BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 70(5), 2022, Article number: e143101
DOI: 10.24425/bpasts.2022.143101

POWER SYSTEMS AND POWER ELECTRONICS

Decentralized fault location, isolation and self restoration (FLISR) logic implementation using IEC 61850 GOOSE signals

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Abstract. Fault location, isolation and self restoration (FLISR) automation is an essential component of smart grids concept. It consists of a high level of comprehensive automation and monitoring of the distribution grid improving the quality of energy supplied to customers. This paper presents an algorithm for decentralized FLISR architecture with peer-to-peer communication using IEC 61860 GOOSE messages. An analysis of short circuit detection was presented due to the method of the grid earthing system. The proposed automation model was built based on communication logic between configured intelligent electronic devices (IED) from ABB and Siemens. The laboratory tests were conducted in a half-loop grid model with a bilateral power supply (typical urban grid). The laboratory research concerned three locations of short circuits: between substation and section point, between two section points and between section point and normally open point (NOP). The logic implementation was developed using State Sequencer software offered by Test Universe.

Key words: smart grids; distributed grid automation; IEC 61850; GOOSE signals; FLISR; FDIR; FLIR.

1. INTRODUCTION

The reliability of energy supplies is one of the major goals of the power industry. Eliminating power disruptions allows us to reduce economic losses and improve customer satisfaction. The intensive development of smart grids is characterized by a high level of comprehensive automation and monitoring of the distribution grid. It can result in fewer and shorter outages and an increase in grid efficiency, reliability, and security. One of the possibilities arising from these conditions is FLISR technologies and systems. The automation involves dedicated hardware (automated switches, reclosers and line monitors), communication networks and distribution management systems (DMS), outage management systems (OMS), supervisory control and data acquisition (SCADA) systems, grid analysis, models, and data processing tools [1]. Its task shall include fast grid reconfiguration, post-fault power restoration and the reduction of the outage time and number of customers affected by power supply interruption. In some European countries [2, 3], the USA [2, 4, 5] as well as in Japan [6], the transformation process takes place to a significant extent and distribution system operators (DSO) have already experienced FLISR automation. Emerging economies such as Brazil have also implemented it to a large extent as pilot projects [6].

The dynamic of FLISR automation development depends on many factors, such as:

- Financial possibilities.
- Assumed goals.
- Commonly available technologies.
- Policies of local research centers.
- Offers of companies providing solutions for smart grids in each region.

There are indicators developed for comparing electrical utilities performance reliability, i.e., SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) [7]. They reperesent the average time and frequency of interruptions affecting the customers. It should be noted that in order to assure a reduction in SAIDI and SAIFI indicators of the power system, the time from the moment of shorting of power to restoring it to the receivers in the undamaged part of the network must be less than 3 minutes. In Vietnam, where the FLISR system was installed in the city of Da Nang, the abovementioned indicators are expected to be reduced by 16% and 43% respectively [8]. Other technical methods of reducing electricity supply indices focus on investments in the grid, i.e., replacing overhead lines with cable lines or creating alternative connections between critical grid nodes [9].

2. FLISR AUTOMATION OVERVIEW

2.1. Architecture

Considering the communication method of devices and the principle of operation, three main types of FLISR architecture

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Manuscript submitted 2022-04-26, initially accepted for publication 2022-08-03, published in October 2022.

can be distinguished [10, 11]:

- centralized,
- semi-centralized,
- decentralized.

The abovementioned division is illustrated in Fig. 1. The communication with the master system and/or dispatching panel for the automatic restitution application is marked as a continuous line, and the communication between the devices in the system, aimed at implementing its functionality, is marked as a dashed line.

