average time delays of the relays in the different topologies is presented, which confirms the accuracy of clustering; for example, topologies 12–14 which belong to the same cluster, appear subsequently in the bar diagram.

The method achieves a reduction of 7.65% and 1.56% in the overall average time delays of the relays, ultimately reaching a value of 0.567. This indicates that the proposed method outperforms both the conventional method and Method 1 in terms of reducing time delays in relay operations.

Fig. 12 presents the final operation time delays for all relays in Topology 12 considering the maximum three-phase close-in short circuit current. These delays account for both main and backup pairs, as defined in Table 6. It is important to note that some relay pairs, namely ((R1, R8), ((R6, R8), ((R8, R10), ((R11, R9), ((R13, R11)) show a zero-time delay for Topology 12. This indicates that, due to the outage of line L12 in this specific topology, there is no current flowing through these relays during the three-phase close-in fault scenario, meaning that there is no need for coordination between these pairs.

4.3. Reliability Improvement in adaptive protection systems (RIAPS) (Method 3)

In the Sections 4.1 and 4.2, the relay settings were determined using

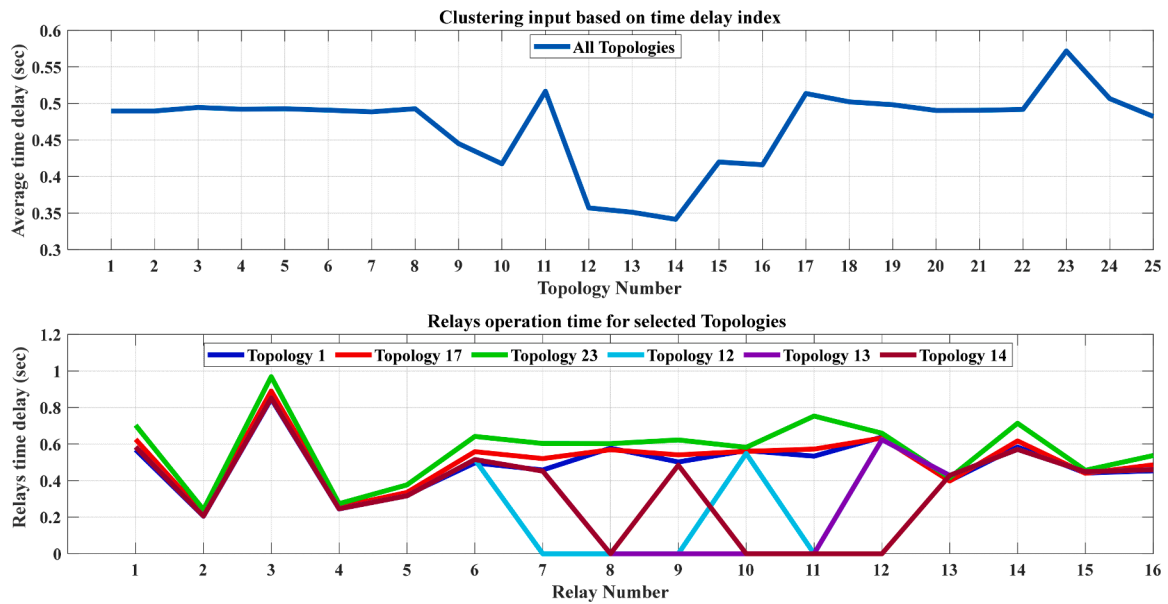


Fig. 10. Clustering input for Method 2.

Table 5

Topology clusters by using Method 2.

Cluster 1	Cluster 2	Cluster 3	Cluster 4
14·13·12	1-8,11 17-22,24,25	23	16·15·10·9

Table 6

Optimal settings for the OCRs at the cluster 3 & 4 by using Method 2.

Main relays	Optimal settings for the OCRs				Backup relays
	Cluster 3		Cluster 4		
	TDS	I_P (kA)	TDS	I_P (kA)	
1	0.32	0.115	0.31	0.148	5,8
2	0.05	0.102	0.05	0.118	4
3	0.39	0.022	0.27	0.093	1
4	0.20	0.022	0.14	0.093	6,15
5	0.10	0.265	0.07	0.396	3,15
6	0.26	0.265	0.26	0.396	2,8
7	0.38	0.098	0.39	0.152	2,5
8	0.29	0.098	0.24	0.152	10
9	0.35	0.051	0.35	0.097	7
10	0.47	0.051	0.38	0.097	12
11	0.18	0.134	0.22	0.154	9
12	0.46	0.134	0.43	0.154	14
13	0.24	0.165	0.23	0.234	11
14	0.18	0.165	0.18	0.234	16
15	0.22	0.076	0.16	0.239	13
16	0.33	0.076	0.24	0.239	3,6
$\sum t$	29.18		25.85		
$t_{average}$	0.663		0.646		

clustering into four groups, without considering potential failures of the central server and communication links. In this method, an additional setting group is assigned for robust settings, which would be activated in the event of a central server or communication link failures. This approach ensures coverage for all or most of the network topologies. When a failure occurs, an alarm is triggered for the operator simultaneously with the activation signal for the last setting group dedicated to the robust settings. The logic for activating the setting groups may vary depending on the manufacturer. For example, in ABB’s centralized protection device known as SSC600, the last setting group holds higher priority, allowing important settings to be stored in this group. In other

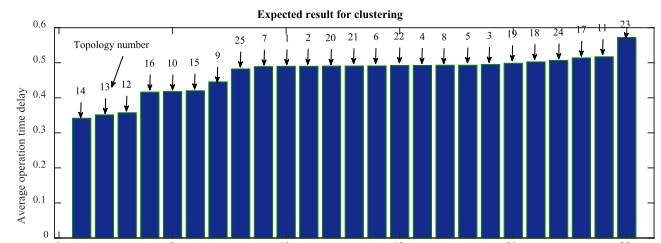


Fig. 11. Bar diagram of the average time delays of the relays in each topology.

words, when two setting groups receive an activation signal, only the last one with higher priority will be activated. Once the alarm command and activation signal are deactivated, the robust setting group is disabled, and the settings are reset to the normal operating conditions. In terms of activating the relevant setting group using the IEC 61850 standard, relay communication supervision is facilitated through GOOSE engineering. This is accomplished by configuring the “Max time” parameter within the GOOSE control block, which represents the background heartbeat cycle time. The Max time parameter determines the duration of the supervision heartbeat, enabling the client to detect any failures or disruptions in the communication source within the specified timeframe. The value of this parameter can range from “1000 ms” to “60000 ms” and ensures continuous transmission of messages by the protection relay, even in the absence of data changes. This continuous transmission allows the receiver to detect any loss of communication, thus enabling effective supervision of the communication link. This method involves activating the last setting groups in Scheme 1 (presented in Fig. 2) or taking the necessary actions by the operator in Scheme 2 (shown in Fig. 3). Considering that the relay can store four different setting groups, and one setting is allocated for robust settings, the number of clusters needs to be reduced to three. This robust setting is derived from a traditional method and will not be superior to a setting obtained from clustering. However, it serves as the only viable solution to salvage a significant portion of the networks that lack redundancy schemes in the event of communication link unavailability. In this case, the clustering results are presented in Table 7. The settings for clusters 1 and 2 are the same as cluster 1 and cluster 2 in Method 2, respectively. The settings for the other clusters are shown in Table 8.

