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Advanced Fault Current Indicators for MV Overhead Lines

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SUMMARY

In situations where transient disturbances occur in the MV network, it is very important to locate the fault-site and the cause of such disturbances in the shortest time possible. When insulation breakdowns start, it may take from a few hours to several days before transient breakdowns turn into a permanent fault. The fault-locating process can be efficiently and accurately carried out only by installing fault indicators or disturbance recorders/protection relays in the depths of the distribution network. This way the entire network is divided into a number of smaller sections, thus enabling the network operator to locate the weak insulation before a permanent fault occurs.

Early last year, installation of advanced fault indicators for MV overhead lines was implemented at Elektro Ljubljana. In addition to the detection of faults, the latest generation of indicators provides detailed insight into the state of MV lines during unexpected events and the sensing of disturbances which could potentially cause a fault.

The innovative design of these indicators enables the implementation of different advanced methods for fault-current detection, which has become very important for fast and accurate locating of faults in networks with a resonant-earthed neutral point. Earth-fault detection in resonant-earthed MV networks is very difficult and cannot be reliably detected by devices with the conventional steady-state methods being used today. In cases of detected faults or the sudden exceeding of the electrical parameters of the line, a data record of the disturbances is transferred from the indicators to the server. This way a detailed analysis can be carried out of events that might potentially or might already have caused a fault.

KEY WORDS

fault current indicator FCI, distribution automation system, fault detection, isolation and restoration, faults on MV distribution lines, fault direction, resonant earthing of neutral point, fault diagnosis

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INTRODUCTION

The reliability of the operation of a medium-voltage network and consequently the reliability of supply to clients are to a large extent influenced by the proper maintenance of MV distribution infrastructure and by faults that are in most cases the result of bad weather situations. Faults appear more often on overhead lines, which is why Elektro Ljubljana has adopted various measures for reducing faults. For the past 20 years it has been investing funds in an automation system for the MV network, comprising reclosers, remote-controlled line switches, and devices for the detection and signalling of faults.

Elektro Ljubljana is currently using approximately 190 fault indicators for overhead lines. Of these, 110 are older generation and enable the remote signalling of detected faults and the detecting of earth faults in networks with resistence earthed neutral point. In recent years, Elektro Ljubljana has been intorducing the implementation of a neutral resonant earthing system, which has reduced the number of short-term power outages caused by earth faults. In cases when the earth fault is not automatically cleared, the resistor in the neutral point is turned on and the system switches to the normal protection scheme. This way the faulty outgoing feeder is detected and is either switched off by the protection at the outgoing feeder or by the recloser installed in the line. In most cases the first-generation indicators successfully detect faults under such changed circumstances, since the turning on of the resistor in the neutral point provides a big enough earth fault current.

Since the expansion and, in particular, the cabling of the network increase the capacitive currents of individual sections, the sensitivity of indicators at such sections must be significantly reduced in order to preserve the selectivity of earth fault detection and prevent false detections when faults are located ahead of the installed indicators. It would therefore be sensible to introduce indicators which could reliably detect faults at such sections without their sensitivity being reduced, thus preserving sufficient sensitivity to high impedance faults and, consequently, with a lower fault current. Furthermore, in order to ensure long-term usability of the newly-installed indicators, a suitable type of indicator must be provided that would enable reliable detection of earth faults in resonant-earthed MV networks whenever operation is planned during an earth fault without the feeder being switched off. Moreover, by increasing the share of dispersed production in some parts of the network, problems may occur with the reliable detection of faults. The newly-installed LOK 200 indicators from Sipronika meet these criteria and, at the same time, enable certain functionalities that are important for diagnosing events and which provide quality input data for DMS.
At Elektro Ljubljana the installation of indicators began with the installation of indicators with light signalization of detected faults and continued with indicators that enabled the sending of messages about the detection of a fault to the mobile phones of the workers on duty. Today, all of the indicators are connected via communication channels to SCADA, where a special view shows the alarms and the data on the status of the devices themselves. When faults are detected, these alarms and data appear on the display of the medium-voltage network, thus enabling the dispatcher to locate the fault faster.

I. CRITERIA FOR DECIDING TO INSTALL INDICATORS

Indicators are the cheapest form of distribution automation system and are installed primarily on long, branched feeders. The most suitable feeders are those that experience relatively frequent power outages, whereas an individual section experiences them relatively rarely. Because of long distances to individual branches, the fault localisation times are reduced. Likewise reduced is the number of times the switching equipment has to operate to find the fault and, consequently, the wear of the switching devices is reduced due to lower number of operations under high fault-current conditions.

