Enhanced Fault Detection and Accelerated Switching Methodology in Power Systems Utilizing GOOSE Messaging: Centralized Control Switch Acceleration (CCSA)

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Abstract: This paper introduces the CCSA (Central Control Switch Acceleration), a novel approach to fault detection and switching in power distribution networks, based on the IEC 61850 protocol and GOOSE messaging. Current protection in high voltage distribution systems relies on non directional overcurrent protection and time delayed switching based on individual IEDs (Intelligent Electronic Devices). However, these methods are limited in response speed and coordination. CCSA enhances protection by accelerating the switching response through a centrally controlled communication scheme, using GOOSE messages to coordinate and trigger protective actions within 50 milliseconds. The CCSA method reduces fault clearing times by leveraging existing network infrastructure (optical and metallic connections) and employs VLAN segmentation and unique MAC addresses for precise communication. In practical tests with Elvac, ABB, and Siemens devices, CCSA demonstrated improved reliability and minimized service disruption. Results from real world fault scenarios show that CCSA significantly decreases the time and extent of service interruptions, thereby protecting against economic losses and enhancing operational efficiency in power grids.

Keywords: IEC61850 protocol; nondirectional; overcurrent; protection; acceleration

1 Introduction

The growing integration of Distributed Generation (DG) into AC power systems poses significant challenges in fault detection and protection methodologies. As the complexity of these systems increases, traditional fault management techniques may fall short in ensuring the reliability and efficiency of power delivery. Recent advancements in communication protocols, such as the Generic Object Oriented Substation Event (GOOSE) protocol outlined by Shi and Druzhinin [1], have emerged as pivotal tools for enhancing fault detection capabilities. Their research underscores the critical need for automated systems that can swiftly identify and mitigate faults, particularly in environments where DG is present. Moreover, the application of machine learning techniques, such as Long Short-Term Memory (LSTM) networks has been explored by Han and Kim [2] to enhance fault identification in closed loop distribution systems. This approach demonstrates the potential of predictive analytics to improve response times and accuracy in dynamic network conditions, ultimately facilitating more resilient power systems. The adoption of the IEC 61850 standard is also highlighted in various studies, including that of Ali and Eissa [3], which emphasizes accelerated protection schemes that harness this protocol to achieve quicker fault response times. The ability to implement such protocols not only enhances the performance of existing systems but also mitigates the detrimental impacts of faults, ensuring stable operation. Additionally, the effectiveness of directional overcurrent relays (DOCR) has been a focal point in recent research. Baňas et al. [4] demonstrate the role of DOCRs in maintaining stability within complex network configurations, while Singh and Gupta [5] explore optimization strategies that can further enhance their coordination in protective relaying applications. The exploration of current only approaches in distribution protection by Ukil et al. [6] signifies a shift towards innovative methodologies that prioritize real time fault isolation, which is crucial in modern smart grid environments. The utilization of automatic reclosers in transmission line fault management has been further examined by Moula and Ahammed [7]. Their work highlights the importance of reclosers in minimizing system downtime following faults, emphasizing the growing significance of these devices in high availability power systems. Complementary studies on optimal recloser placement, such as those conducted by Dhole et al. [8] and Mercado and Sanchez [9], reveal how strategic positioning can substantially improve service quality and reliability in distribution networks. Furthermore, the incorporation of smart grid communication standards, as discussed by Gungor et al. [12], is crucial for achieving efficient fault detection and coordination. The IEC/IEEE C37.60-2018 standard [13-15] provides a necessary framework for the implementation of automatic circuit reclosers in AC systems, ensuring robust fault response capabilities up to 38 kV. In summary, the literature indicates a clear trend toward the adoption of advanced protection schemes, innovative fault detection methods, and strategic deployment of reclosers to enhance the reliability of modern power systems. [16-19] These advancements are essential for reducing outage durations and optimizing fault management in increasingly complex electrical networks. [20-22] This paper introduces the Central Control Switch Acceleration (CCSA) method as a novel approach to fault detection switching using GOOSE, building upon the foundational knowledge presented in these studies and contributing to the ongoing evolution of power system protection.

2 Discussion and Introduction to the Concept

The current connection of IEDs (Intelligent electronic devices) to the distribution system from a communication perspective is shown in Figure 1. All existing protective elements (Digital Relay Protections) are interconnected through internal LAV/VLANs to switches, which are then connected to routers, forming a unified communication network. This network is supplemented by time synchronization via GPS. All connections are realized using a combination of optical and metallic cables. Such a setup allows the application of various switching methods based solely on status signaling, without internal control of individual devices. This means that coordinated control can be achieved solely through communication. The following section describes how the distribution network is currently protected, and the introduction of a new control method based on IED signaling, while maintaining the original protection in the event of communication failure. Distribution networks are currently protected by switching commands from individual devices with a certain time delay. Sections are protected against overvoltage, undervoltage, overcur-rent, and at higher levels against frequency changes. For the real network (affecting 50,000 civilian consumers and more than 250 companies in distribution in Slovakia) where the CCSA method was applied, current distribution parameters are set to protect against overcurrent (using traditional relay protections), while overvoltage, undervoltage, and frequency changes are only signaled (without tripping) using the same devices. Similarly, ground faults are only signaled. CCSA uses all these signals for controlled switching of power circuit breakers without the need for a direct response from the protection system.