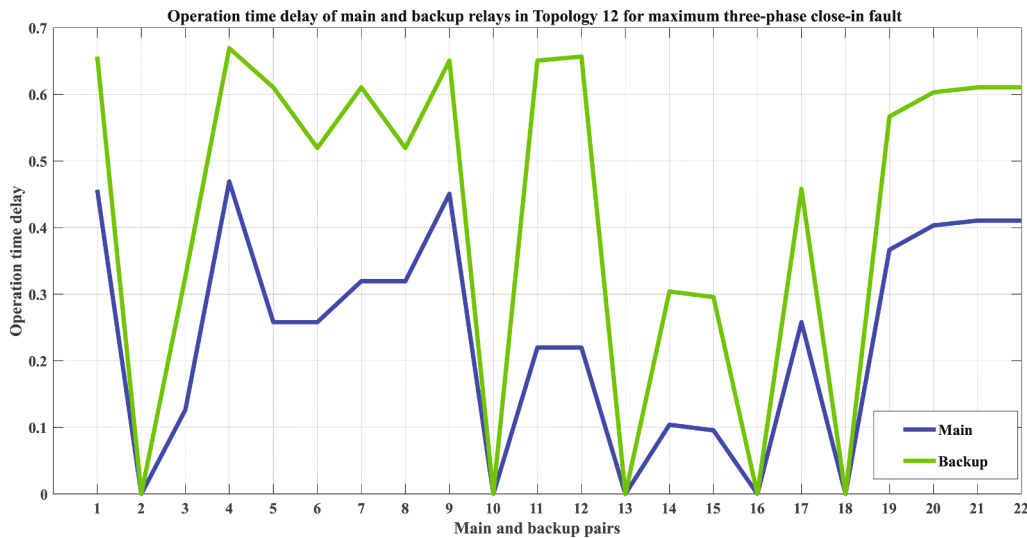


Fig. 12. Operation time delay for a selected scenario in cluster 1 (Topology 12).

Table 7
Topology clusters by using method 3.

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

Table 8
Optimal settings for the OCRs at the cluster 3 & 4 by using Method 3.

Main relays	Optimal settings for the OCRs				Backup relays
	Cluster 3		Cluster 4		
	TDS	I_p (kA)	TDS	I_p (kA)	
1	0.31	0.148	0.29	0.292	5,8
2	0.05	0.118	0.05	0.292	4
3	0.27	0.093	0.27	0.199	1
4	0.14	0.093	0.12	0.160	6,15
5	0.07	0.396	0.08	0.382	3,15
6	0.26	0.396	0.23	0.396	2,8
7	0.39	0.152	0.22	0.342	2,5
8	0.24	0.152	0.15	0.342	10
9	0.35	0.097	0.15	0.373	7
10	0.38	0.097	0.20	0.373	12
11	0.22	0.154	0.10	0.477	9
12	0.43	0.154	0.24	0.477	14
13	0.23	0.234	0.17	0.388	11
14	0.18	0.234	0.12	0.388	16
15	0.16	0.239	0.15	0.239	13
16	0.24	0.239	0.20	0.239	3,6
$\sum t$	25.85		26.40		
$t_{average}$	0.646		0.614		

In this case, the total average of time delays of main and backup relays (0.563 s) decreases by 8.31%, 2.26%, and 0.7% in comparison with the conventional method, the Method 1 and Method 2, respectively. For this network (IEEE 14-bus test system), the RIAPS method is the best option because it achieves the best results in terms of time delays and performance. By changing the setting group to the robust one, the RIAPS method improves the protection system’s performance when facing failures.

4.4. Time delay-based clustering of the relays by using automatic clustering algorithm (Method 4)

The automatic clustering algorithm described in Section 2.2 assumes that the maximum number of setting groups that can be saved by relays

is 4. Based on the separation and cohesion indices presented in the objective function of the algorithm, it determines whether the clustering should be performed into four groups or fewer. The results of the clustering obtained using the Automatic Clustering Algorithm are presented in Fig. 13 and Table 9.

The settings for Cluster 1 and Cluster 2 are shown in Table 10. Comparing with the conventional method, the average time delays of the relays in Cluster 1 decline by 30.78%, while in Cluster 2, they increase by 3.75%. The total average time delay of the relays decreases by 0.49% compared to the conventional method, reaching 0.611 s. Furthermore, in 19 out of 22 pairs of relays (main and backup) in Cluster 2, the relay coordination is superior to the traditional method. In this method, due to the smaller number of setting groups, the availability of relays in the protection system is better compared to clustering into more groups. The two extra setting groups can also be utilized for other purposes similar to Method 3. For example, one of the additional setting groups can be dedicated to the robust setting group to handle communication link and central server failures, or for seasonal variations such as summer and winter due to temperature variations, thus adjusting relay settings.

Fig. 14 depicts a bar diagram illustrating the average time delays of the relays in different topologies. The arrangement of the bars in the diagram confirms the accuracy of the clustering, as topologies belonging to the same cluster appear consecutively. This visual representation reinforces the consistency of the clustering results, ensuring that similar topologies are grouped together in the analysis.

Fig. 15 displays the convergence of the automatic clustering algorithm, highlighting that its convergence occurs later compared to the K-

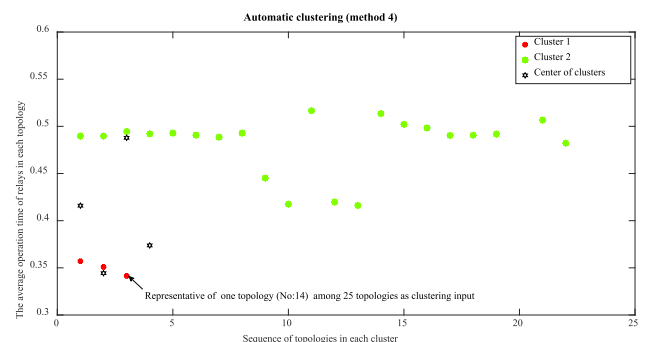


Fig. 13. Automatic clustering for relays up to 4 SGs.

Table 9
Topology clusters by using Method 4.

Cluster 1	Cluster 2
12–14	1–11, 15–25

Table 10
Optimal settings for the OCRs at the cluster 1 & 2 by using Method 4.

Main relays	Optimal settings for the OCRs				Backup relays
	Cluster 1		Cluster 2		
	TDS	I_p (kA)	TDS	I_p (kA)	
1	0.29	0.123	0.31	0.292	5,8
2	0.05	0.117	0.05	0.292	4
3	0.30	0.033	0.29	0.200	1
4	0.19	0.033	0.14	0.160	6,15
5	0.09	0.302	0.07	0.395	3,15
6	0.22	0.302	0.24	0.395	2,8
7	0.12	0.215	0.24	0.342	2,5
8	1.16	0.194	0.16	0.342	10
9	0.05	0.127	0.17	0.373	7
10	0.05	0.127	0.20	0.373	12
11	1.16	0.192	0.10	0.477	9
12	0.13	0.214	0.25	0.477	14
13	0.23	0.156	0.18	0.388	11
14	0.12	0.174	0.11	0.388	16
15	0.17	0.124	0.16	0.239	13
16	0.22	0.124	0.20	0.239	3,6
$\sum t$	14.47		27.41		
$t_{average}$	0.425		0.637		

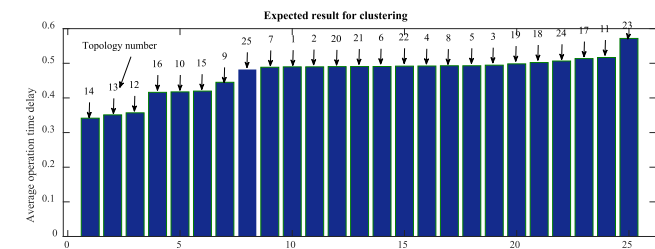


Fig. 14. Bar diagram of the average time delays of the relays in each topology.

means clustering depicted in Fig. 8.

