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ÚSTAV ELEKTROENERGETIKY

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DISTANCE PROTECTION DESIGN USING DIGITAL INPUT DATA

DISTANČNÍ OCHRANA VYUŽÍVAJÍCÍ DIGITÁLNÍ VSTUPNÍ DATA

ZKRÁCENÁ VERZE PH.D. THESIS

Obor: Silnoproudá elektrotechnika a elektroenergetika
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Klíčová slova

Sampled Values, IEC 61850-9-2, overcurrent protection, , distance relay, protection relay, MATLAB, merging unit, GOOSE, Ethernet, SVScout, delay time, IED, time synchronization, machine learning, ROCs, Simulink, Omicron CMC 256plus, power quality, enerlyzer, comtrade.

Keywords

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Místo uložení práce

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Chapter 1

INTRODUCTION

The numerical relay is a focal concept of the power system automation for protecting the equipment and limiting the damage. The Thesis explains the signal processing of power quality disturbances using MATLAB 2016, MathWorks, Natick, MA, USA) Simulink, especially the power quality impact on the measurements of the power system quantities; the test simulates the function of protection in power systems in terms of calculating the current and voltage values of short circuits and their faults. Power system automation has several levels to integrate between the power substations and the substation supervisory system (SCADA). The IEC 61850 standard helps digitize substations as part of equipment to device communication that is needed for protection, control, monitoring and measurement functions. The most recent part of the IEC 61850 communication protocol is the IEC 61850-9-2 part for the transmission of sampled values SV. This standard applies to electronic current transformers voltage with digital output, merging units –MUs –and an intelligent electronic device such as protection devices, field controllers and energy meters. The IEC 61850 standard unites the structure, requirements, and communication specifications that can be implemented during sharing of data among IEDs, the first announcement of the cooperation and creates a platform between the substation automation system (SAS) and the substations (IEC 61850 2003) [1]. The challenges to implementing the IEC 61850 are processing a huge amount of real time data and replacing some parts of substations to create a better environment to implement IEC 61850. The use of IEC 61850 as the basis for smart grids includes the use of merging units (MUs) and deployment of relays based on microprocessors. IEC 61850 standard defines communication protocol for intelligent electronic devices at electrical substations. It describes in IEC 61850-9-2 sampled values and how to digitalize measurements. Transferring data in digital format is used for the protection and monitoring application. The challenge nowadays is sharing the current and voltage measurements in substations and uses it for monitoring and protection application. Due to the fact that current and voltage transformers are able to convert the analog signals to digital format. The IEC 61850 standard for substation authorizes the combination of all control, protection and monitoring functions by one protocol, nowadays, all manufacturers realize the importance and the need to merge the communications of all IEDs in a substation, numerous IEDs can control commands at high speed and share data. This coordinated control can partly eliminate the need for wiring in a substation. Many utilities have already established systems of interconnected IEDs, which make IEDs measurements available to use for centralized substation and control, whilst, the majority of data in IEDs is left uncollected due to the traditional techniques were designed to support SCADA. IEC 61850 was created to be an internationally standardized method of communications and integration with goals of supporting systems built from multivendor IEDs networked together to perform protection, monitoring, automation, metering, and control [2]. A microprocessor provides the ability to process large amount of information and to make the tripping decision trip, another important application of permanent power quality monitoring is a distribution power quality recorder (DPQR) in the digital relay that can be used to define the measurements of events which occurred in the power system such as internal/external fault diagnosis, fault measurements, zero current sequences and disturbance recording. The hierarchy structure of power system automation contains electrical protection, control, measurement, monitoring and data communications. The power system automation is a system that is integrated into the various components connected to the power network. The numerical relay is a focal concept of the power system automation to protect the equipment and limit the damage. The system's components have better communication with each other; the information is exchanged via dozens of communication protocols; the concept can be characterized by only one sensor obtaining and collecting information from the network instead of a sensor per each component in the power system. The power system automation has several levels to integrate into the power substations and the substation supervisory system (SCADA). They include Sampled Values (SV) and Generic Object Oriented Substation Event (GOOSE) protocols which are mapped directly to the Data Link layer for reduced protocol overhead hence increased performance; and Generic Substation State Event (GSSE) protocol which features its own custom protocol mapping [3]. IEC 61850-9-2, process bus is defined as standard:

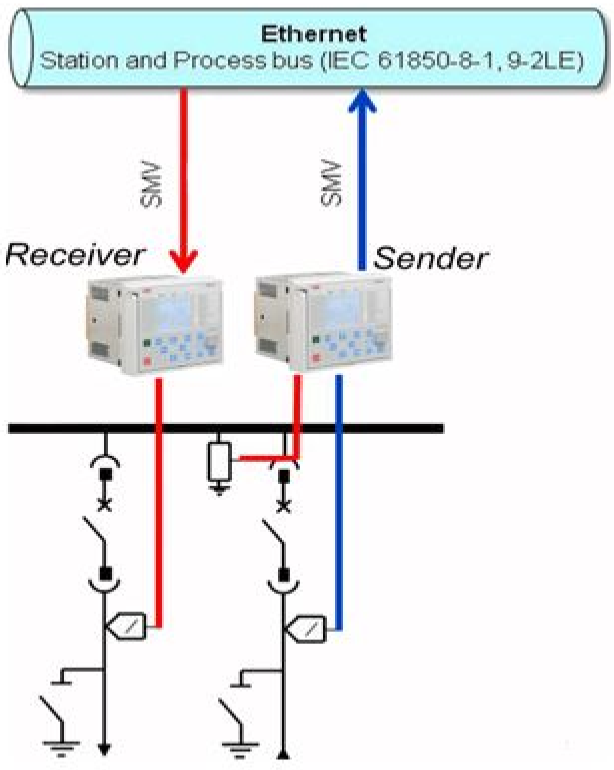
- IEC 61850-9-2 standard for communication networks and systems in substations, part 9-2: "Specific Communication Service Mapping (SCSM) - Sampled values over ISO/IEC 8802-3" [4].
- Implementation Guideline for digital Interface to instrument transformers using IEC 61850-9-2 to facilitate implementation and enable interoperability, the UCA International Users Group created a guideline that defines an application profile of IEC 61850-9-2, which Commonly referred to as IEC 61850-9-2LE for "light edition" [1].