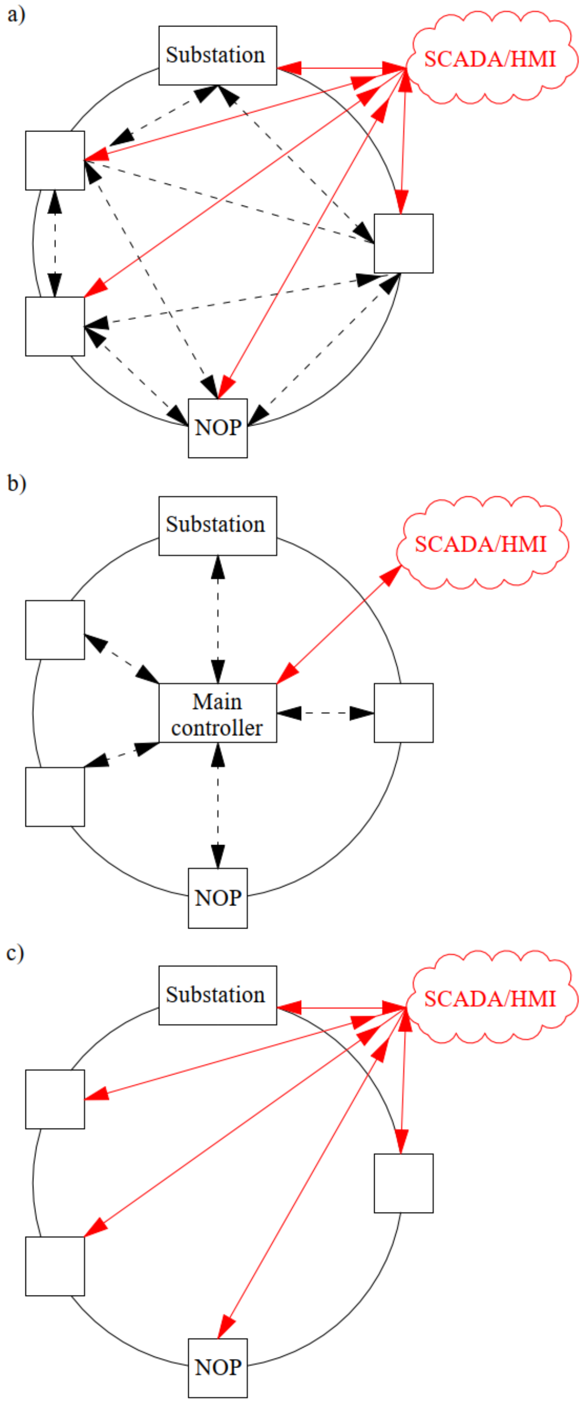

Fig. 1. FLISR architecture: a) decentralized; b) semi-centralized, c) centralized

Considering the centralized architecture, FLISR automation is implemented as a module controlled by the superior system, i.e., SCADA and is responsible for the decisions about the start of the algorithm and its course of action [12]. It can be applied to an entire grid but is mostly used by the master system providers [10]. As communication with executive components of automation is carried out directly with the master system and all data from the distribution grid are collected by the monitoring system, the centralized architecture provides the best optimization of switching and grid operation in terms of load distribution [13]. However, the communication system for such a solution requires high bandwidth, and the duration of the application may be long. It has also a significant degree of complexity in design and implementation. An example of centralized FLISR is presented in [12] as a DMS module in 25 kV distribution grid tested in the Smart Utility Test Center (SUTC) in Canada.

The semi-centralized architecture is based on a central controller mostly installed in the main power supply station (MPS station), which makes decisions and gives commands related to the operation of FLISR. It also implements communication with the superior system. The executive elements are RTU devices installed in places of potential grid intersection. Their role is to supply the central controller with information about the status of the grid nodes in which they are installed. In comparison to the solution based on a centralized architecture, the requirements for the bandwidth of communication links are smaller and the operating time is shorter. Implementation of such a system is less complicated and cheaper, but the degree of optimization compared to the central system is smaller [13]. The semi-centralized FLISR architecture was successfully installed and used in Siemens Distribution Feeder Automation System (SDFA), implemented as a reliable power supply to the Ibuprofen plant in Orangeburg, SC in the USA [14].

In a system of decentralized architecture, there is no central unit in a physical form or an application responsible for decisions related to the operation of FLISR. Microprocessor devices installed in the system in addition to the ability to control and identify short circuits (or to receive information from another device identifying the short circuit) must have modules allowing to build of proper logic. Communication takes place on a peer-to-peer basis, where all devices perform an equivalent role. Such a system is quick and easy to implement, as it is based on action in individual steps – the same for each sectioning element [10]. It also allows the implementation of a multi-agent system (MAS) solution, where autonomous logical and physical units are implemented to achieve the assigned goals [11]. The multi-agent approach is effective for grids with a complicated topology, also with distributed generation. The demonstration of the FLISR system based on a multi-agent approach was used in West Virginia Super Circuit Project in the USA [15].

2.2. Principle of operation

The operation of FLISR automation can be based on algorithms built on logic for appropriate signals embedded in controllers, a multi-agent approach or more advanced methods such as the genetic algorithm [16] or Prim's algorithm [17]. However, in any case, the operation of automation should be carried out with the principles described below.

The initial conditions

Automation of quick grid reconfiguration and restoration should not work in cases when the switch in the MPS station is open due to planned manual switching, automation has been blocked (e.g., from the operator panel or via the remote or local switch located in section point) or when another restitution automation works (e.g., automatic load shedding) [18]. Some solutions additionally block the operation of the automation in case of communication or error failure (e.g., switch position error) in any of the system components [19], and some reject the element, increasing the isolated section [13]. In case of the absence of blocking signals, the FLISR automation should be initiated after the definitive opening of the circuit breaker in the MPS station (after an unsuccessful operation of automatic reclosing, if installed), loss of voltage and/or current in line, as well as after registered activation of the units responsible for short circuit detection.

Locating the short circuits

Accurate detection of short circuits in every point of the grid is crucial for the proper functioning of FLISR automation. After the detection of a short circuit, FLISR automation defines its location and separates it from the healthy part of the grid. It is achieved by reclosers installed in the grid nodes. The location of the short circuit is identified with the accuracy of the line segment between the section points. It is based on information from fault indicators that can identify the occurrence of a short circuit in a given part of the grid regarding or not its direction. In the case of compensated grids where measurement signals for ground faults, especially resistive ones, can be comparable to noise, the directional fault indicators seem to be appropriate. The short circuit location is based on the occurrence of indications of the opposite direction at two adjacent section points. For grids where short circuit currents are always significant, identification can take place based on two adjacent points, where the short circuit was registered only in one of them.

In MV networks, short circuit detection is based on current and voltage measurements in steady or transient states. In this paper, only steady state analysis will be considered.