The direct benefits of installing indicators are shorter outages of the distribution network, a reduction in the number of working hours spent looking for faults and in the number of kilometres covered. Indirect benefits are a reduction in CO_2 emissions, in unnecessary exposure of workers to traffic, and in wear reduction of the switching equipment.
The criteria for choosing the location are branches from the main feeder and ring designed radial operated feeders. In case when an indicator at a branch is active more than anticipated, it is replaced by another automation element like recloser. Indicators can also be installed on long feeders in series if we wish to split the feeder into several segments. It is sensible to install them particularly in locations with dispersed household consumption. If we suspect that a specific network location is causing a greater number of short-term faults, fault indicator can provide first insight into this part of the network.
Indicators are the cheapest form of automation, both from the aspect of installation and of maintenance. Above all, they must operate reliably and communicate properly.

II. EXPERIENCE WITH OPERATION

From early 2015, when the indicators were installed, to April 2016 the fault indicators have sent the following total number of recorded alarms:

- Earth fault - transient: 129
- Earth fault - permanent: 32
- Phase-to-phase fault - transient: 150
- Phase-to-phase fault - permanent: 40
- Feeder power outage: 1569

A transient earth or phase-to-phase fault means that the duration of the fault current was longer than the time delay for fault detection set in the indicator, but that no permanent outage occurred. In some cases there was a fast or delayed autoreclosing operation; in any case, for 35s after the fault began the feeder undoubtedly operated normally.

The number of alarms does not reflect the actual number of events, since the same event can be detected by several indicators at once. This is particularly noticeable in the number of feeder power outages, since the same outage is detected by all indicators located on the same feeder.

When comparing the diagnostic data of certain events recorded simultaneously by several indicators on the same feeder, we noticed great consistency among event creation timestamps, which proves that the indicators are appropriately time synchronised. This allows for easier analysis and comparison of data on the same event, coming from various sources – from the protection or from one or several indicators.

Based on the list of alarms received from the indicators and from the actual events on the MV network, it can be concluded that the indicators were working properly during that time period.

III. DESCRIPTION OF INDICATOR AND FUNCTIONALITIES

The basic function of a LOK 200 indicator is the detection of earth and two-pole and three-pole phase-to-phase faults. The indicator is intended for use on overhead lines and is installed at a distance of 3m below the feeder conductors, as shown in Figure 1.

Figure 1: Fault Indicator and Installation of Indicator on the Pole of an MV Line

The fault detection method is based on the principle of measuring the electric and magnetic field generated by the voltage and current in the feeder conductors. The device is compact and not in contact with any high-voltage conductors; all parts of the device, except for the photovoltaic module, are built into one casing. It enables local signalling of detected faults with a light signal and remote reporting via the GSM mobile phone network, using the SMS and GPRS services.

The device detects and signals the following statuses and events:

- Earth fault (transient or permanent; separate signalisation);
- Two-pole and three-pole phase-to-phase fault (transient or permanent; separate signalisation);
- Presence of voltage on the MV line;
- Device status (proper operation of electronic assemblies, battery status, GSM signal strength);

In addition to reporting the above-mentioned information, the device also enables many other functionalities, such as local recording of information about events and the operation of the device itself (e.g. diagnosing the communication pathway), indicative measuring of the load current, the direction of the energy flow, the installation of additional modules for connecting with other elements and devices (connection with RTU, with MV switches that are equipped with position sensors), and for operating and controlling other devices).

The device can be upgraded with additional sensors; among others, the device can be expanded with a module for detecting interrupted conductors. It is known that such faults are extremely difficult to detect. The detection of this type of fault shares quite a few similarities with the LOK 200 indicator, which is why it would be sensible to implement both functionalities in a single device, thus increasing the price efficiency of the solution.

The device has autonomous power supply provided by the built-in accumulator battery and the photovoltaic module; however, despite the constant charging of the battery, when planning the device we had to make sure that average energy consumption would be as low as possible. Bearing in mind that substantial emphasis is placed on the transfer of information about the status and events on the line, sufficient energy must be provided for the communications part – the GSM/GPRS module, which consumes a substantial amount of energy during its operation, in comparison with the rest of the device. Therefore the only sensible solution is to charge the battery using solar energy, because only that way can we ensure the battery a long service life, regardless of the intensity of communication.

IV. FAULT DETECTION METHOD

The fault detection method is based on the measuring of the resultants of the magnetic and electric field, generated by the feeder currents and voltages. At the measurement point, i.e. in the spot where the indicator has been installed, the dominant component of the magnetic field is directed horizontally, whereas the dominant component of the electric field is directed vertically and curves from the vertical towards the horizontal direction in the vicinity of the pole. When measuring and digitally processing the values of magnetic and electric field, the amplitudes and phases of the measured signals – phasors – are taken into account.