5. Real-time hardware-in-the-loop implementation of the proposed scheme

In a laboratory setting, the methodology described can be applied using a hardware-in-the-loop setup as demonstrated in Fig. 16. Communication between devices in this setup, which is shown in Figs. 17 and 18, is identical to Scheme 1 and Scheme 2 (Fig. 1 and Fig. 2). However, instead of using a real grid, a power system is modelled in MATLAB and executed by a real-time simulator. In this testbed, the OPAL-RT simulator is capable of generating sampled values (IEC 61850-9-2 LE) at a frequency of 80 per cycle. This can eliminate the need for merging units or amplifiers, as shown in Fig. 18. In essence, if only one merging units is available at a university laboratory, it is still possible to implement centralized protection scheme covering up to 30 feeders by exporting an SCL (ICD) file from the sole MUs and make necessary modifications. Additionally, the setup allows for publishing or subscribing to GOOSE (IEC 61850-8-1) messages for tripping and monitoring the status of CBs.

To achieve protection coverage for up to 30 feeders, the OP6500 simulator sends sampled values at a sampling rate of 4000 Hz to the

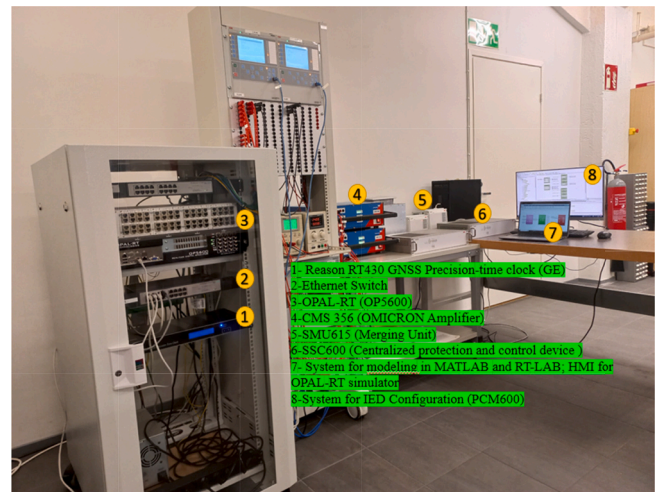


Fig. 16. Hardware-in-the-loop setup for centralized adaptive protection scheme.

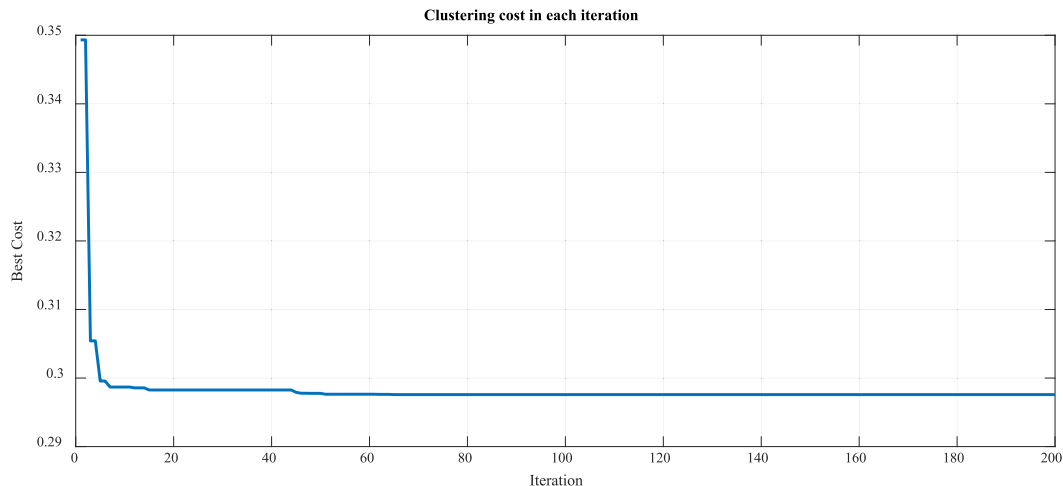


Fig. 15. Convergence of automatic clustering using HHO.

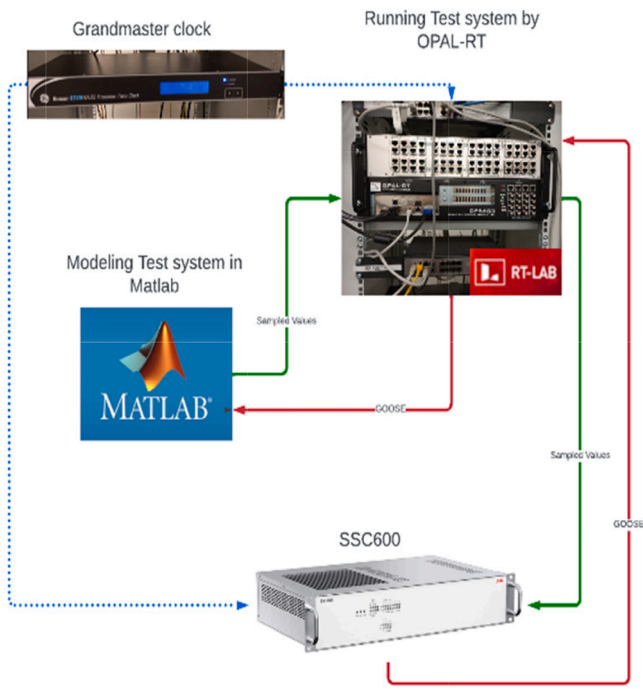


Fig. 17. Hardware-in-the loop implementation of centralized adaptive protection scheme without MUs and amplifiers.

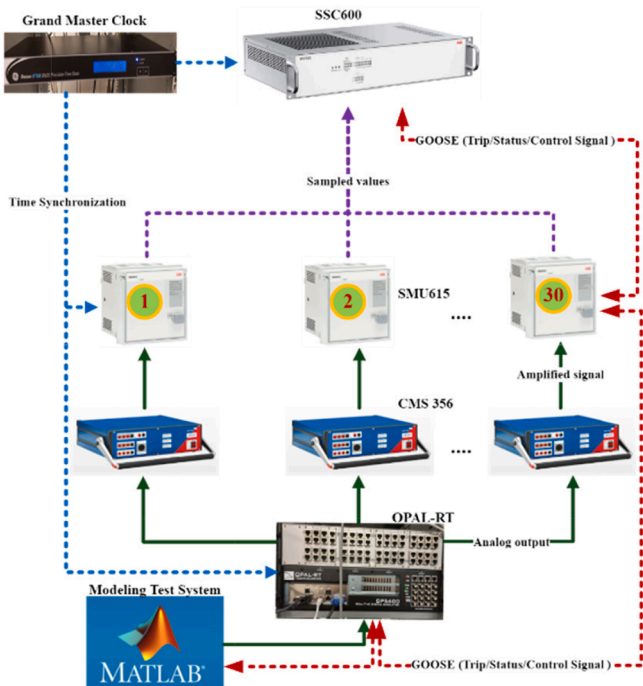


Fig. 18. Hardware-in-the loop implementation of centralized adaptive protection scheme with MUs and amplifiers.