Current operating principle: IEDs (Intelligent Electronic Devices) installed on power lines monitor parameters such as current, voltage, and temperature, detecting faults based on predefined algorithms. These data, including information on short-circuits or voltage failures, are transmitted to central systems using protocols like IEC 61850 or DNP3, where they are processed in real-time through SCADA systems. Operators receive notifications about faults and can obtain detailed information, while the IEDs perform protective functions, such as line disconnection. Fault data are archived for further analysis, allowing for optimization of maintenance and preventive measures. IEDs send the signal directly to the circuit breakers for tripping.

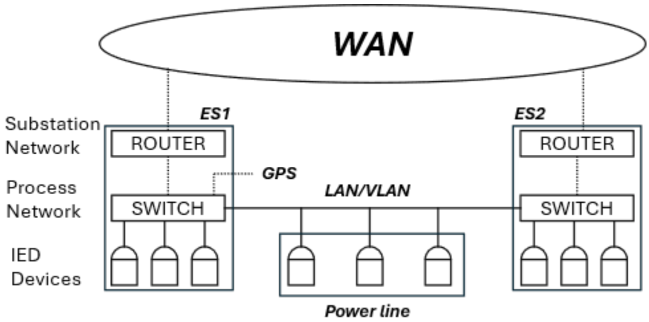


Figure 1
Communication network in actual power grid

Operating principle with added CCSA: The acceleration stage in protective devices uses logic that allows blocking or releasing nondirectional overcurrent stages, with communication occurring through IEC 61850 GOOSE messages. This protocol, using the physical and data link layers of the ISO/OSI communication model according to IEC 61850-9-2, is used to transmit time critical data such as GOOSE messages and sampled values. Addressing is done using MAC addresses since IP addresses are not used in this case. For precise operation of the acceleration stage, it is essential to ensure unambiguous identification using a unique MAC address for GOOSE messages and the application's message ID, while VLANs enable message transmission between devices in different networks. Key to the proper functioning of communication is the configuration of minimum and maximum time parameters. The minimum time ensures fast signal transmission after a state change, while maximum time is critical for monitoring communication quality and allows immediate blocking of the acceleration stage in the event of communication failure. The added acceleration stage increases the system's response speed during critical conditions. Unlike the current system, which relies on standard data transmission via IP addresses, the acceleration stage uses MAC addresses and VLANs for faster GOOSE message and sampled value transmission. A major difference is the precise configuration of minimum and maximum time parameters—minimum time ensures fast signal transmission after a state change, while maximum time monitors communication quality and enables quick blocking of the acceleration stage in case of failure. This new approach improves response time and ensures greater reliability in the event of communication break downs, providing more efficient protection for the power grid.

The faults in distribution networks at the high voltage (HV – 110 kV for grid in Slovakia) level represent a significant problem. They affect the supply of energy for customers and lead to economic losses. To mitigate the impact, it is important to quickly and accurately define faults. In the environment of high voltage distribution systems, are extensively used Reclosers for line automation. Figure 2 shows the current protection system for most distribution networks worldwide, with actual RCL setting in Slovak distribution system.

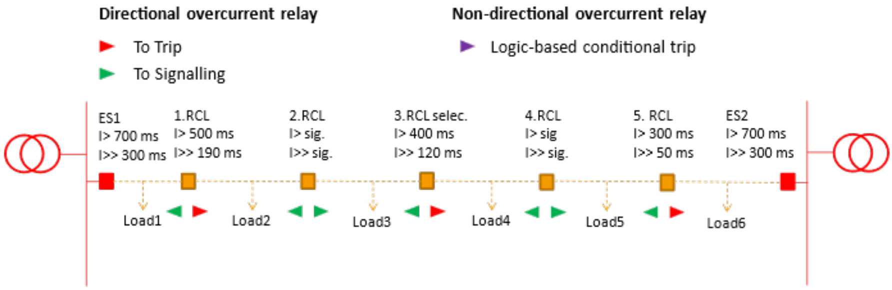


Figure 2

Actual setting of RCL in Slovak distribution system directional overcurrent protection stages

With the construction of optical infrastructure in distribution grid, we have decided to use optical communication and the IEC61850 protocol. Thanks to the optical and metallic data infrastructure for communication, which most distribution networks already have in place, it is possible to add an acceleration stage (CSAA) based on nondirectional overcurrent stages to the existing RCL [14-15].

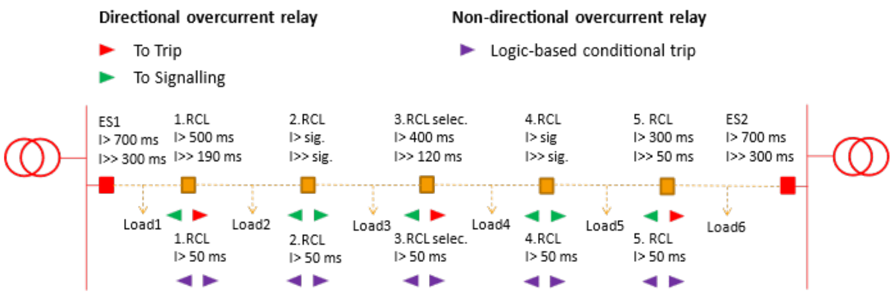


Figure 3

Actual setting of RCL in Slovak distribution system directional overcurrent protection stages

At this stage, the protective function is ensured by a conventional method using time grading, where the first recloser has operating times of 500 ms in case of overload and 190 ms in case of a short-circuit. According to current standards, each subsequent protection must be time graded, meaning that disconnection times for a certain number of protections in a protected section reach a limit. This disadvantage is precisely eliminated by CCSA, where the signal reaches from every point within 50 ms. This means that time selective disconnection is no longer a criterion. Since the protections operate with classic selective switching under certain blocking conditions, they are still able to function in the standard mode in case of communication loss. However, adding the CCSA acceleration stage introduces a new layer to the system, serving as an enhancement to the existing functionality. The logic of the acceleration stage lies in evaluating the signal, where the protection that first detects a fault compares it with others in its vicinity and based on that, determines whether to trip or not. An example of the switching process is shown in Fig. 4.