During normal feeder operating conditions, when nominal voltage and load current are present, the phasors are rather static and change slowly. The magnetic field changes the most depending on and proportionally to the load current. Since the voltages and currents of the three-phase feeder are mostly symmetrical, the resulting field has much smaller amplitude than the individual components contributed by each phase voltage or current. The size of the resulting field depends on the geometric ratios or the distribution of the conductors with regard to the measurement point.

In the case of an earth fault, the magnetic field changes depending on the value of the earth fault current. The resulting field changes in any event, but there are special cases when the amplitude stays the same, but the phase changes. Or the other way around: the amplitude changes, whereas the phase remains the same. Moreover, there have been cases where, depending on the geometric distribution of conductors, the amplitude of the magnetic field was actually reduced due to a specific earth fault current. That is why when calculating the fault current the algorithm must take into account the magnetic field phasors before the earth fault started and while the earth fault lasts. This means that the algorithm must continuously adapt itself to current conditions and react only to instant changes.

The algorithm for calculating the fault current amplitude takes into account the information about the fault type and evaluates the change accordingly. If the amplitude of the calculated fault current exceeds the threshold which has been set in the indicator's sensitivity settings, then the change is treated as a fault and is signalled accordingly. For this to occur, the time criterion must also be met, i.e. the fault current must last longer than the pre-set time.

V. EARTH FAULT DETECTION IN RESONANT-EARTHED NETWORKS

The fault detection method described in the previous chapter does not enable the determination of the direction of the fault current, which prevents successful detection of earth faults in networks with an entirely resonant-earthed neutral point. For this reason, various methods which enable the determination of the direction of the fault current are being used in practice to successfully detect earth faults in such networks, e.g.:

- the transient method – the moment a fault occurs, a transient appears in the fault current, resulting from the fast discharging of the phase-to-earth capacitance of the conductor that has come into contact with the earth.
- the method of higher harmonic components measuring – the current of higher harmonic components is not compensated by a Petersen coil, which is why their content is relatively higher in the fault current loop than in the capacitive current of the remaining part of the network.
- detection of a pulsating fault current – by periodically switching on and off the capacitor bank, together with the coil in the neutral point, only the fault current between feeding substation snd fault site changes, whereas the capacitive current of the remaining part of the network does not.
- the wattmetric method – measuring the active component in the fault current.

When selecting the method for detecting the direction of an earth fault and its implementation in the fault indicator algorithms, we decided to use the following methods:

1. **Transient method** (Figure 2):
    - The transient is created when the phase-to-earth capacitance of the conductor that has come into contact with the earth is discharged.
    - Comparison of the polarity of the current transient and of the electric field. If both are in the same phase, the fault lies in the direction of the load.
    - If the transient is in opposite phase to the electric field, the fault is on the incoming feeder side.