SSC600 device. The initial step involves application configuration in the IED software, including time synchronization (GNRLTMS1), receiving sampled values (SMVRECEIVE), disturbance recorder (RDRE1), over-current relay (PHLPTOC), receiving the open status of CB1 (GOOSRCV), and protection block (Protection) for activating setting groups shown in Fig. 19. Then process bus, GOOSE, and the signal matrix engineering, which connects the status of three CBs to the application is also conducted and shown in Fig. 20 and Fig. 21.

After conducting IEC 61850 engineering for the process bus, GOOSE, and the signal matrix between the first merging unit and the central relay using the IED software, PCM600, the ICD file from the first merging unit and centralized device is exported and uploaded to RT-LAB (Fig. 22), enabling the transmission of sampled values and the status of circuit breakers upon receiving GOOSE messages from the centralized protection and control devices (SSC600). For the remaining merging units, the ICD files from PCM600 are copied as new feeder devices, and the necessary settings such as AppID, Sampled Value ID, MAC Address, and Configuration Revision are adjusted accordingly. In GOOSE engineering, each GOOSE control block requires specific parameters, including AppID, MAC Address, Configuration Revision, Max time, and Min time. The Max time parameter represents the background “heart-beat” cycle time, expressed in milliseconds, and can range from 1000 ms to 60000 ms. The protection relay continues to transmit the message within the designated heartbeat cycle, even when there are no changes in the data. This continuous transmission ensures that the receiver can identify any loss of communication, thereby enabling communication supervision. The Min time parameter signifies the maximum response time, also measured in milliseconds, to data changes. This time interval allows the receiver to discard messages that have become outdated. For protection relays, the value of the Min time parameter is consistently set at 4 ms for the transmitted data. Regarding time synchronization, the setup considers the use of Reason RT430 GNSS Precision-time clock and Oregon Syn1588 PCI (Installed in OPAL-RT). PTP with power profile C37.238–2011 is chosen as the synchronization mode, and a peer-to-peer delay mechanism is employed. The synchronization achieved has an accuracy of 100 nsec. The modeling also includes epoch time in seconds and nanoseconds, as well as the PTP state, which shows the 9 states of synchronization: initializing, faulty, disabled, listening, pre-master, master, passive, uncalibrated, and slave. For more detailed information, you can refer to the OP5600 catalogue, which provides comprehensive specifications and features of the OP5600 real-time simulator. From the provided configuration in Fig. 22, it can be observed that the SCL file for the IEC 61850-8-1 (GOOSE) publisher is the same as mentioned earlier, which is the ICD file exported from the first merging unit and subsequently modified for other two publishers. As for the GOOSE subscriber, the ICD file exported from the centralised protection device is utilized. In the case of IEC 61850-9-2 (sampled values) publishing, there is no need for ICD files when configuring the RT-LAB.

After completing these steps, the final settings of protection functions and IEC 61850 engineering in PCM600 are written into SSC600. Now the centralised protection scheme is ready to study some cases.

There are various scenarios that can be considered, such as the outage of each source, loads, transformers, and changes in the load levels. However, for the sake of simplicity, only four scenarios have been taken into consideration to demonstrate the reliability of the centralised protection and control scheme using the IEC 61850 standard and the model of Sundom Smart Grid in Finland (Hannu Laaksonen & Hovila, 2016). The test system, as shown in Fig. 23, is part of Sundom Smart Grid operating at a dual voltage of 110/21 kV. Three feeders originate from main substation, each connected to different distributed generation (DG) sources and loads. Feeder 1 connects to a 3.6 MW wind farm located 0.733 km away. This wind farm operates at a lower voltage of 575 V. Feeder 2 connected to a 400-kW solar farm located 23.15 km distant. Finally, Feeder 3 delivers power to a load located at a distance of 7.035 km.

The main topology, which assumes no outages, is referred to as Topology I (SG1). When the first, second, and third feeders, which are equipped with fault controllers in the simulation model, encounter outage, the resulting network configurations are referred to as Topology II (SG2), III (SG3), and IV (SG4), respectively. For these four scenarios, the relay settings are stored in four distinct setting groups (SGs) within the SSC600. After receiving sampled values (SVs) from the SMU615, which triggers a trip action that alters the network topology in the

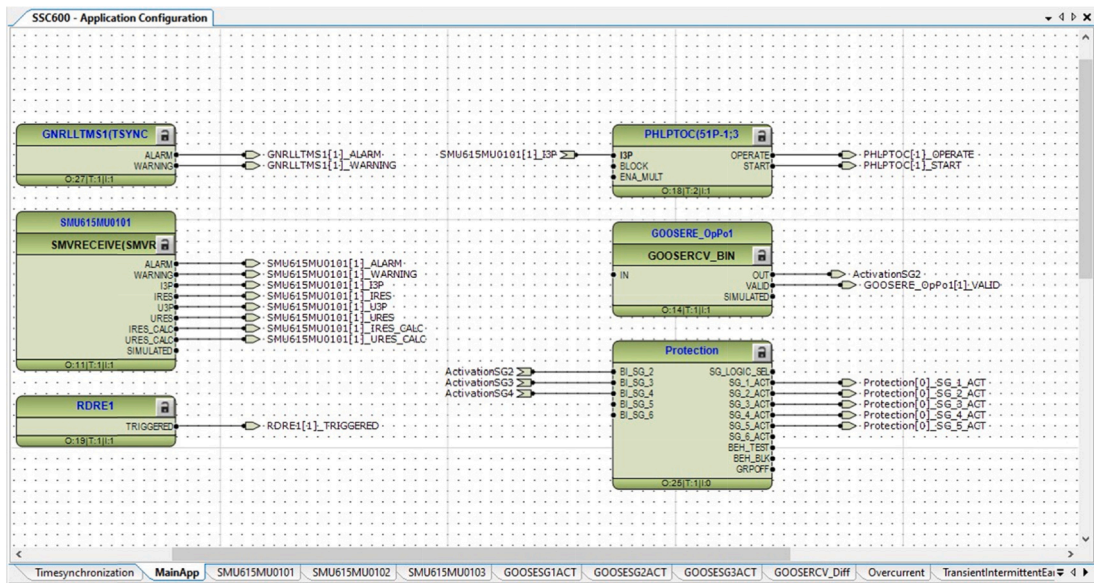


Fig. 19. Protection function blocks in the Application Configuration interface of PCM600.