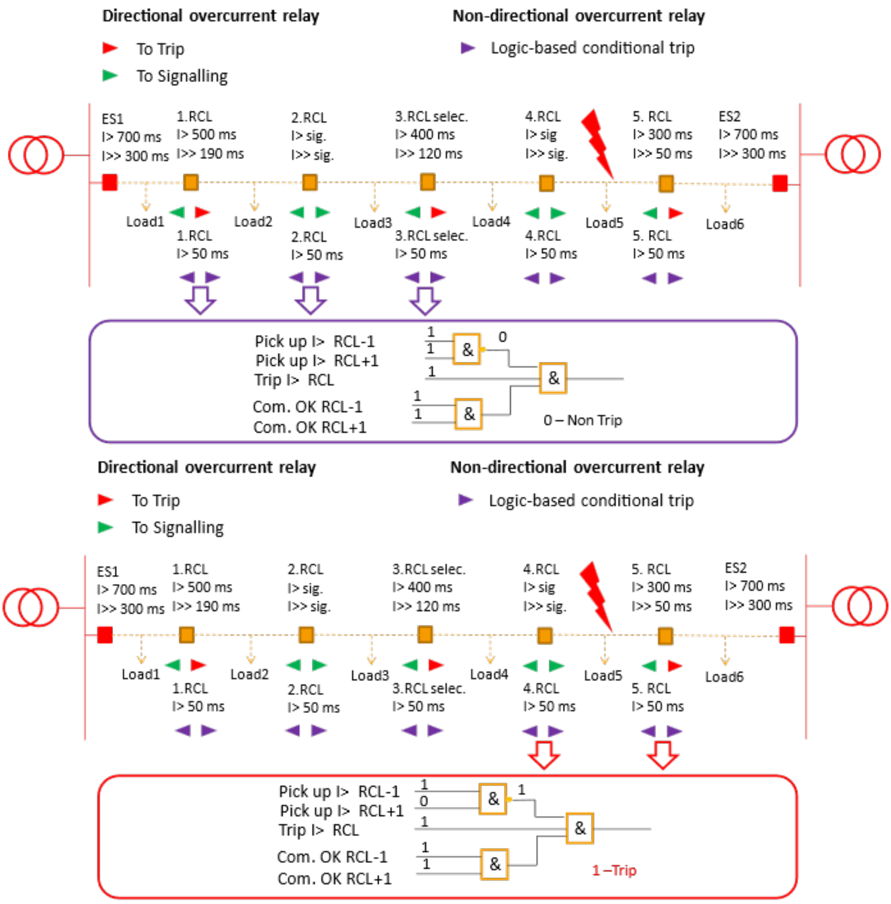


Figure 4

Example of a fault and application of acceleration logic

For illustration, the fault will occur behind the fourth recloser. At the substation, the first, second, and third reclosers will have the acceleration stage blocked, as communication with neighbors will be fine, and they will also receive start information from their neighbors. On the fourth recloser, communication with neighbors will be fine, it will receive start information from its neighbor (recloser 3), while its next neighbor (recloser 5) does not detect the fault. Based on the implemented logic, the acceleration stage will be turned off.

3 Testing on Real Devices in Laboratory (ELVAC, ABB, SIEMENS)

For testing purposes, five Elvac RTU7M devices were used, representing protections in the reclosers. ABB REF 630 protective relay and SIEMENS 7SJ621 protection represented the protection of the station's outputs. All devices were deployed and tested on a real electrical grid located in Slovakia. Due to confidentiality agreements with the grid operator, specific location details and parts of the operational data are withheld. However, the data and parameters presented in Tables 1 and 2 reflect actual field measurements and operational configurations.

Table I
Test settings for protection devices

Device name	Overcurrent stage		Tripping stage	
	Direction	Time	Direction	Time
REF 630	nondirectional	0,7 s	nondirectional	0,15 s
RTU 1	forward	0,5 s	nondirectional	0,05 s
RTU 2	forward	0,4 s	nondirectional	0,05 s
RTU 3	forward	sig.	nondirectional	0,05 s
RTU 4	forward	0,4 s	nondirectional	0,05 s
RTU 5	forward	0,5 s	nondirectional	0,05 s
7SJ621	nondirectional	0,7 s	nondirectional	0,20 s

Table I outlines the configurations used for testing the overcurrent and tripping stages of different protection devices, including Elvac RTU7M reclosers, the ABB REF 630 relay, and the SIEMENS 7SJ621 relay. These settings control how each device reacts to overcurrent faults in the grid. The overcurrent stage refers to the point where the device detects that the current exceeds a set threshold and initiates protective actions. In the case of the tripping stage, this is when the device disconnects a section of the grid to prevent damage, typically after confirming that the fault persists.

REF 630: This relay detects nondirectional overcurrent, meaning it responds to faults in any direction, after 0.7 seconds. Once the fault is confirmed, the tripping stage activates after 0.15 seconds.

RTU 1, 2, 3, 4, 5 (Elvac RTU7M): These reclosers are set to detect overcurrent in the forward direction. RTUs 1 and 5 respond after 0.5 seconds, RTU 2 reacts after 0.4 seconds, and RTU 3 uses signal based fault detection (indicated as "sig."). All RTUs have a nondirectional tripping stage that occurs after 0.05 seconds.