In networks earthed by a resistor, current-based methods are sufficient for short circuit detection and earth-fault indicators based on the earth-current criterion. While for phase-to-phase short circuits an overcurrent criterion is sufficient (or a directional overcurrent criterion if a distributed generation is installed in the network), in compensated networks a problem of low values of measurement signals may occur. In these networks, in the case of earth faults, an exclusive use of current-based methods is insufficient to detect the short circuit. However, the author in [20] states that for reclosers located deep in a compensated network, it is often possible to use only an earth-overcurrent criterion. The reason is an extremely low capacitive current in an overhead line behind the point where the recloser is installed.

Detecting ground faults located closer to the HV/MV substation based exclusively on the earth-current criterion is effective only for low short circuit resistance. The value of the earth-current decreases with the increase of the transition resistance. In addition, zero-sequence current measurement is affected by the accuracy of the zero-sequence component filter. For Holmgreen's current transformers, the error is equal to 5 A, and for Ferranti's earth-fault current transformer, it is equal to 2 A [21]. Figure 2 presents an example of the effectiveness of ground fault detection (using the I0 > criterion) depending on the transition resistance and used filter. The coefficient "*a*" from Fig. 2 is the ratio of the capacitive current of a given overhead line and the capacitive current of the whole network. The network parameters carried out for calculations were network capacitive current ICS equal to 100 A and rated current of arc suppressing coil IR equal to 105 A.

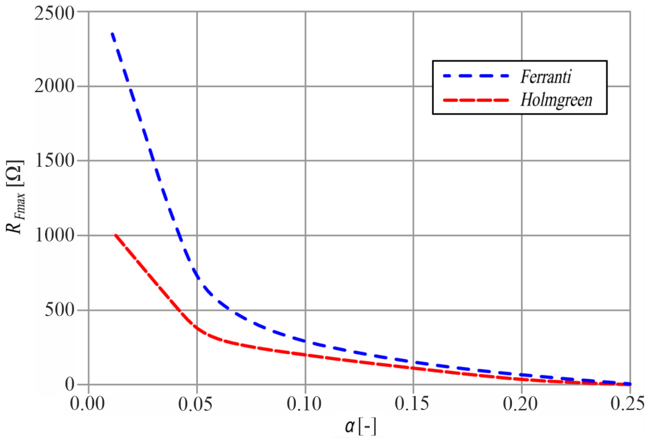

Fig. 2. Maximum transition resistances detected for an exemplarynetwork with its neutral point earthed by inductive reactance [21]

Isolation of damaged section

For a centralized and semi-centralized architecture, the decision entity sends commands to open appropriate switches to cut off the damaged part of the line from the rest of the network, based on the information obtained from the section points. In the case of distributed architecture, this decision is deduced by system components based on signals available from FLISR automation. Sectioning devices for distributed automation can successively check the states of their neighbors according to the direction from or to the MPS station [19]. Finally, after switching, the auxiliary contacts of the switches are checked for an error.

Restoring the power

The power is restored by closing the switch in the MPS station and the switch from the alternative supply side (NOP – normally open point or distributed generation). However, before these operations, it is necessary to check whether the conditions for permissible loads are fulfilled for [18]:

- The transformer in the MPS station (if the NOP is in contact with the area of the grid supplied from another station).
- Line.
- The switching capacity of the connector from the alternative supply side.

- Rated currents of electrical apparatus and switchboards in the network.
- If installed, available distributed generation power.

Checking of the abovementioned conditions is carried out based on the measured current values before and after the short circuit and rated data of the grid elements [13]. After closing each switch, it is required to check that the short-circuit indicators are not energized and the voltage returned to the grid nodes where it was expected (or, if the system works only based on current measurements, a load current was recorded – excluding a short circuit current).

3. PROPOSED DECENTRALIZED FLISR ALGORITHM

In this paper, the scalable and configurable algorithm for decentralized FLISR architecture was proposed, based on peer-to-peer communication using IEC 61850 GOOSE messages. Its principle of operation is to locate and isolate the short circuit and restore the energy to the healthy part of the grid according to the proposed logic.

3.1. The algorithm assumptions

The developed algorithm of FLISR automation is suitable for an MV network with a neutral point earthed by a resistor due to the overcurrent (interfacial fault) and overcurrent (earth fault) criteria to record the occurrence of a short circuit. The required network topology is a looped grid with bilaterally powered stations (typical city network), working with a NOP (power supply from another field of the same MPS station or another MPS station). It was assumed that the current capacity of cables and bilaterally powered stations are always sufficient to supply all loads, regardless of the network configuration (change of cut point and/or power side). Section points and NOP are equipped with disconnectors capable of switching on and off operating currents. All elements are capable to perform the FLISR automation. The system is based on a distributed architecture.

For the purpose of this paper, only selected issues related to the logic of FLISR automation were presented. To simplify the presented problem, the designed automation, in relation to cooperation with other automation devices, uses only one start signal (line disconnection) and one reset signal, which restore the grid to the normal state. The extended research model will include:

- Cooperation with the automatic reclosing automation.
- Block signals from other automatics or remote/local switches.
- Conditions for loss of voltage or load currents.
- Damages to the communication links.
- Signaling the elapse of allowable time for operation.
- Errors in the position of switches.
- Damage to relays.
- Occurrences of more than one short circuit as well as short circuits during and after reconfiguration.
- Communication with the superior system.