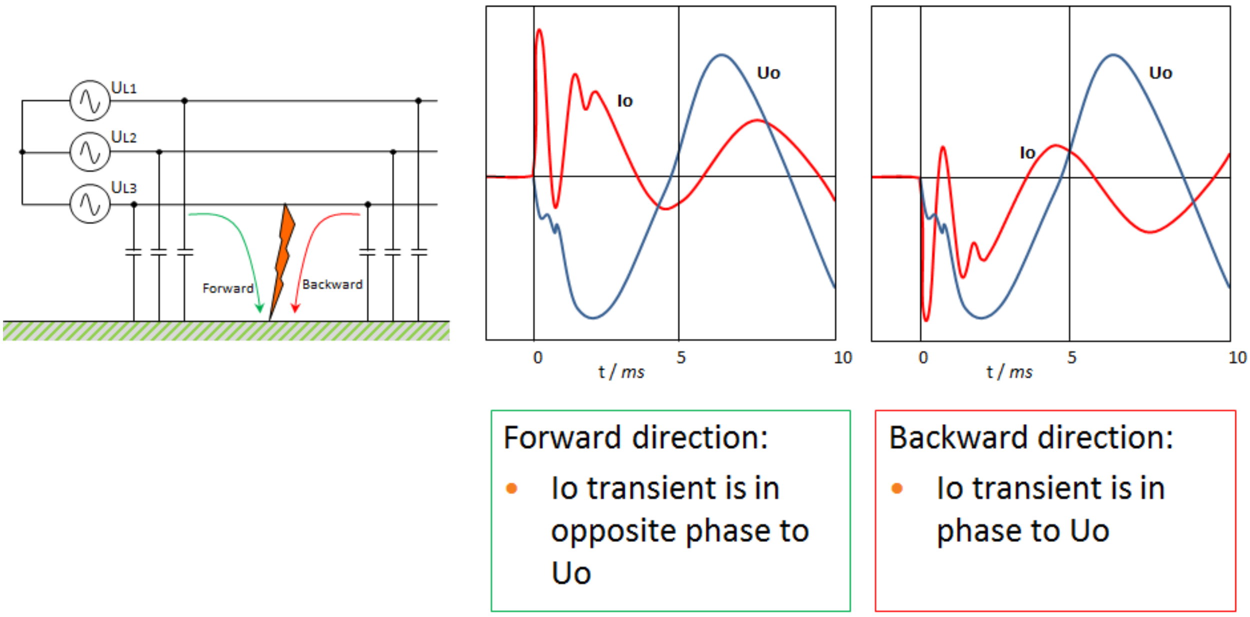

Figure 2: Principle of the Transient Method for Detecting the Direction of an Earth Fault

The development of a transient method for detecting an earth fault was a rather demanding process, since we had to ensure the detection of fast changes in the measured signal and simultaneously keep the indicator's energy consumption as low as possible. In order to achieve low energy consumption, the device's microprocessor must be on standby most of the time. In the development process we used a simulation on a three-pole model of a resonant-earthed network, in which we converted the response to an earth fault into electric signals in order to simulate an electric and magnetic field. Using these signals we excited an electric and magnetic field in a test environment, which in turn excited the fault indicator. Figure 3 shows the result of the simulation of an electric and magnetic field in the event of an earth fault through a impedance of 1 ohm; in Figure 4 the impedance amounted to 1 kohm. In both cases the indicator reliably detected the direction of the fault current.

The legend for the two oscillograms below:

- Electric field – green
- Magnetic field – red
- Transient signal of the magnetic field, filtered through a 3rd order high-pass filter f=2 kHz

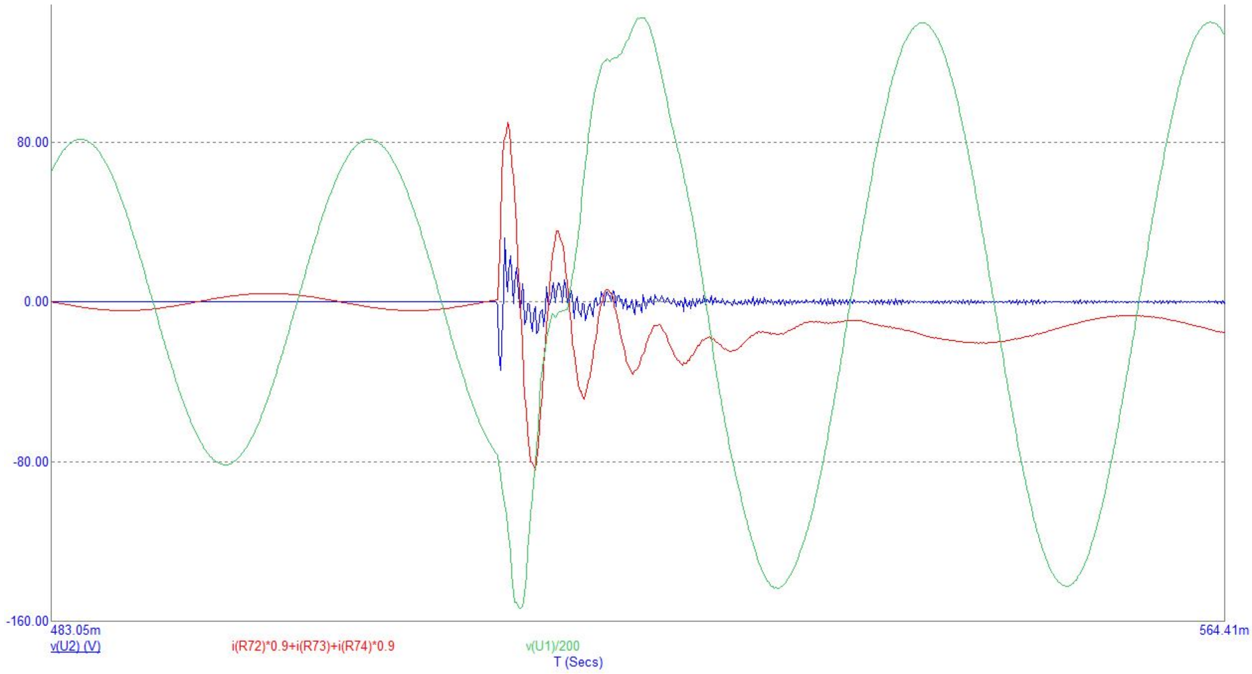

Figure 3: Oscillogram of an Electric and Magnetic Field, Fault Impedance 1 Ohm, Computer-Simulated on a Model of a Resonant-Earthed Network