SIEMENS 7SJ621: This relay also operates nondirectionally, detecting faults after 0.7 seconds and tripping after 0.20 seconds.

In summary, the nondirectional devices trigger on faults from any direction, while directional devices (such as the RTUs) only react to faults in a specific direction, typically forward. The tripping times are shorter than the overcurrent detection times, indicating a faster response once the fault is confirmed.

Table II
Communication settings for GOOSE messages

Device	IED Name	Application ID	MAC address
REF630	REF630_01	3	01-0C-CD-00-03
RTU1	RTU1	1006	01-0C-CD-00-06
RTU2	RTU2	1007	01-0C-CD-00-07
RTU3	RTU3	1008	01-0C-CD-00-08
RTU4	RTU4	1009	01-0C-CD-00-09
RTU5	RTU5	1010	01-0C-CD-00-10
7SJ621	AEA_01	1011	01-0C-CD-00-11
Device	**VLAN ID**	**Min Time**	**Max Time**
REF630	10	10 ms	300 ms
RTU1	10	10 ms	300 ms
RTU2	10	10 ms	300 ms
RTU3	10 (20)	10 ms	300 ms
RTU4	20	10 ms	300 ms
RTU5	20	10 ms	300 ms
7SJ621	20	10 ms	300 ms

Table II outlines the communication settings for GOOSE (Generic Object-Oriented Substation Event) messages, which are used to coordinate the protection devices. GOOSE messages are part of the IEC 61850 protocol, enabling fast and reliable communication in electrical protection systems.

IED Name: This refers to the unique identifier for each protection device on the network.

Application ID: This identifier links specific GOOSE messages to the respective protection devices, allowing the system to recognize and process the correct information.

MAC Address: Since IEC 61850 GOOSE messages operate at the data link layer (Layer 2), MAC addresses are used instead of IP addresses to identify devices on the network.

VLAN ID: The Virtual LAN (VLAN) IDs segment the network into different communication groups, improving the efficiency of communication. Devices within the same VLAN can quickly exchange messages. In this case, RTU 3 is assigned to both VLAN 10 and VLAN 20, indicating that it communicates with devices in both groups.

Min Time: This refers to the minimum time required to transmit a GOOSE message after a change in state (e.g., detecting a fault). All devices in the test are set to a minimum time of 10 milliseconds (ms), ensuring that signals are transmitted promptly.

Max Time: This is the maximum allowable time for a message to be transmitted. It is set to 300 ms for all devices, providing a safeguard to monitor communication quality. If a message is delayed or not received within this time, corrective actions can be taken, such as blocking or releasing an acceleration stage.

In conclusion, these communication settings ensure rapid coordination between protection devices, with fast message transmission (within 10 ms) and safeguards to monitor the quality and reliability of communication. The VLAN configuration further segments the network for more efficient data flow, and the MAC address-based system ensures that messages reach the correct devices without using IP addresses. In the following Table III, IV, abbreviated expressions were used where TFB stands for 'The fault behind', TFA stands for 'The fault ahead'. ES/PG stands for 'power grid'. These tables illustrate a portion of the testing results, which demonstrate the response speed of individual devices.

TABLE III
Acceleration results in protection on the power grid with REF630

Device	TFB PG		TFB 1.RCL		TFB 2.RCL		TFB 3.RCL		TFB 4.RCL		TFB 5.RCL	
	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking
REF630	160 ms	-	x	yes	x	yes	x	yes	x	yes	x	yes
RTU1	-	-	80 ms	-	x	yes	x	yes	x	yes	x	yes
RTU2	-	-	-	-	75 ms	-	x	yes	x	yes	x	yes
RTU3	-	-	-	-	-	-	84 ms	-	x	yes	x	yes
RTU4	-	-	-	-	-	-	-	-	80 ms	yes	x	yes
RTU5	-	-	-	-	-	-	-	-	-	-	79 ms	yes
7SJ621	-	-	-	-	-	-	-	-	-	-	-	-

TABLE IV
Acceleration results in protection on the power grid with 7SJ621

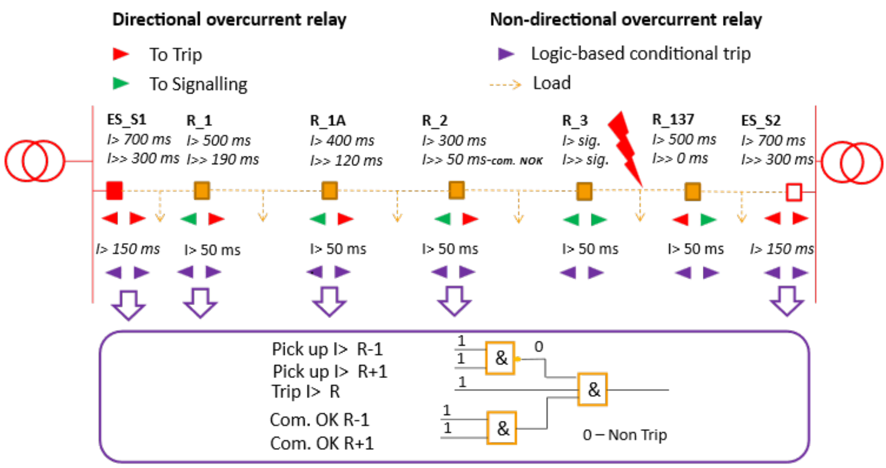
Device	TFA of PG		TFA of 5 .RCL		TFA of 4.RCL		TFA of 3.RCL		TFA of 2.RCL		TFA of 1.RCL	
	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking	Trip	Blocking
REF630	-	-	-	-	-	-	-	-	-	-	-	-
RTU1	-	-	-	-	-	-	-	-	-	-	78 ms	yes
RTU2	-	-	-	-	-	-	-	-	85 ms	yes	x	yes
RTU3	-	-	-	-	-	-	79 ms	-	x	yes	x	yes
RTU4	-	-	-	-	85 ms	-	x	yes	x	yes	x	yes
RTU5	-	-	81 ms	-	x	yes	x	yes	x	yes	x	yes
7SJ621	220 ms	-	x	yes	x	yes	x	yes	x	yes	x	yes