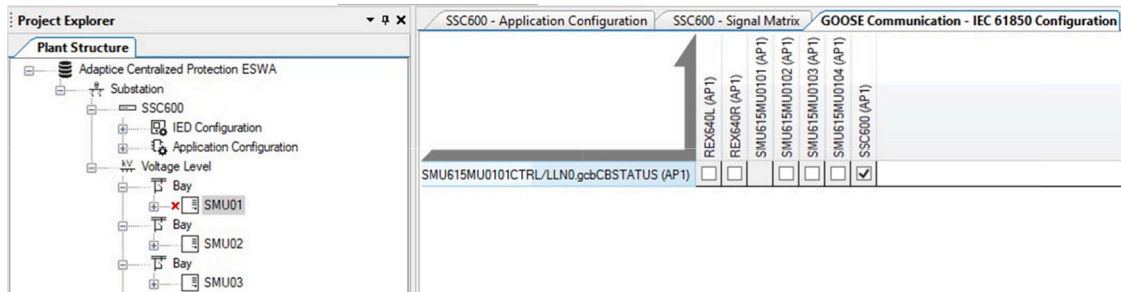


Fig. 20. Signal matrix engineering for the MU of the first feeder.

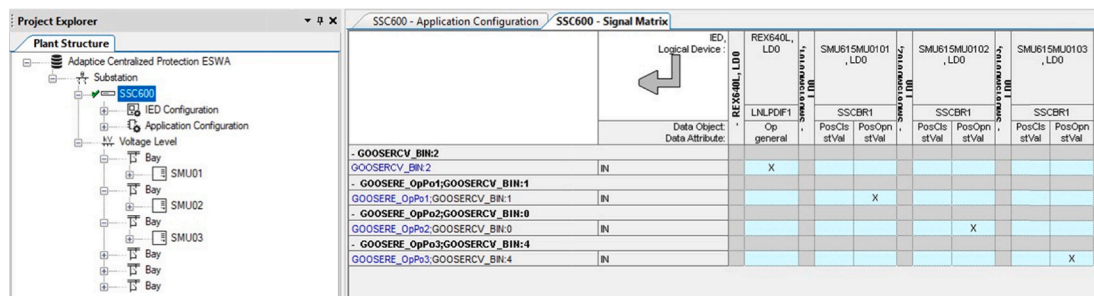


Fig. 21. Signal matrix engineering for receiving the status of CBs from real-time simulator.

OPAL-RT system using the GOOSE protocol, the circuit breakers are opened, the status of the breakers is transmitted from the OPAL-RT to the SSC600 using a GOOSE message. This communication is used to activate the corresponding setting group associated with the new topology. It is worth noting that SSC600 has different logics for setting group activation. In this case study logic mode 1 is selected, meaning that the higher the setting group, the higher the priority. This is shown in Table 11 according to the technical manual of the relay. In practical applications, it is often recommended to allocate the higher setting group of the inverse-time overcurrent relays to scenarios where the settings can also cover other topologies or situations of significant importance. This approach is considered crucial to ensure reliable protection and adequate coordination between relays in power systems.

The operating time of the relay is determined using the IEC standard

inverse curve, which is defined by equation (11) and the relays setting are as Fig. 24.

Upon successful configuration and setting, the SSC600 is capable of seamlessly changing the SGs based on different topologies, namely I, II, III, and IV. The relay operation after applying three-phase close-in faults in three feeders is depicted in Fig. 25. Prior to the fault occurrence, SG1 is active, indicating the absence of any outage. Subsequently, in response to the faults, the overcurrent relays promptly issue trip commands. These trip signals are transmitted to the OPAL-RT platform using GOOSE messages, triggering the opening of the corresponding circuit breakers in the real-time simulation model. Following the breaker openings, the status of the breakers is communicated back to the SSC600, allowing it to accurately determine the current grid topology and subsequently adjust the setting group accordingly.

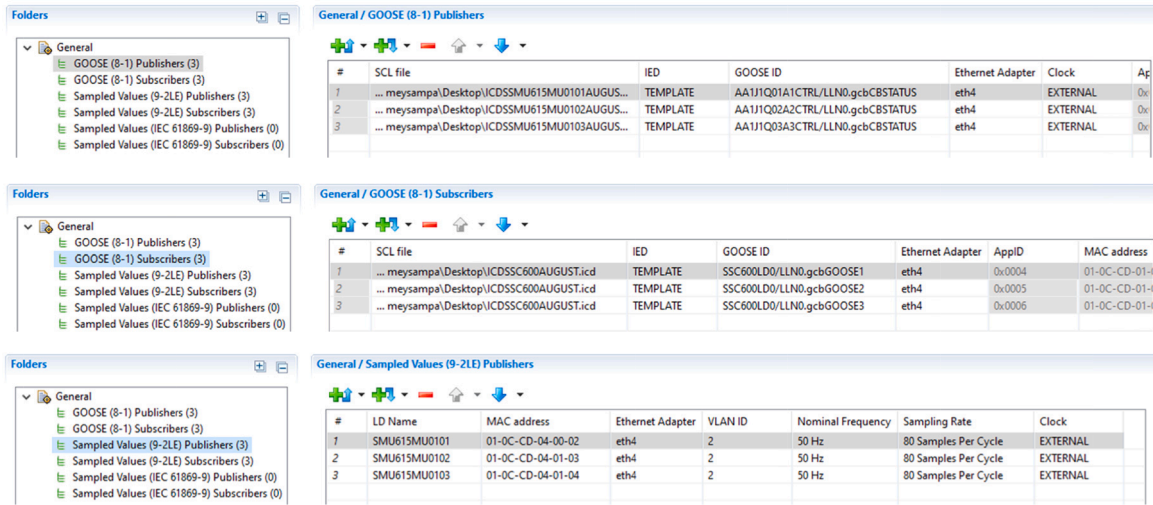


Fig. 22. Application of generated SCL files in RT-LAB software for configuration of IEC 61850.

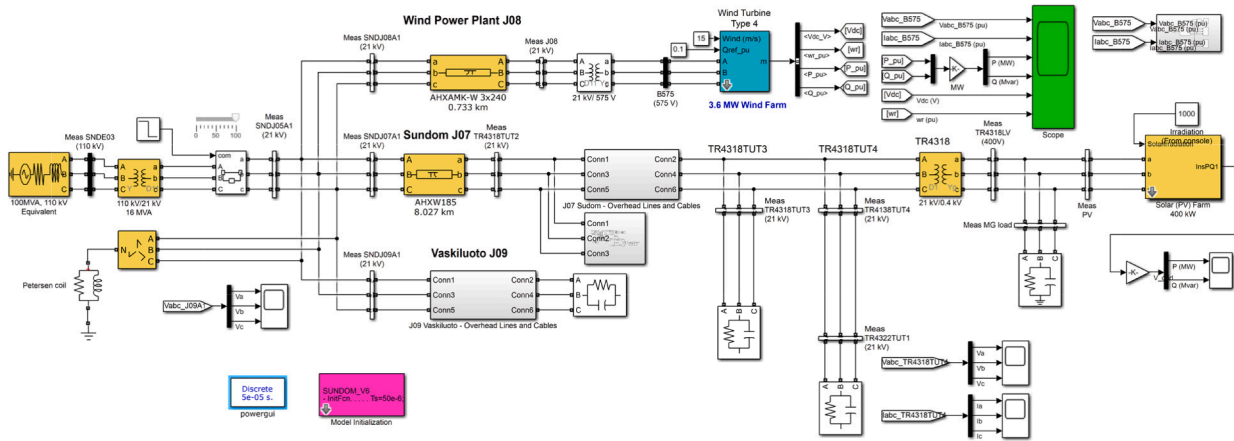


Fig. 23. Test system.