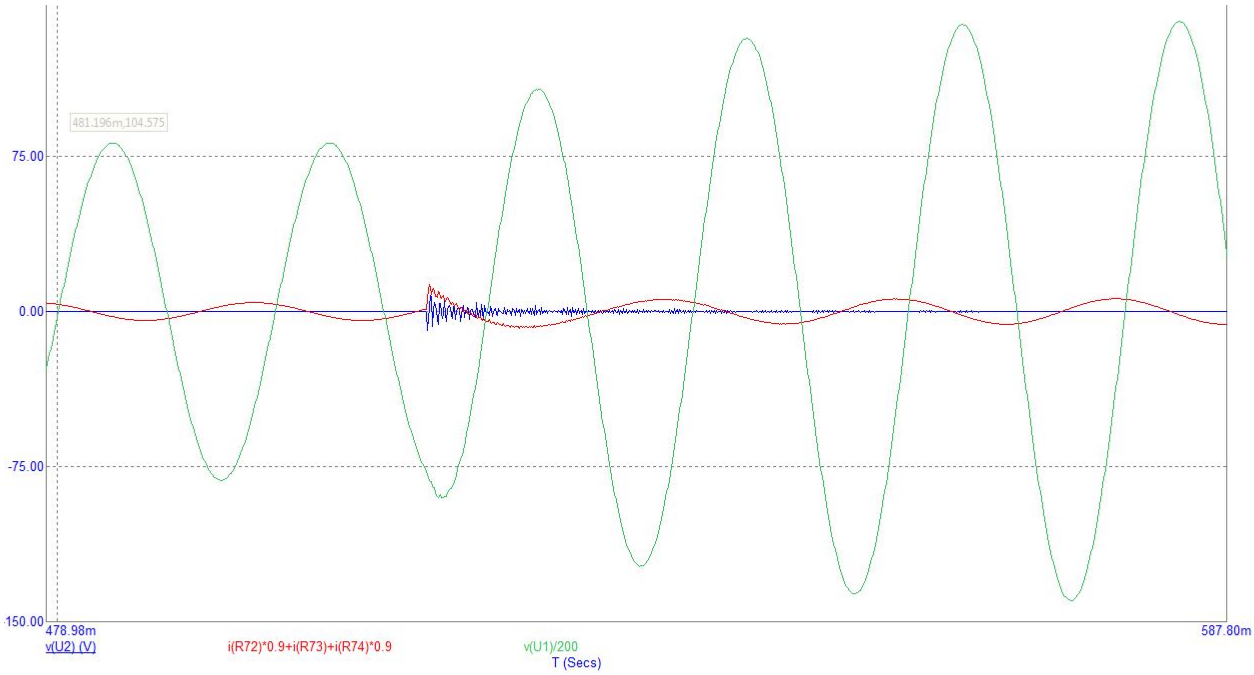

Figure 4: Oscillogram of an Electric and Magnetic Field, Fault Impedance 1 Kohm, Computer-Simulated on a Model of a Resonant-Earthed Network

2. **Measurement of Higher Harmonic Components of the Magnetic Field** (Figure 5):
   - Higher harmonic components of the fault current are not compensated by a Petersen coil.
   - The content of higher harmonic components is present only in the fault current loop.