In Table 3 and Table 4, individual fault simulation tests are described sequentially from the beginning of the simulated protected section to the end. It is shown that, in the event of a fault before Recloser No. 1, only the REF630 protection correctly responded using the CCSA, while the other protections received only information about the disconnection through messages. In the next test, a fault behind Recloser No. 1, the RTU1 protection correctly responded with the CCSA acceleration stage, while the REF630 protection was blocked via GOOSE communication through the CCSA acceleration stage logic. All simulated faults were triggered as expected. The nearest protection to the fault switch off recloser using the acceleration stage, with all protections upstream blocked through acceleration stage logic, and all protections downstream from the fault receive switching information. This principle works the same for both ring and radial networks. The logic element is described in the example of operation.

4 Results from Real operation

4.1 Second Fault Exemple 1

On example 1 a fault occurred when high voltage conductors were found fallen on the ground. The acceleration element responded before the protection system activated and correctly shut down the affected section. The following diagram illustrates the fault location and shows which reclosers were disconnected.



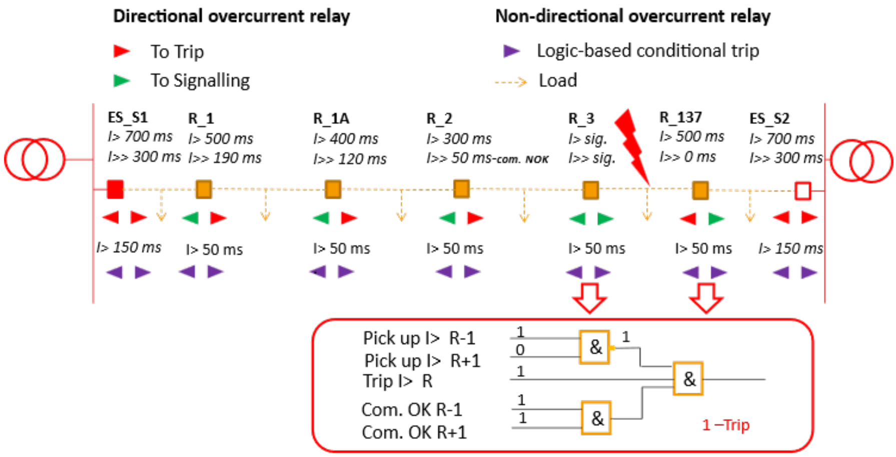


Figure 5
Settings on the real respective line

In the following diagrams (Figs. 6, 7, 8, 9, 10), the switching and blocking by the acceleration stage can be seen during faults on individual reclosers in a real network. During this fault, approximately 700 electricity consumers were disconnected by the correct operation, preventing the potential disconnection of up to 2,000 consumers (Censored location in real power grid in Slovakia).