3.2. The algorithm

The proposed solution can be implemented on relays with configurable binary inputs and outputs as well as a fault indicator feature. Only one half-loop (left side) was considered in the algorithm, as illustrated in Fig. 3 where P1, …, Pn are section points equipped with short circuit indicators, and NOP is a normally open point.

The start signal (turn off the line) forces the start of FLISR automation. Sectioning points devices check indications of their fault indicators and then, based on exchanged signals from other points and their own indications, they determine the fault location and open appropriate disconnectors isolating the faulty part.

After receiving signals from the auxiliary contacts of disconnectors, their next step is to send signals to close the feeder CB (circuit breaker) and NOP switch in order to restore the power supply in the healthy area of the network. From this moment, the automation waits for a reset signal which should be sent after repairing the damaged section. After receiving this signal, switching operations are conducted to restore the normal state of the network, taking into account a proper order of switching, so as not to connect two different feeders.

Communication between devices installed in the system takes place using the IEC 61850 standard and is based on the GOOSE messages. To understand the meaning of the names of the signals presented in Table 1, it should be assumed that in the case of short-circuit indicators signals, the term "upper" means section point towards the substation from the point taken under consideration, and "lower" in the direction towards NOP (to determine which direction the signal comes from). In the case of sending signals informing about the position of the switches, it considers the faulty section, which is limited by two sectioning points. In this way, the point closer to the substation is referred to as "upper" and closer to the NOP as "lower". The directions of GOOSE signal transmission are illustrated in Fig. 4.

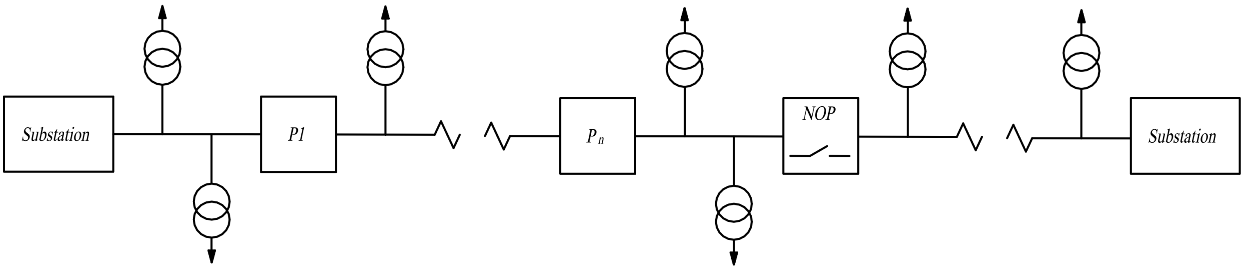

Fig. 3. The network for the developed algorithm

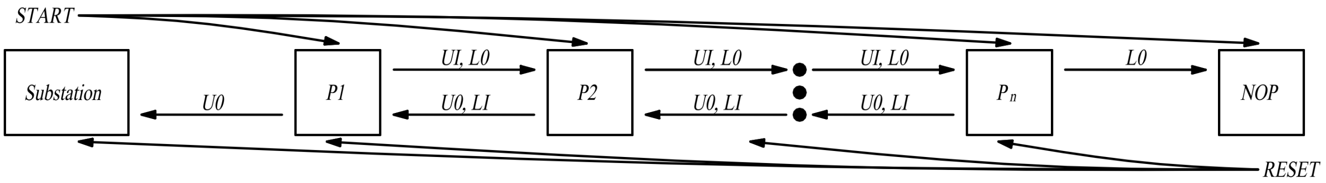

Fig. 4. Directions of GOOSE signals

3.3. Implemented logic

The logic implemented in the section point controllers has the same structure, with a slight difference in extreme points – closest to the substation and closest to the NOP. It allows the scalability of the system in case of adding new sectioning points to the half-loop. In that situation, only settings of the GOOSE signals sent between these points must be configured and new START and RESET subscribers must be added. The ideological structure of the section point logic is shown in Fig. 5, where suffixes "_send" and "_rcv" indicate whether the signal is properly transmitted or received. The signal "DC_opened" means an open position of auxiliary contacts of the disconnector and "control_open" and "control_close" are the signals given respectively for the opening and closing of the disconnector.

An identification of the side of the section points where the fault occurred is based on two cases:

1. If the section point has its own short-circuit indicator active and a short-circuit indicator is inactive at the lower point, it means that the section point is the isolating point from the substation side,
2. If the section point does not have its own short circuit indicator active and the short circuit indicator is active at the upper point, it means that the section point is the isolating point from the NOP side.

It should be noted that logic uses only the signal of the open position of the switch. If the disconnector driver requires a persistent signal, in some cases the signal of a closed position or a negated signal of a closed position should be used until a sig-