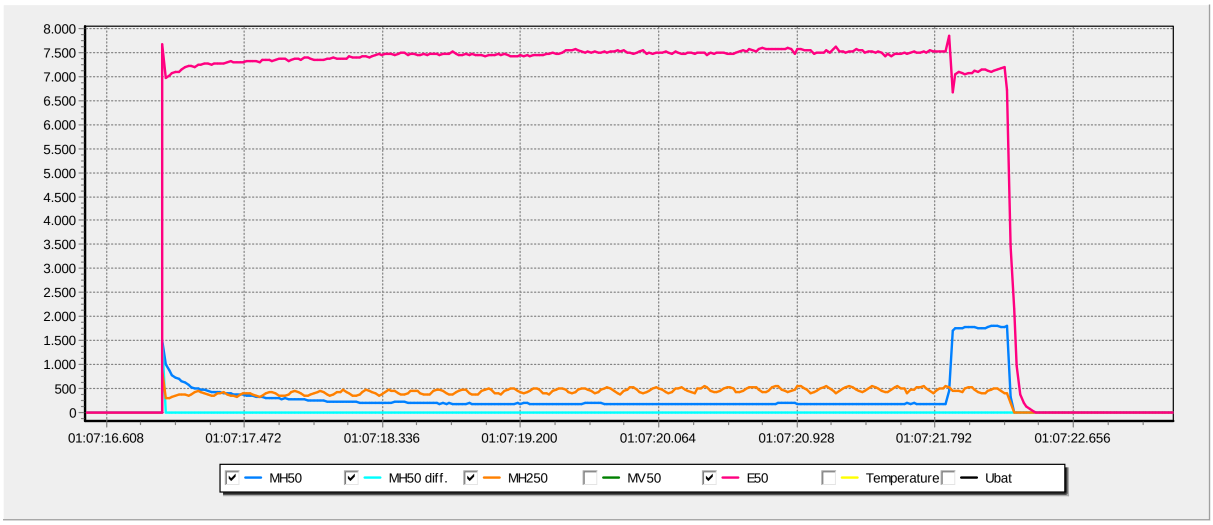

Figure 5: Recording of a typical fault in a resonant-earthed network, with a distinct fifth harmonic component (orange) in the fault current which exceeds the basic harmonic component (blue) in amplitude.

3. **Other methods:** pulsation of the fault current (Figure 6), injecting a current of a specific form or frequency during the earth fault

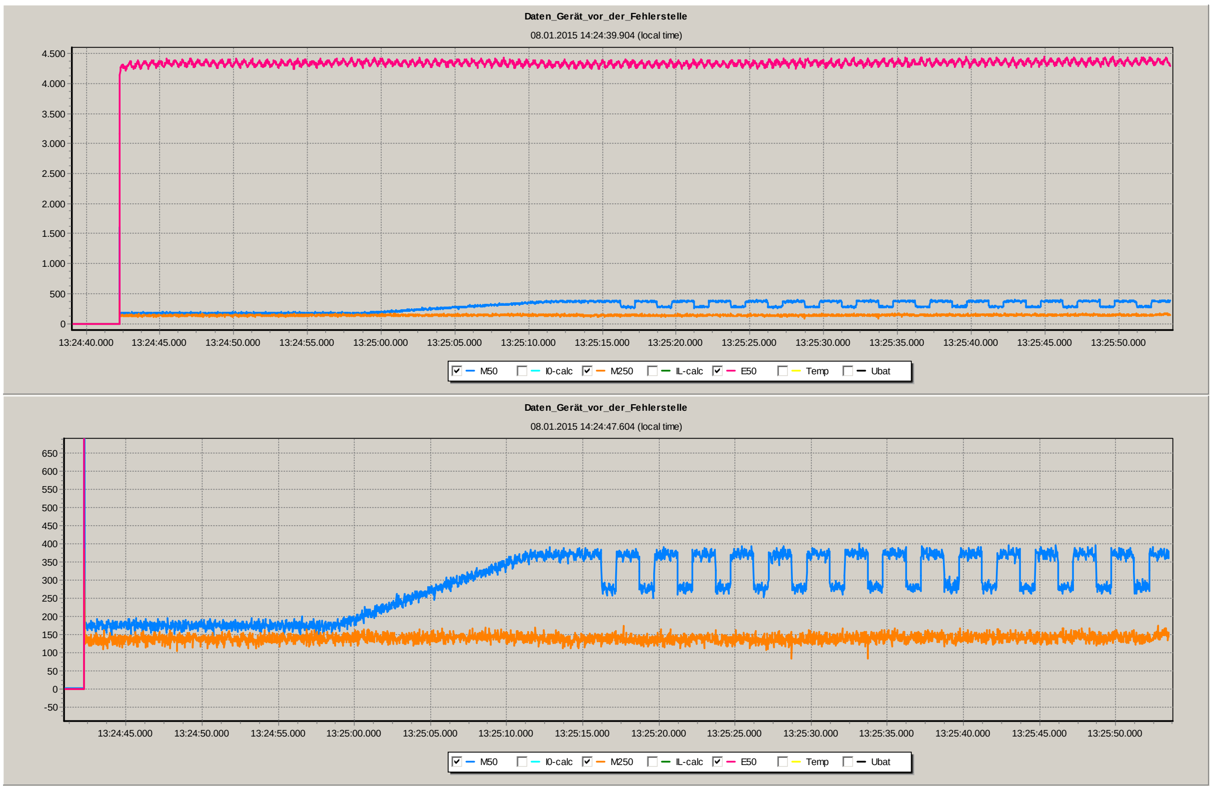

Figure 6: Recording of a Fault in a Resonant-Earthed Network with Pulsation of the Fault Current

VI. REMOTE REPORTING AND MONITORING SYSTEM

The basic requirement of a modern automation system for distribution networks is that the communications of each solution are integrated into a remote monitoring and control system and into other support systems for ensuring the reliability and stability of the operation of distribution networks, such as DMS and OMS. For the fault indicators in the system described above we used communication via the GSM network, which is well branched in Slovenia and in all of the developed countries and in the majority of the less-developed ones, and which ensures suitable coverage of potential locations with the GSM signal. The SMS service is used for reporting alarms and events on the network, because it provides greater reliability in locations with a poorer GSM signal. Data communication via GPRS is used for the telemonitoring of devices. The quantity of data ranges between 5 and 20MB per month, depending on the number of events and the frequency of sampling electrical signals during normal operation.