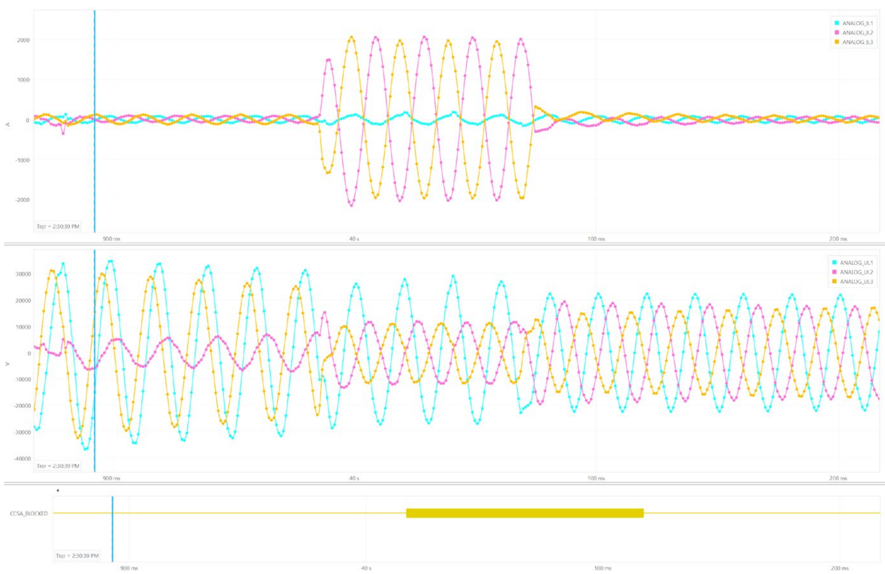


Figure 6
Tripping blocked according to CCSA on protection REF630

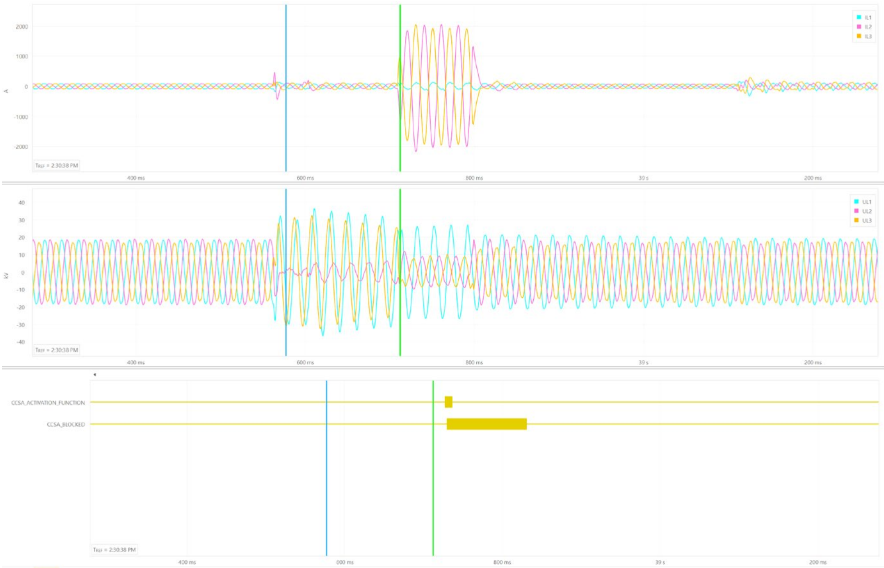


Figure 7
Tripping blocked according to CCSA on recloser R_1

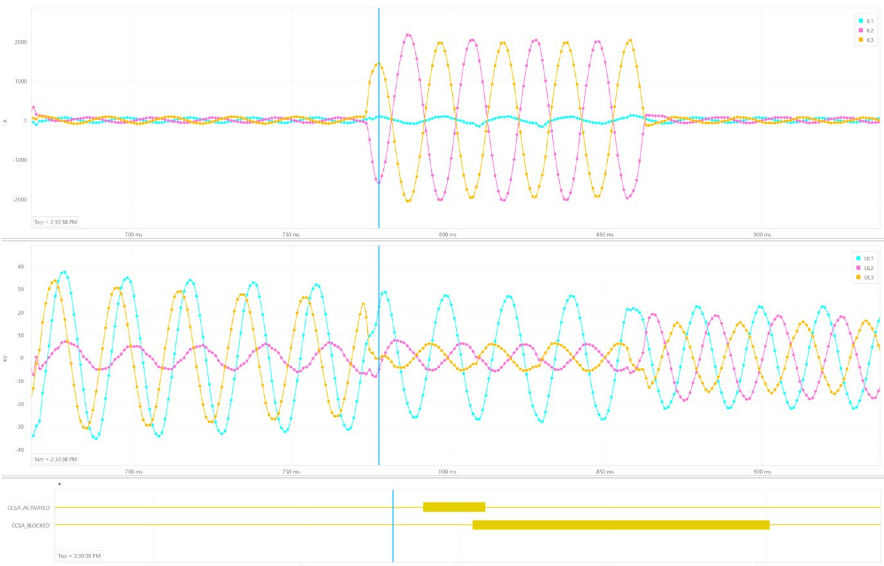


Figure 8
Tripping blocked according to CCSA on recloser R_1A

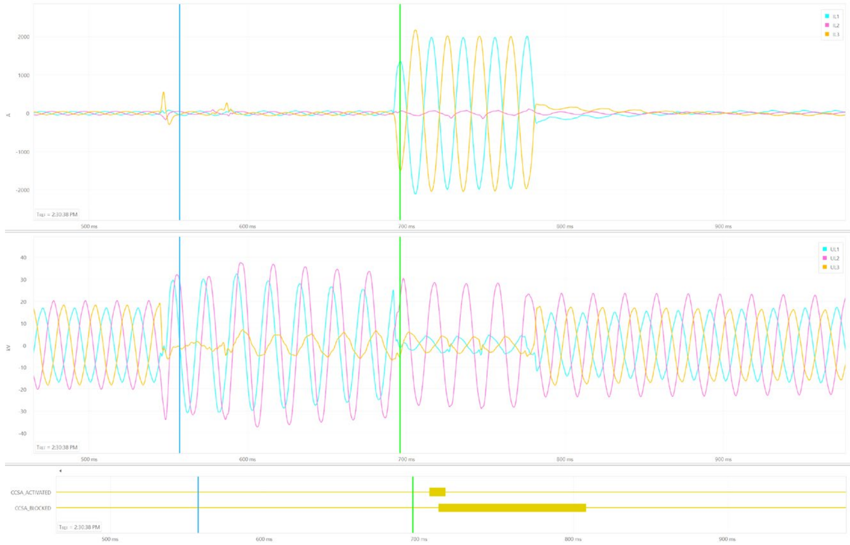


Figure 9
Tripping blocked according to CCSA on recloser R_2

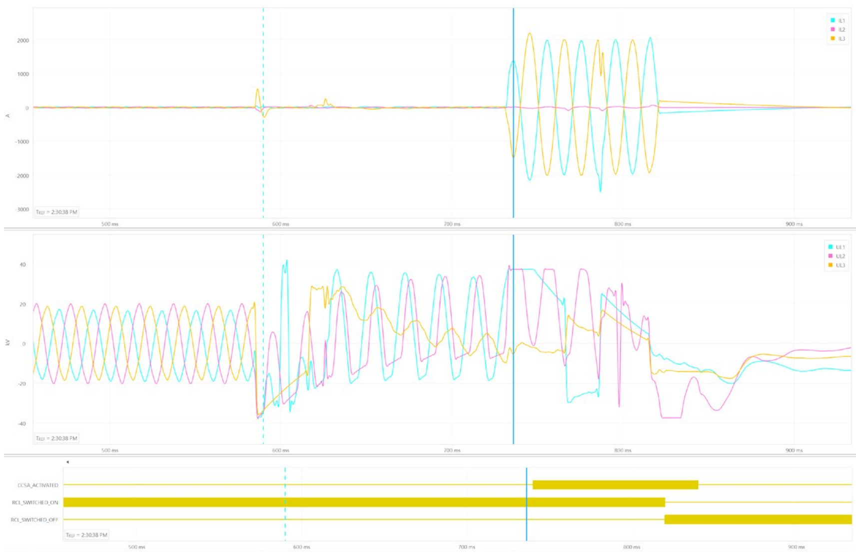


Figure 10
Tripping blocked according to CCSA on recloser R_3

All datasets used in the analysis were obtained directly from protection device exports during real fault events in the electrical grid. Therefore, no simulations were performed in external software. The figures and results are based entirely on real operational data collected from the protection systems.