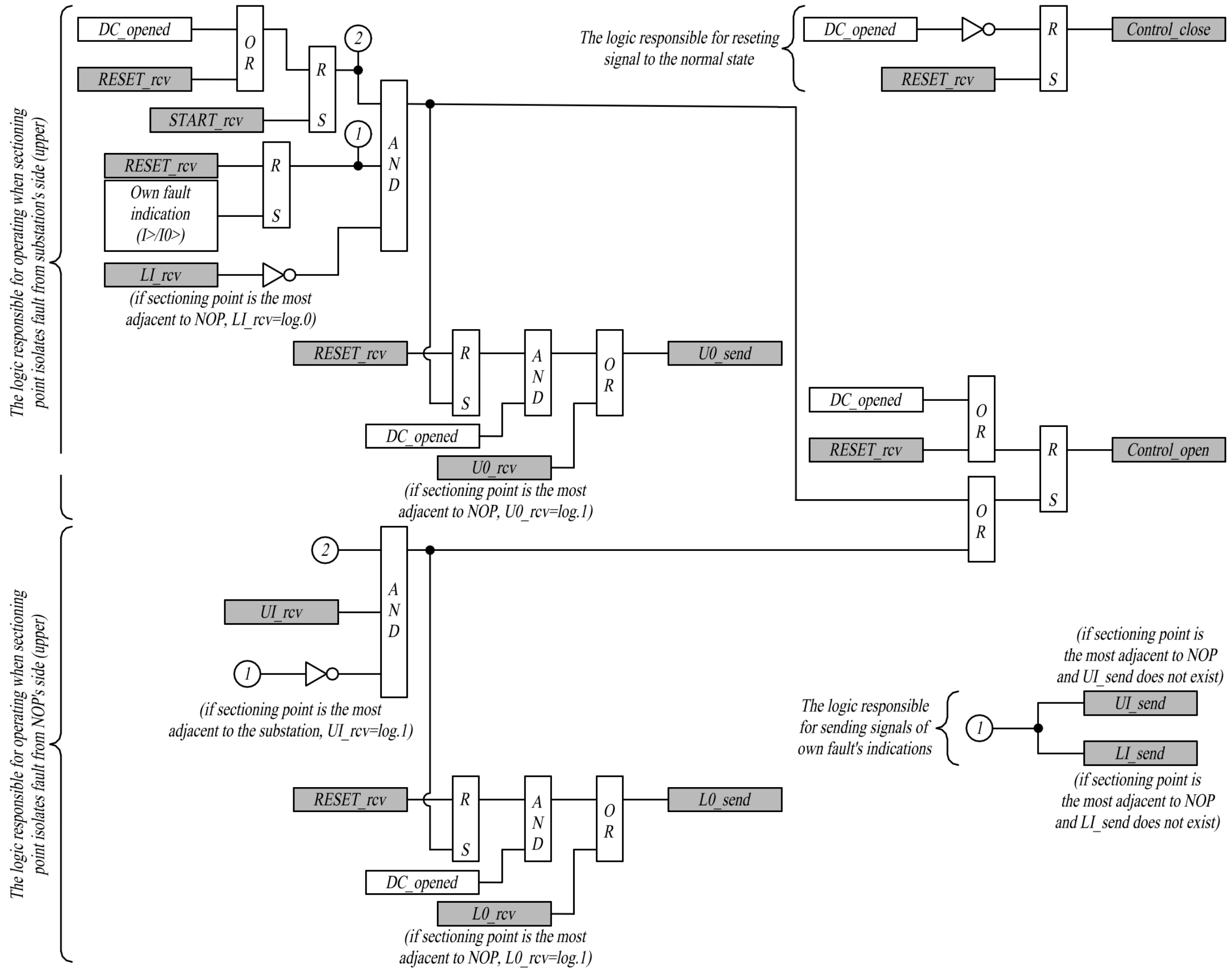

Fig. 5. The diagram of logic for the section point

Table 1
GOOSE signals used in the developed FLISR system

Signal name	Description
START	This signal is sent to all devices by the controller installed in the feeder when it receives a signal (e.g. from the relay) of definitive closing. It initiates the operation of automation.
RESET	This signal is sent from NOP to all devices in order to restore the normal state of the network. It must be delivered to the controller in NOP from another source, e.g. from SCADA.
UI	Upper point indication. This signal is generated by the section point device when it registers a short circuit. It is sent to the next section point towards the NOP.
LI	Lower point indication. This signal is generated by the section point device when it registers a short circuit. It is sent to the next section point towards the substation.
UO	Upper point open. This signal is generated when the section point opens its disconnector to isolate it from the fault or when it receives it from another section point. It is sent to the substation controller through all system components.
LO	Lower point open. This signal is generated when the section point opens its disconnector to isolate from the fault location or when it receives it from nother section point. It is sent towards the NOP through all system components.

nal of the desired position is received. For a part of the drives, it is enough to receive a pulse instead of a continuous signal.

The substation controller is obliged to close the circuit breaker in the feeder substation or to propagate the start signal. Related logic is shown in Fig. 6.

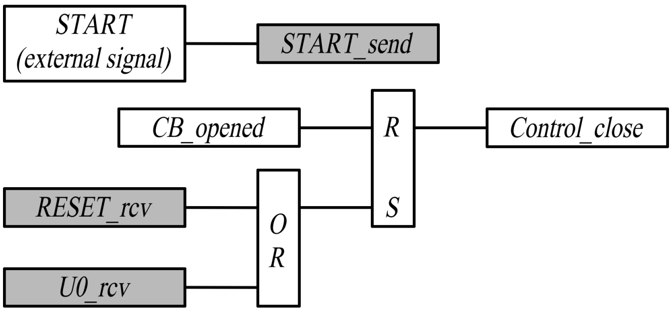

Fig. 6. The diagram of the logic for the controller in substation

The controller in NOP is installed to close its disconnector when the short circuit is isolated from its side and open it when the reconfiguration to normal state is done. Related logic is shown in Fig. 7.