Figure 7 shows the basic scheme of the communication structure. The project at Elektro Ljubljana described above has been implemented in accordance with this scheme and enables the transfer of alarms to SCADA, complete telemonitoring of devices, and the obtaining of data on the events recorded by these devices.

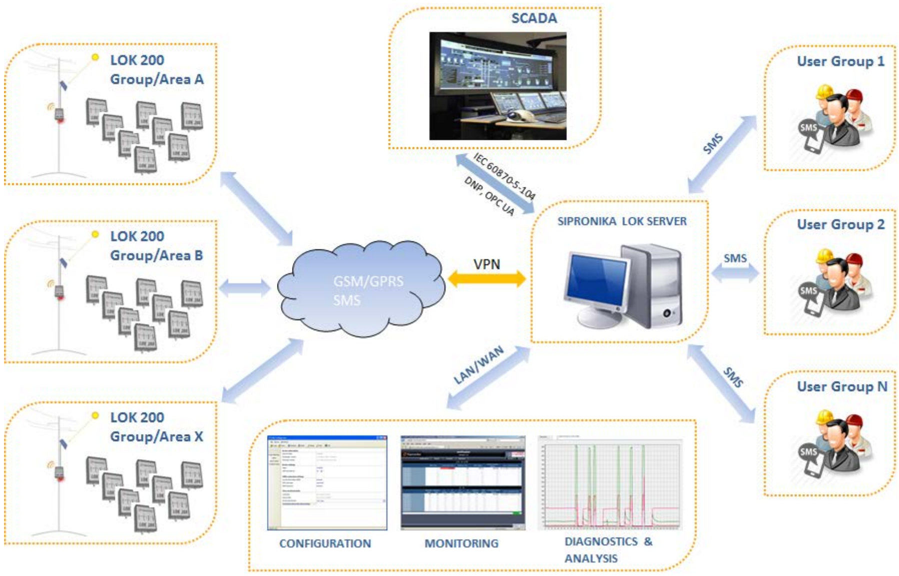

Figure 7: Server and User System for Communication with Indicators

The remote reporting system consists of a telecommunications infrastructure and a server with modularly designed software that can be adapted to the needs of the user. Figure 8 shows the basic architecture of the server software. It contains the following building blocks and functions:

1. SCADA Gateway: a communication concentrator that receives SMS messages from the indicators and submits them to SCADA according to the IEC60870-5-104 protocol. SMS messages can also be sent to the mobile devices of users – network maintenance personnel, but Elektro Ljubljana did not opt for this solution.
2. Online server for monitoring the operation of the communication concentrator: a multi-user online server enables access to data on the basic status of indicators (indicator operation, current alarms, status of the GSM signal and battery) and a review of the database of events received by the concentrator.

3. Server for the telemonitoring of indicators: remote configuration of parameters, software updates of devices, transfer of diagnostic data on the device's operation and the transfer of recorded data on events occurring on the line via a GPRS connection.
4. Diagnostic data server: captures data on the measured values of the monitored electrical quantities of the line, which provides detailed insight into events on the line in the case of faults and into the operation of indicators in such cases.

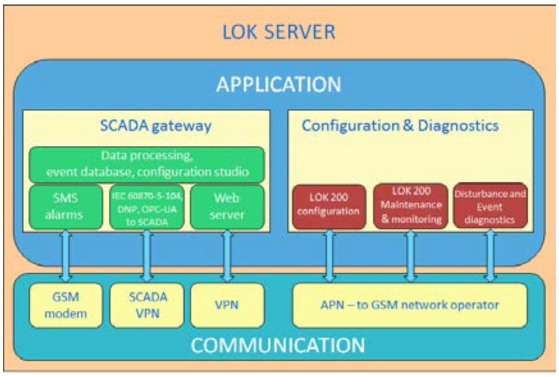

Figure 8: Server Architecture

The first-generation fault indicators which had been installed at Elektro Ljubljana sent messages about detected faults directly to the mobile phones of the workers on duty. After the indicators were integrated into the SCADA system, there was no longer a need to send data to the workers on duty, since fault localisation was afterwards managed by the dispatcher in the Distribution Management Centre/DMC.