4.2 Fault Exemple 2

On example 2 a fault occurred, during which the dispatcher was notified of sparking (arching) on the line, leading to a shutdown with the help of the acceleration element. A tree branch was found under the line at the site (the equipment remained undamaged). The acceleration element responded before the protection system activated and correctly shut down the affected section. The following diagram illustrates the fault location and shows which reclosers were disconnected.

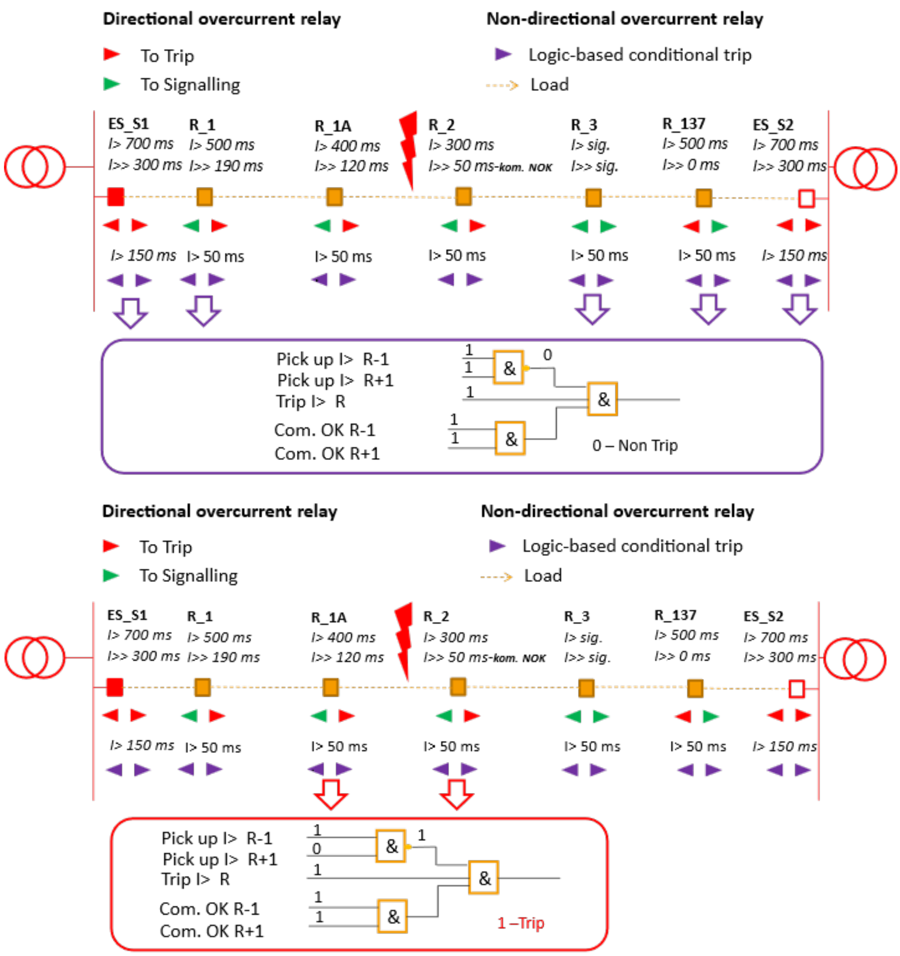


Figure 11

The sequence from RCL R_2, which tripped the fault

In the following diagrams (Figs. 12, 13, 14), the switching and blocking by the acceleration stage can be seen during faults on individual reclosers in a real network. During this fault, approximately 1,400 electricity consumers were disconnected by the correct operation, preventing the potential disconnection of up to 7,000 consumers (Censored location in real power grid in Slovakia).