Parameter Setting

Parameter Name	IED Value	New Value
Operation	on	on
Num of start phases	3 out of 3	3 out of 3
Start value #	1.10	1.10
Start value Mult #	1.0	1.0
Time multiplier #	0.025	0.025
Minimum operate time	40	40
Reset delay time	20	20
Operating curve type #	IEC S.T. inv.	IEC S.T. inv.
Type of reset curve #	Def time reset	Def time reset
Measurement mode	DFT	DFT

Fig. 24. Overcurrent relays setting in SSC600.

The results indicate that, in all three cases, after applying faults to feeders 1, 2, and 3 (F1, F2, and F3), GOOSE messages were sent to the CBs in the OPAL-RT system, successfully disconnecting them within 200 ms, with F3 taking nearly 100 ms. Upon receiving the status of the CBs after opening using the GOOSE message, the setting group, which was initially SG1, seamlessly changed to 2, 3, and 4 after F1, F2, and F3, respectively. After ending GOOSE, the setting groups reverts to its previous state.

While there are numerous settings, logics, and descriptions related to IEC 61850, the limitations of this paper prevent us from delving deeper into this section. Our group plans to explore this further in future

works, utilizing the same setup but incorporating 5G as the communication medium in different use cases. It is important to emphasize that changing the setting group was a contributing factor to the reduced availability of relays in the literature. However, the results shown in Fig. 26 demonstrate that this process takes less than 100 ms, which is a promising development for centralized protection and control devices. It is important to note that changing a setting group after issuing trip signal can be influenced by several factors. These include the communication protocol used to activate setting groups (e.g., GOOSE, MMS), dedicated communication links, and other communication network characteristics. Additionally, using GOOSE messages for communication between CBs and the SSC600 relay in our HIL setup achieves setting group changes within 1–2 ms for all tested cases, as shown in the event recorder data. This significantly improves the availability of the power system protection scheme. It is also important to acknowledge that the status of circuit breakers can undergo immediate changes upon receiving a GOOSE message in OPAL-RT. However, the exact timing of these changes in real-world scenarios varies due to various factors, including the opening time of the circuit breakers. In certain cases, the actual timing may be extended by approximately 40 ms compared to the previously mentioned values.

6. Conclusion

In this paper, hardware-in-the-loop implementation of centralized

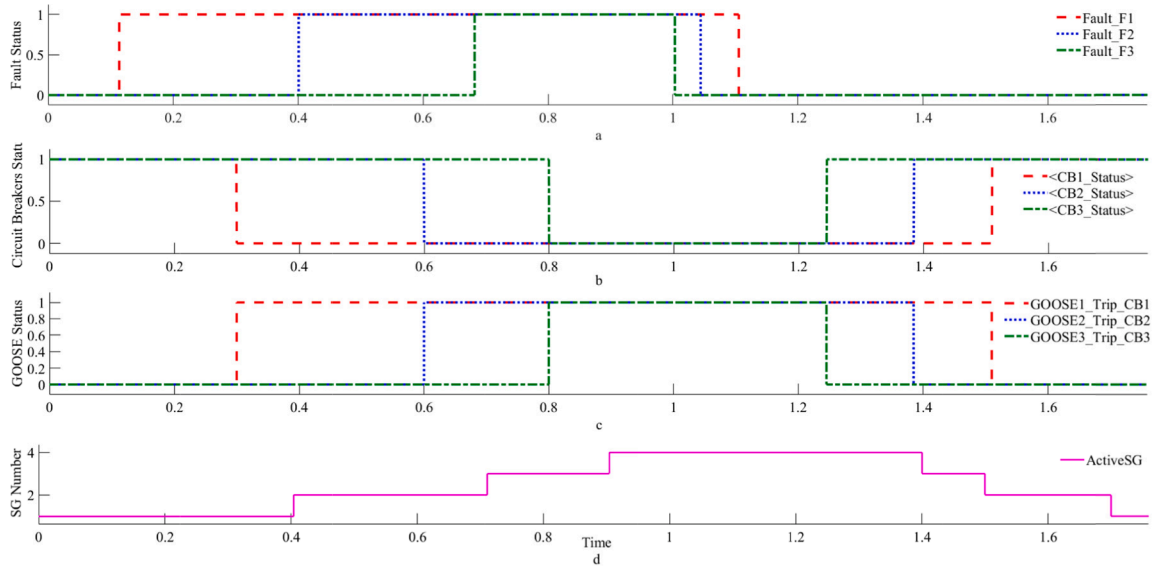


Fig. 25. (a) Fault occurrence in feeders, (b) Status of circuit breakers, (c) GOOSE trip signals to open circuit breakers, (d) Active setting group number.

Date	Time	Source	Function	Description	Value

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

Fig. 26. Monitoring the setting group changing time in SSC600.

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, by 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

Table 11
Setting group (SG) activation logic.

GOOSE INPUT FOR ACTIVATING SGs					
Active SG	SG2	SG3	SG4	SG5	SG6
1	0	0	0	0	0
2	1	0	0	0	0
3	0 or 1	1	0	0	0
4	0 or 1	0 or 1	1	0	0
5	0 or 1	0 or 1	0 or 1	1	0
6	0 or 1	0 or 1	0 or 1	0 or 1	1

links fail. Results of the optimal setting groups obtained by using this method illustrate that not only the reliability of the protection system will be increased but also the average time delay is improved. Table 12 shows the summary of proposed methods. In future research, there is a plan to conduct hardware-in-the-loop simulation of the second scheme (Fig. 3), incorporating 5G communication. Additionally, it is recommended in the future research to consider various critical factors such as dependability, security, and availability. It is worth noting that changing the setting group in relays may have implications for these factors. In future studies, exploring the numerical positive potential impact of the clustering on dependability and security, while potentially reducing availability, would be valuable. We also recognize that a more comprehensive study would ideally incorporate different DG sources from different types in the test system. This approach would allow for a more direct investigation of their impact on adaptive centralized protection systems.

CRedit authorship contribution statement

Meysam Pashaei: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Hasan Rastegar:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision. **Seyed Farhad Zandrazavi:** Software, Validation, Formal

Table 12

The summary of the paper contribution and suggested methods.