VII. DIAGNOSTIC DATA SERVER

One of the most powerful tools of the aforementioned fault indicator system is the diagnostic data server, which gives the user detailed insight into the operation of the line and of the disturbance events resulting from permanent faults or from short-term electrical breakdowns that can develop into a permanent fault. The system is based on the capture and storage of electric and magnetic field samples and on the calculated values of the fault current. All of the recorded samples bear timestamps, which enable precise comparison with the data captured from protection relays at the outgoing feeders or from the remote-controlled reclosers on the network.

During normal operation, when there are no fast changes of electrical quantities, samples are captured periodically every minute or every 15 minutes. In the event of a fast change of any electrical quantity, the fast sampling and recording of phasors of individual quantities is activated. The temporal resolution of recorded samples amounts to 20 ms, which is sufficient for precisely determining the type and course of the event. The captured measured samples, which are temporarily stored in devices, are transferred to the server when a GPRS connection is established. The server also contains a graphic tool for visualization and printing the archived data in the form of graphs. The following information can be seen on the graphs:

- the electric field;
- the horizontal magnetic field – the basic harmonic component;
- the horizontal magnetic field – the 5th harmonic component;
- the calculated fault current I_0;
- the calculated phase-to-phase fault current;

- battery voltage;
- device temperature.

Below are the images of two events recorded by indicators. Figure 9 shows a diagram of the course of a phase-to-phase fault with two unsuccessful autoreclose attempts. It can be seen that before the first reclosing, the status of the line briefly returned to normal after reclosing and was then followed by another phase-to-phase fault. A transient occurrence is clearly noticeable in the current upon reclosing due to the magnetisation of the cores of the MV/LV transformers.

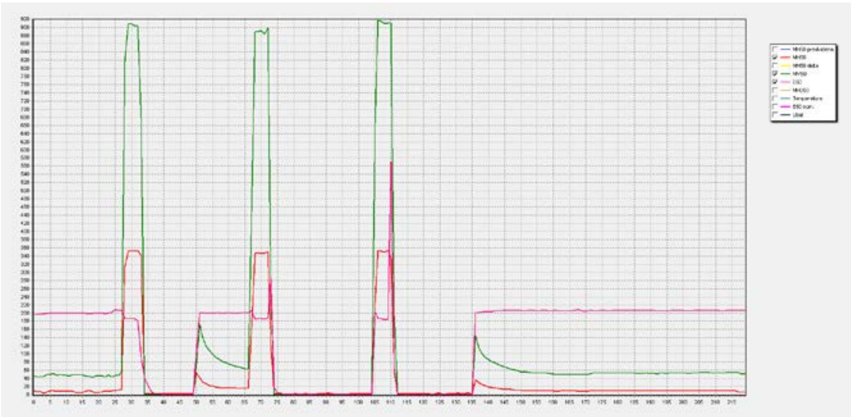

Figure 9: Example of a Diagram of a Phase-to-Phase Fault and Reclosings, Captured by an Indicator

Figure 10 shows the operation of a line with frequent short-term electrical breakdowns from phase to earth; also visible are the changes to the load of the line due to the switches located after the fault indicator being turned on and off. The diagram was recorded just after a sleet in 2014, when conditions were still highly unstable and faults occurred very frequently.

Figure 10: Example of a Diagram of Transient Faults and Relosings, Captured by an Indicator

VIII. CONCLUSION

Fault indicators are the most basic level of the automation of a medium-voltage network. They represent the cheapest solution, both from the aspect of installation and of maintenance. Indicators have the best cost/benefit ratio.

The described solution is technologically advanced and sets new standards in the implementation of fault detection algorithms for such devices. The advanced algorithms used in this solution enable extremely high reliability and precision in detecting faults and provide the option of using the device under various operating conditions, according to the type of network (resonant earthing), and under operating conditions in which the level of dispersed production is increasing. Advanced indicators present an additional source of input data for DMS when eliminating the effects of faults quickly and efficiently.

This solution presents a flexible basis for the further implementation of new algorithms that are compatible with future fault detection methods. The devices can be remotely upgraded with new and improved versions of software. Furthermore, this solution can be expanded with sensors that provide additional information and in a cost-effective way contribute to increasing the level of the obsrvability and controlability of distribution networks.

The project implementation is an example of successful cooperation between several Slovenian partners, i.e. research and development companies, and an electricity distribution company as the end user. This solution is the result of exclusively Slovenian knowledge and experience; the system is also open to the needs of new potential partners that can contribute to increasing the functionalities with new solutions.

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