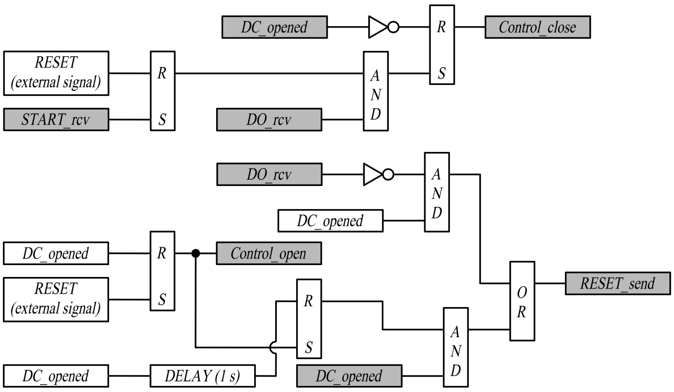

Fig. 7. The diagram of the logic for the controller in NOP

4. LABORATORY TESTS

The laboratory stand was built using specialized hardware and software:

- REL650 from ABB company (relay with main distance function) as an equivalent of the controller in an MPS station.
- Two 7SD5 from Siemens company (relays with the main function of phase comparison) corresponding to devices at section points P1 and P2, designated 7SD_1 and 7SD_2, respectively.
- REL670 from ABB company (relay with the main distance function) as an equivalent to the controller in NOP.
- CMC256 tester.
- Switches.
- PC with DIGSI 4.9, PCM600 and Test Universe 3.01 software installed.

The field controllers from ABB and Siemens are IEDs with the ability to communicate with each other and register the short circuit independently or by using additional devices (e.g., modem or autonomous short circuit indicators). In each of the relays binary inputs and outputs were used, and in case of 7SD5 relays also an overcurrent and earth fault function were installed as a part of the short circuit indicator. The communication between devices was carried out in a LAN network built on the Ethernet switches, presented in Fig. 8.

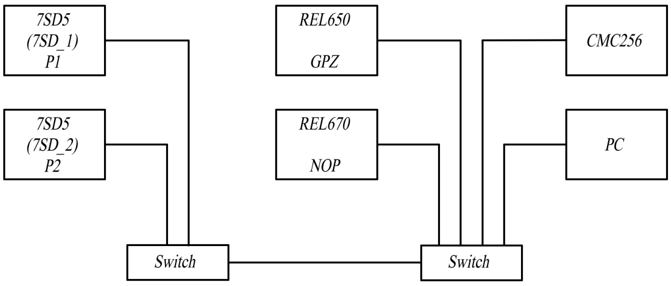

Fig. 8. Laboratory devices connected to LAN

During the tests, only one half-loop (left side) was considered, as illustrated in Fig. 9, where P1 and P2 are section points equipped with short circuit indicators, and NOP is a normally open point.

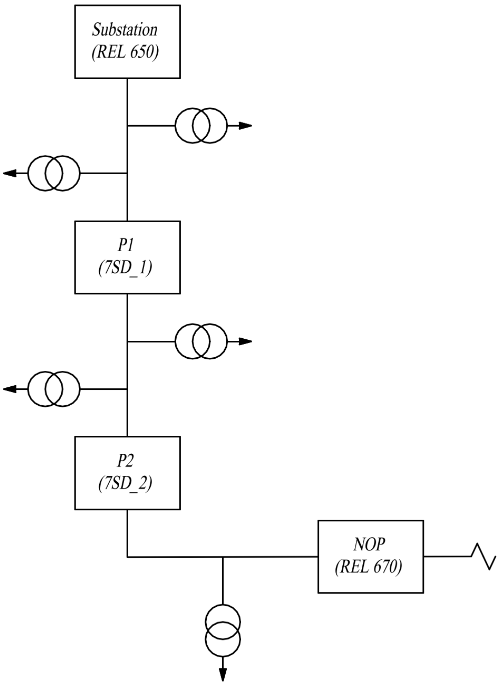

Fig. 9. A section of the grid used for the laboratory tests

After the assignment of binary inputs and outputs of each device, the next step was to create the connections for binary and analog signals. Then, the configuration of the abovementioned relays took place in accordance with the following steps:

1. Configuration of signals, logic and functions activation for 7SD5 relays.
2. Configuration of GOOSE messages (broadcasted by 7SD5 devices) and station file *.scd.
3. Import of the prepared *.sdc file to the configuration environment of ABB devices.
4. Configuration of the REL650 relay logic.
5. Configuration of the REL670 relay logic.
6. Configuration of receiving and sending GOOSE messages in the ABB environment.
7. Uploading settings to ABB devices.
8. Export of station file *.scd and import it to the Siemens configuration environment.
9. Configuration of the station file *.scd in the Siemens environment – receiving GOOSE messages.
10. Uploading settings to Siemens devices.

Test Universe 3.01 application and CMC 256 tester were used for the tests. The second one is equipped with 12 binary inputs and 4 binary outputs and allows to force three-phase currents on two analog outputs. ABB's and Siemens' relays were connected to the CMC 256 tester. State Sequencer module of Test Universe program facilitating transitions between individual states was used to carry out the tests. The states have been configured to simulate responses to the next steps of FLISR automation reflecting the changes in switches positions in response to the control signals sent by the relays. Transitions to the next states could take place only when the tested automation responded correctly. Three tests of automation operation were carried out in the order described below.