Method	advantages	disadvantages	t_{avg}	Robust SG
Conventional	No need to activate different SGs	Long time delays of relays Miscoordination among relays	0.614	–
Method 1	Low computational burden (In offline setting, calculation is not the main concern)	Overlooking the effect of TDSs on the clustering process Ignoring communication failure	0.576	NO
Method 2	Considering the effects of TDSs on the clustering process Improvement in time delays of relays compared to previous ones	Overlooking communication links failure	0.567	NO
Method 3	Shorter time delays of relays Coping with the communication links and central server failure in networks that lacks full redundancy	Considering only cohesion index in clustering process	0.563	YES
Method 4	Coping with the communication links and central server failure Shorter time delays of relays in cluster1 Considering both cohesion and separation indices in clustering	The time delays of relays are long compared to Method 3. However, better than traditional method.	0.611	YES

analysis, Writing – original draft, Writing – review & editing, Visualization. **Kimmo Kauhaniemi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Hannu Laaksonen:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- Abbasi, A., Karegar, H. K., & Aghdam, T. S. (2019). Adaptive protection coordination with setting groups allocation. *International Journal of Renewable Energy Research*, 9(2). <https://doi.org/10.20508/ijrer.v9i2.9266.g7647>
- Alam, M. N. (2019). Adaptive Protection Coordination Scheme Using Numerical Directional Overcurrent Relays. *IEEE Transactions on Industrial Informatics*, 15(1). <https://doi.org/10.1109/TII.2018.2834474>
- Alam, M. N., Chakrabarti, S., & Pradhan, A. K. (2022). Protection of Networked Microgrids Using Relays with Multiple Setting Groups. *IEEE Transactions on Industrial Informatics*, 18(6). <https://doi.org/10.1109/TII.2021.3120151>
- Ataee-Kachoe, A., Hashemi-Dezaki, H., & Ketabi, A. (2023). Optimized adaptive protection coordination of microgrids by dual-setting directional overcurrent relays considering different topologies based on limited independent relays' setting groups. *Electric Power Systems Research*, 214. <https://doi.org/10.1016/j.epr.2022.108879>
- Barranco-Carlos, A., Orozco-Henao, C., Marín-Quintero, J., Mora-Flórez, J., & Herrera-Orozco, A. (2023). Adaptive Protection for Active Distribution Networks: An Approach Based on Fuses and Relays With Multiple Setting Groups. *IEEE Access*, 11, 31075–31091. <https://doi.org/10.1109/ACCESS.2023.3261827>
- Carlos, A. B., Henao, C. O., Quintero, J. M., Florez, J. M., & Orozco, A. H. (2022). Clustering Techniques Performance for the Coordination of Adaptive Overcurrent Protections. *2022 IEEE ANDESCON: Technology and Innovation for Andean Industry, ANDESCON 2022*. Doi: 10.1109/ANDESCON56260.2022.9989786.
- Chabanloo, R. M., Safari, M., & Roshanagh, R. G. (2018). Reducing the scenarios of network topology changes for adaptive coordination of overcurrent relays using hybrid GA–LP. *IET Generation, Transmission and Distribution*, 12(21). <https://doi.org/10.1049/iet-gtd.2018.5810>
- Chattopadhyay, B., Sachdev, M. S., & Sidhu, T. S. (1992). *Adaptive relaying for protecting a distribution system—A feasibility study*. Doi: 10.1109/wescan.1991.160514.
- Chou, C. H., Su, M. C., & Lai, E. (2004). A new cluster validity measure and its application to image compression. *Pattern Analysis and Applications*, 7(2). <https://doi.org/10.1007/s10044-004-0218-1>
- Cintuglu, M. H., Ma, T., & Mohammed, O. A. (2017). Protection of Autonomous Microgrids Using Agent-Based Distributed Communication. *IEEE Transactions on Power Delivery*, 32(1). <https://doi.org/10.1109/TPWRD.2016.2551368>
- Conti, S. (2009). Analysis of distribution network protection issues in presence of dispersed generation. *Electric Power Systems Research*, 79(1). <https://doi.org/10.1016/j.epr.2008.05.002>
- Davies, D. L., & Bouldin, D. W. (1979). A Cluster Separation Measure. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-1(2). <https://doi.org/10.1109/TPAMI.1979.4766909>
- Detjen, E. D. (1988). Feasibility of Adaptive Distribution Protection System Using Computer Overcurrent Relaying Concept. *IEEE Transactions on Industry Applications*, 24(5). <https://doi.org/10.1109/28.8981>
- El Naily, N., Saad, S. M., Elhaffar, A., Hussein, T., & Mohamed, F. A. (2017). Mitigating the impact of Distributed Generator on medium Distribution Network by adaptive protection scheme. *2017 8th International Renewable Energy Congress, IREC 2017*. Doi: 10.1109/IREC.2017.7925989.
- Faris, H., Aljarah, I., Al-Betar, M. A., & Mirjalili, S. (2018). Grey wolf optimizer: A review of recent variants and applications. *Neural Computing and Applications*, 30, 413–435.
- Ganoo, P., Joshi, S., Valtari, J., & Niveri, H. (2022). Centralized Protection and Control System: Are We Ready for Deployment in the Chemical, Oil, and Gas Industry? *IEEE Industry Applications Magazine*, 28(4), 48–61. <https://doi.org/10.1109/MIAS.2022.3161000>
- Ghadiri, S. M. E., & Mazlumi, K. (2020). Adaptive protection scheme for microgrids based on SOM clustering technique. *Applied Soft Computing*, 88, Article 106062. <https://doi.org/10.1016/j.asoc.2020.106062>
- Heidari, A. A., Mirjalili, S., Faris, H., Aljarah, I., Mafarja, M., & Chen, H. (2019). Harris hawks optimization: Algorithm and applications. *Future Generation Computer Systems*, 97, 849–872. <https://doi.org/10.1016/j.future.2019.02.028>
- Karaboga, D., & Basturk, B. (2007). Artificial bee colony (ABC) optimization algorithm for solving constrained optimization problems. *International Fuzzy Systems Association World Congress*, 789–798. Springer.
- Karimkhan Zand, H., Mazlumi, K., Bagheri, A., & Abdali, A. (2023). Optimal coordination of DOCRs in microgrid via contingency reduction mechanism and clustering algorithms considering various network topologies based on N-2 contingencies. *Expert Systems with Applications*, 234, Article 121061. <https://doi.org/10.1016/j.eswa.2023.121061>
- Kokkonen-Tarkkanen, H., Raussi, P., Horsmanheimo, S., Hovila, P., Kulmala, A., & Borenius, S. (2023). 5G edge for power system applications. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 1871–1875. Doi: 10.1049/icp.2023.1056.
- Kulmala, A., Raipala, O., Hovila, P., Yazadzhiyan, B. -E., Dantas, R., & Scoble, C. (2023). Virtualised centralised protection and control - constellation project case study. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 1670–1674. Doi: 10.1049/icp.2023.0987.
- Laaksonen, H., Ishchenko, D., & Oudalov, A. (2014). Adaptive Protection and Microgrid Control Design for Hailuoto Island. *IEEE Transactions on Smart Grid*, 5(3), 1486–1493. <https://doi.org/10.1109/TSG.2013.2287672>
- Laaksonen, H., & Hovila, P. (2016). FlexZone concept to enable resilient distribution grids - Possibilities in Sundom Smart Grid. *IET Conference Publications*, 2016(CP686), 1–4. <https://doi.org/10.1049/cp.2016.0611>
- Marini, F., & Walczak, B. (2015). Particle swarm optimization (PSO). A tutorial. *Chemometrics and Intelligent Laboratory Systems*, 149, 153–165. <https://doi.org/10.1016/j.chemolab.2015.08.020>