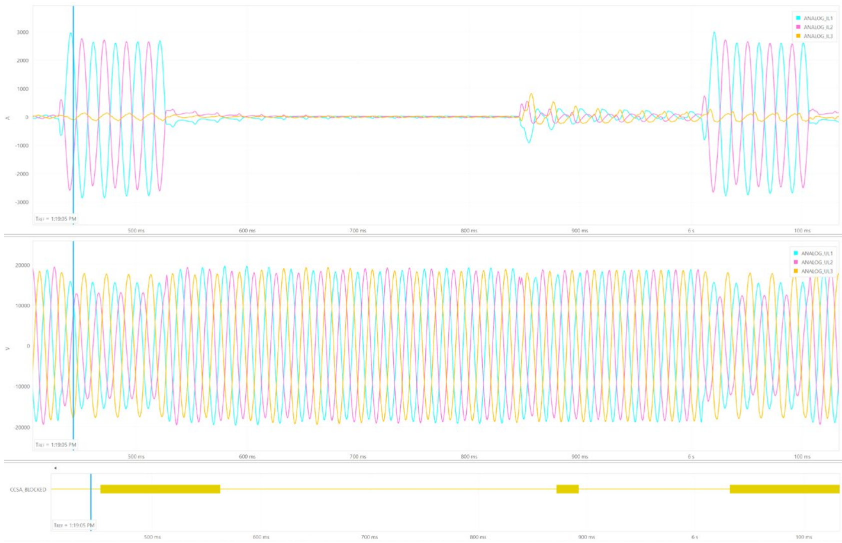


Figure 12
Tripping blocked according to CCSA on protection REF630

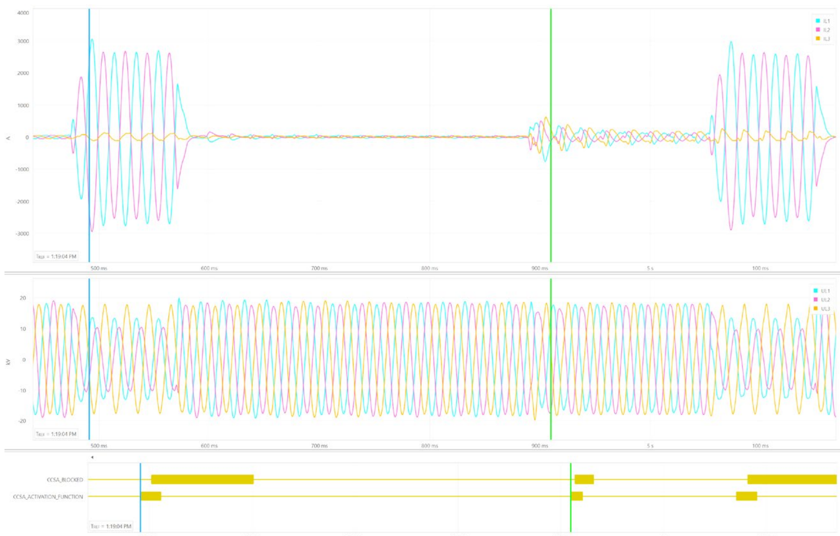


Figure 13
Tripping blocked according to CCSA on recloser R_1

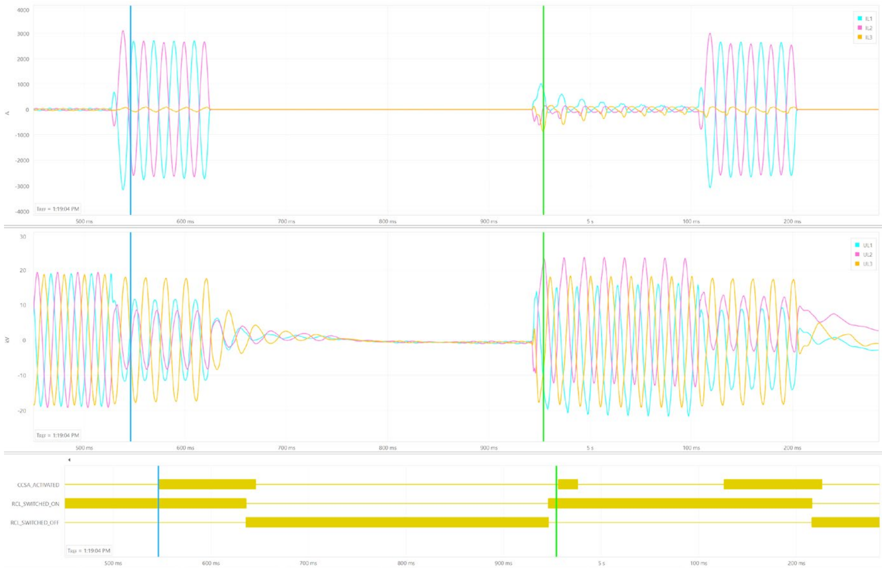


Figure 14

Tripping according to CCSA on recloser R_1A

The faults observed in example 1 and example 2 confirm that the acceleration stage functions as intended, responding to individual faults in the real network within 100 milliseconds. These time metrics demonstrate that, with the implementation of CCSA, fault disconnection can occur significantly faster, saving valuable seconds in certain sections. This rapid response is crucial, especially in cases where electrical arcs may arise, as prolonged exposure could damage equipment, insulators, or conductors (particularly in cable networks). By minimizing time delays, CCSA indirectly enhances the lifespan of critical infrastructure components.

Conclusions

The CCSA (Central Control Switch Acceleration) approach presents a significant advancement in fault detection and protection for high voltage distribution networks. By leveraging IEC 61850 and GOOSE messaging, CCSA enables accelerated fault detection and protective switching with minimal delay, achieving fault clearing within 50 milliseconds. Unlike conventional methods that rely solely on individual IED responses, the CCSA model uses a centrally controlled system that enhances coordination, particularly in nondirectional overcurrent scenarios. The approach capitalizes on existing network infrastructures, including optical and metallic connections, VLAN segmentation, and unique MAC addresses, for precise, reliable communication even under challenging conditions. Real world tests using Elvac, ABB, and Siemens devices demonstrated that CCSA not only improves fault response times but also minimizes service interruptions, as evidenced by actual faults. In these cases, CCSA's rapid response effectively limited the extent of disconnections, reducing potential impacts on customers and preventing further network damage. Real tests on censored power grid corroborated these findings, confirming that CCSA's acceleration element responds faster than traditional protection system. By enhancing system reliability and reducing the risk of prolonged faults, CCSA contributes to the economic and operational stability of power distribution networks. Its deployment on real distribution systems illustrates that CCSA is a viable, scalable solution for modernizing protection strategies in power grids, ultimately extending equipment lifespan and supporting uninterrupted service for consumers.

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