4.1. Short-circuit between NOP and section point 2

In this case, the short circuit was located between NOP and section point 2. The operation of the automation is divided into states marked with letters from 1 to 8) presented in Fig. 10.

The following is a description of the various stages from Fig. 10:

1. The network is in a normal state. The load current flows in the grid.
2. A fault occurs and short-circuit current flows in the network. The fault is switched off after 500 ms. Relays in section points record the fault.
3. Protection in the substation is tripped and the circuit breaker opens. The load in the semi-loop is de-energized. The automation waits for the START signal.
4. After receiving the START signal the controller in the P2 point monitors the opening of the disconnector, based on its own inactive short-circuit indication and lack of UI signal.
5. When the disconnector at P2 opens, a signal for opening disappears after a short time (device self-operating time).

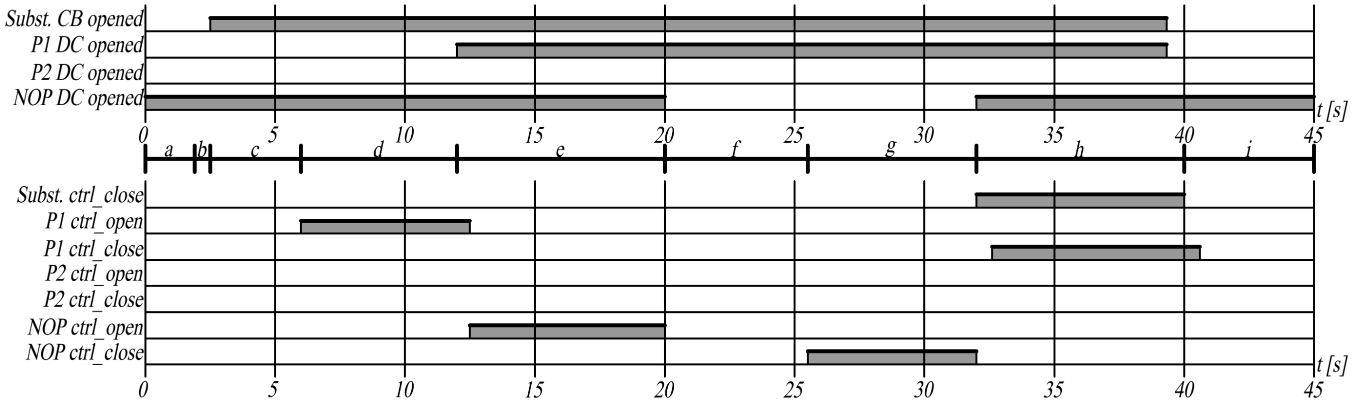

Fig. 10. Test results for a short circuit between section point 2 and NOP

The damaged section is isolated, and it sends a UO signal towards the substation. After receiving the UO signal, the controller in the substation controls the closing operation of the CB.

6. When the CB is closed, a healthy part of the network is reenergized. The automation waits for a RESET signal.
7. After the RESET signal is received, the controller in the NOP transmits this signal to other devices. Point P2 controls the disconnector closing operation.
8. The P2 disconnector is closed, and the network returns to its normal state.

4.2. Short-circuit between section points 1 and 2

During this test, the short circuit was located between section point 1 and 2. The operation of the automation is divided into states marked with letters from 1 to 11 in Fig. 11.

The following is a description of the various stages in Fig. 11:

1. The network is in a normal state.
2. A fault occurs and is switched off after 500 ms. Relay in section point 1 record the fault.
3. Protection in the substation is tripped and the CB opens. The load in the semi-loop is de-energized. The automation is waiting for the START signal.
4. After receiving the START signal controllers at points P2 and P1 monitor the opening of the disconnectors due to the information from point P2, which did not register a short circuit but received a UI signal from point P1. Point P1 registered a short circuit and did not receive a LI signal from point P2.
5. After the opening of disconnectors at points P2 and P1, the damaged section is isolated. Point P1 sends the UO signal to the substation, and point P2 the LO signal to controller in
6. NOP. Then the controllers in the substation and NOP point control the closing of their switches after receiving these signals.
7. A healthy part of the network is reenergized. The automation waits for a RESET signal.
8. When the RESET signal is received, the device in the NOP controls the opening of the disconnector.
9. When the disconnector in NOP is open, it sends a RESET signal to other devices. After receiving the RESET signal, the devices in points P1 and P2 control the closing of their switches.
10. Switches at points P1 and P2 are closed. The network is in its normal state.

4.3. Short-circuit between section point 1 and substation

In this case, the fault location was set between section point 1 and the substation. The operation of the automation is divided into states marked with letters from 1 to 7 in Fig. 12.

The following is a description of the various stages from Fig. 12:

1. The network is in a normal state.
2. A fault occurs and none of the relays in section points record the disturbance.
3. Protection in the substation is tripped and the CB opens. The load in the semi-loop is de-energized. The automation waits for the START signal.