- Memon, A. A., & Kauhaniemi, K. (2021). Real-Time Hardware-in-the-Loop Testing of IEC 61850 GOOSE-Based Logically Selective Adaptive Protection of AC Microgrid. *IEEE Access*, 9, 154612–154639. <https://doi.org/10.1109/ACCESS.2021.3128370>
- Memon, A. A., & Kauhaniemi, K. (2015). A critical review of AC Microgrid protection issues and available solutions. *Electric Power Systems Research*, 129, 23–31. <https://doi.org/10.1016/j.epsr.2015.07.006>
- Mirjalili, S., & Mirjalili, S. (2019). Genetic algorithm. *Evolutionary Algorithms and Neural Networks: Theory and Applications*, 43–55.
- Ojaghi, M., & Mohammadi, V. (2018). Use of Clustering to Reduce the Number of Different Setting Groups for Adaptive Coordination of Overcurrent Relays. *IEEE Transactions on Power Delivery*, 33(3). <https://doi.org/10.1109/TPWRD.2017.2749321>
- Pashaei, M., Karimi, M., Kauhaniemi, K., Asadi, A., Ramlı, S. P., & Pourdaryaei, A. (2023). Intermittent earth fault detection in distribution network based on the voting classification technique. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 3759–3763. Doi: 10.1049/icp.2023.0726.
- Piescorovsky, E. C., & Schulz, N. N. (2017). Comparison of non-real-time and real-time simulators with relays in-the-loop for adaptive overcurrent protection. *Electric Power Systems Research*, 143. <https://doi.org/10.1016/j.epsr.2016.10.049>
- Piescorovsky, E. C., & Schulz, N. N. (2017b). Comparison of Programmable Logic and Setting Group Methods for adaptive overcurrent protection in microgrids. *Electric Power Systems Research*, 151. <https://doi.org/10.1016/j.epsr.2017.05.035>
- Raipala, O., Kulmala, A., Hovila, P., Yazadzhijan, B. -E., Dantas, R., & Scoble, C. (2023). A 5G communication-based wide area protection concept for enabling resilient and reliable loss of mains protection. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 2637–2641. Doi: 10.1049/icp.2023.1102.
- Rao, R. V., Savsani, V. J., & Vakharia, D. P. (2011). Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems. *Computer-Aided Design*, 43(3), 303–315. <https://doi.org/10.1016/j.cad.2010.12.015>
- Rockefeller, G. D., Wagner, C. L., Linders, J. R., Hicks, K. L., & Rizy, D. T. (1988). Adaptive transmission relaying concepts for improved performance. *IEEE Transactions on Power Delivery*, 3(4). <https://doi.org/10.1109/61.193943>
- Saber, A., Zeineldin, H. H., El-Fouly, T. H. M., & Al-Durra, A. (2023). Overcurrent protection coordination with flexible partitioning of active distribution systems into multiple microgrids. *International Journal of Electrical Power and Energy Systems*, 151. <https://doi.org/10.1016/j.ijepes.2023.109205>
- Samadi, A., & Mohammadi Chabanloo, R. (2020). Adaptive coordination of overcurrent relays in active distribution networks based on independent change of relays' setting groups. *International Journal of Electrical Power and Energy Systems*, 120. <https://doi.org/10.1016/j.ijepes.2020.106026>
- Schönborn, S., Birke, R., Kozhaya, D., & Sivanthi, T. (2023). Real-time performance of virtualised protection and control software. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 1817–1821. Doi: 10.1049/icp.2023.1028.
- Shih, M. Y., Conde, A., Leonowicz, Z., & Martirano, L. (2017). An Adaptive Overcurrent Coordination Scheme to Improve Relay Sensitivity and Overcome Drawbacks due to Distributed Generation in Smart Grids. *IEEE Transactions on Industry Applications*, 53(6). <https://doi.org/10.1109/TIA.2017.2717880>
- Singh, M., & Agrawal, A. (2018). Cluster Based Protection Coordination using a New Voltage Current Time Inverse Relay. *IEEE Power and Energy Society General Meeting, 2018-August*. Doi: 10.1109/PESGM.2018.8586611.
- Soni, A. K., Kumar, A., Panda, R. K., Mohapatra, A., & Singh, S. N. (2023). Adaptive Coordination of Relays in AC Microgrid Considering Operational and Topological Changes. *IEEE Systems Journal*, 17(2), 3071–3082. <https://doi.org/10.1109/JSYST.2022.3227311>
- Soni, A. K., Kumar, A., Panda, R. K., Mohapatra, A., & Singh, S. N. (2023). Adaptive Coordination of Relays in AC Microgrid Considering Operational and Topological Changes. *IEEE Systems Journal*, 17(2). <https://doi.org/10.1109/JSYST.2022.3227311>
- Sorrentino, E., & Rodríguez, J. V. (2023). Optimal coordination of directional overcurrent protections considering the occurrence probability of different configurations and the effect of grouping cases. *Electric Power Systems Research*, 218. <https://doi.org/10.1016/j.epsr.2023.109163>
- Thorp, J. S., Adamiak, M., Banerjee, H. N., Bright, J. A., Cease, T. W., Clark, D. M., & Wagner, C. L. (1993). Feasibility of adaptive protection and control. *IEEE Transactions on Power Delivery*, 8(3). <https://doi.org/10.1109/61.252625>
- Urdaneta, A. J., Restrepo, H., Márquez, S., & Sánchez, J. (1996). Coordination of directional overcurrent relay timing using linear programming. *IEEE Transactions on Power Delivery*, 11(1). <https://doi.org/10.1109/61.484008>
- Valtari, J., Dominguez, J., Coggan, R., Starck, J., & Pritchard, C. (2023). Functional testing of virtualized and centralized protection systems. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 3513–3517. Doi: 10.1049/icp.2023.0812.
- Valtari, J., Kulmala, A., Schönborn, S., Kozhaya, D., Birke, R., & Reikko, J. (2023). Real-life pilot of virtual protection and control - experiences and performance analysis. *27th International Conference on Electricity Distribution (CIRED 2023)*, 2023, 2268–2272. Doi: 10.1049/icp.2023.1219.
- Wong, J., Tan, C., Rahim, N., & Tan, R. H. G. (2023). Communication-Less Adaptive Overcurrent Protection for Highly Reconfigurable Systems Based on Nonparametric Load Flow Models. *IEEE Transactions on Power Delivery*, 1–8. <https://doi.org/10.1109/TPWRD.2023.3330730>
- Wong, J. Y., Tan, C. K., Rahim, N. A., & Tan, R. H. G. (2023). A Communication-less adaptive protection scheme for Self-Healing distribution systems. *International Journal of Electrical Power and Energy Systems*, 148. <https://doi.org/10.1016/j.ijepes.2023.108992>
- Zanjani, M. G. M., Mazlumi, K., & Kamwa, I. (2018). Application of μ PMUs for adaptive protection of overcurrent relays in microgrids. *IET Generation, Transmission and Distribution*, 12(18). <https://doi.org/10.1049/iet-gtd.2018.5898>
- Zhang, G. Bin, Guo, B. Q., & Liang, Y. (2011). A classification method for adaptive relay protection setting system based on clustering analysis. *APAP 2011 - Proceedings: 2011 International Conference on Advanced Power System Automation and Protection*, 3. Doi: 10.1109/APAP.2011.6180633.