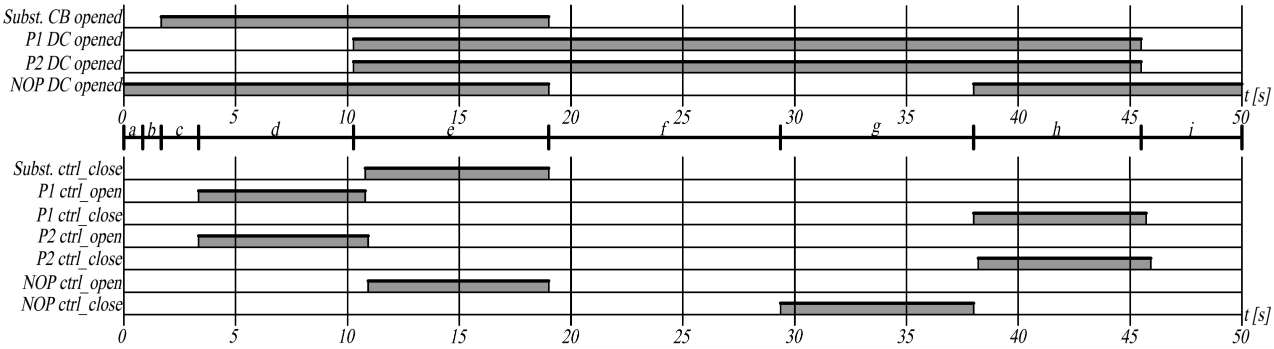

Fig. 11. Test results for a short circuit between and section point 1 and 2

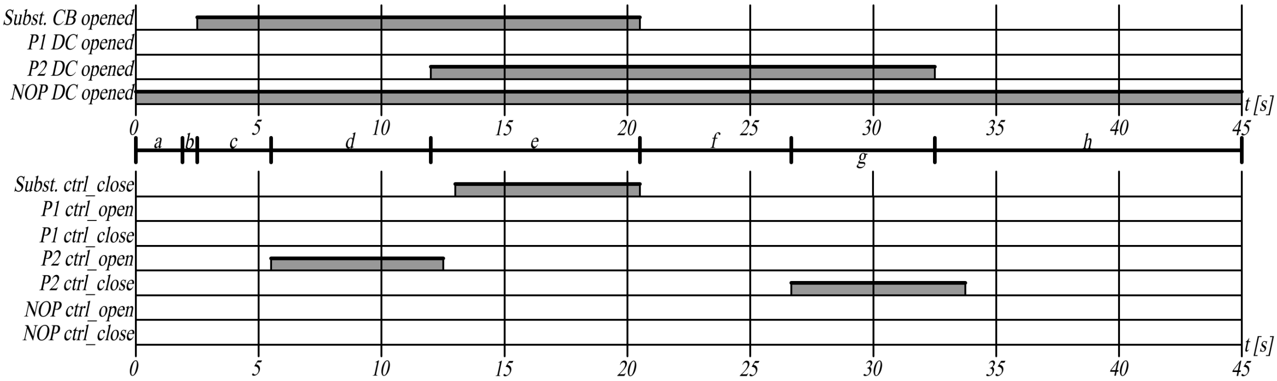

Fig. 12. Test results for a short circuit between the substation and sectionpoint 1

4. After receiving the START signal, the controller in point P1 monitors the opening of the disconnector. Point P1 did not register a short circuit.
5. After the disconnector in point P1 was opened, the damaged section is isolated. The device at P1 sends a LO signal towards the NOP. After receiving the LO signal, NOP controllers send signals to close their disconnectors.
6. A healthy part of the network is reenergized. The automation waits for a RESET signal.
7. When the RESET signal is received, the device in the NOP controls the opening of the disconnector.
8. The disconnector in NOP is open and the controller sends a RESET signal to other system components. After receiving the RESET signal, the devices in point P1 and the Substation control the closing of their switches.
9. Switches at point P1 and substation are closed. The network is in its normal state.

For all cases, all algorithm steps gave satisfactory results and all switching operations took place in the correct order and there were no undesired switching operations. The operating time of the automation depends mostly on the movement time of the switches. Considering the disconnection drives available on the market, the time of one switching usually does not exceed 10 s. In all cases, the time set in the State Sequencer module was about 8 seconds. The self-operating time of the controllers is negligibly small compared to the time needed for all switching. In practice, the duration of outages is reduced by FLISR automation due to the elimination of time required for sending field crews to manually restart the switch and quicker restoration of energy to the healthy part of the grid. It can also be reduced by improving methods for locating the short circuits.

5. CONCLUSIONS

The idea of remodeling currently existing grids into Smart Grids allows us to implement FLISR automation, which is a reliable solution to enhance grid efficiency, reliability, and security. However, the best results are obtained while considering the distributed architecture of FLISR automation, due to the greater opportunities for monitoring the system and its scalability and compatibility with modern grids. The proposed distributed FLISR automation, which is suitable for grids earthed by resistors or for reclosers located deep in the compensated network, was implemented for bilaterally powered loop topology with field controllers installed in MPS station, NOP and section points. Communication was based on GOOSE messages.

This paper focuses on building the logic of field controllers as a part of the implementation of distributed FLISR automation in the abovementioned grid. It is known that the distributed approach, despite its complexity and high economic cost due to reclosers and field controllers installed in every node of the grid, significantly facilitates managing the grid and its expansion. Moreover, the distributed FLISR architecture significantly shortens the time from registering, locating, and isolating the short circuit to restoring the power to customers. It allows us to reduce SAIDI and SAIFI indicators and leads to the reduction of economic losses and improvement of customer satisfaction. A departure from centralized and semi-centralized FLISR architecture will also allow us to reduce the human factor during the decision process of the grid management system.

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