Chapter 2

THE STATE OF THE ART

This chapter describes the standard IEC 61850 which is a communication protocol for electrical devices used in substations. This uses the sampled values and GOOSE protocols which are mapped directly to the data link layer for reduced protocol overhead. In this chapter, IEC 61850 standard is discussed including parameters for sampled rate of analogue values, configurable for content of dataset.
sampled values are important in electrical parameters they are beneficial in such a way that they enable sharing of values, transmit sampled analogue and digital values, sending of data in data link layers, interference and providing time coherent SMV. The sampling rates are defined in this chapter as the transmission speed is 100 Mb/s so 80 samples per period for protection application.
Testing of multifunctional distance protection devices is also discussed in this chapter. The measurement of active, reactive and apparent power or power factor are often available from the relays when they are required in the substation automation system. Another technique is explained here which is quadrilateral relay algorithm and protection. It includes the calculation of bandwidth. The algorithm of distance relay required input signals which are harmonic magnitude, phase of three voltage and current signals each, zero sequence magnitude and phase current to measure phase quantities.
Relay characteristics and impedance diagram play an important role in measuring the values of electrical parameters. Distance relay has a feature of inherent remote back up functionality. Its resistive coverage is better than any mho type characteristic for short lines. The quadrilateral characteristic is the most appropriate for the earth fault impedance measurement while the polygonal impedance characteristics are highly flexible in terms of fault impedance coverage for both phase and earth faults. Omicron is a testing device used for the testing of IEDs functionality and offers the IEC 61850 communication. The delay time of SMV can be defined by the number of hops in a network, internal application delay of protection, store and forward latency, theoretical maximum delay, recommended max delay setting and a new term named queue latency. The queue latency is defined as when the port has started to send a full sized frame before SMV frame and switch has been configured to prioritize SMV. Another precaution is important to reduce error which is network packet analysis to make safe the packet traffic. This part describes the experimental measurement provided on the test setup in the laboratory of protection relays at the Brno University of Technology. PCM600 is a tool providing control and configure ABB IEDs, it is an adapted tool with IEC 61850 standard, which enables data exchange and provides efficient functionality for application configuration. PCM600 offers data transfer between IEDs. The settings in PCM600 offer a view and modify IED parameters. These parameters can be exported and imported in XRIO format or other formats [5]. Configuring Process bus to share voltage information between two IEDs (REF615 outgoing feeder and REF615 incoming feeder) is summarized in the following steps:

- In this test, the process bus communication enables voltage sharing between IEDs as (SMV- Sampled Measured Values). Digital values of current and voltage transfer over an Ethernet network.
- SMVSENDER function block should be added to enable and active sending sampled values according to IEC 61850 standard. The communication channel is established and REF615 sender starts sending the voltage as sampled values (80 samples per cycle).
- In PCM600, a new project is created for two feeder relays REF615 (incoming and outgoing). IEC 61850 Configuration Tool offers Client Server Communication and matrix of available IEDs which are connected to the switch. One protection relay should be selected to be Sender protection relay. The SMVAENDER function block provides share the sampled values from sender protection relay as process bus sender.



Obr. 1: REF615 Outgoing feeder – REF615 incoming feeder

Chapter 3

THE AIMS OF THE DISSERTATION

The objectives of the dissertation are as follows:

- Defining the protection function algorithms.
- Creating a Simulink model for distance relay protection which can define the fault type, fault impedance and total harmonic distortion.
- Evaluation of harmonic impact on the digital relays and comparing the protection model with a physical digital relay.
- Testing the merging units of the digital relay and Omicron device in the laboratory and compare the functions and timing analysis. By using neural net pattern recognition, we could find the relation between the inputs (number of samples/ms—interval time between the packets) and the source of the data.
- Developing real time application that subscribes the data stream coming from a station near protection laboratory in Brno University of Technology. IEC 61850-9-2 LE SMs are used to transmit the traffic to university laboratory with 16 km of fiber optic cable . The application built using MATLAB and can read the traffic from the ethernet port, the traffic decoded and convert from ASCII to the decimal numbers then draw the current and voltage values. The application developed without using any need for additional hardware.

Chapter 4

THE IMPACT OF CURRENT TRANSFORMER SATURATION ON THE DISTANCE PROTECTION

This chapter describes the impact of the current transformer saturation on the distance relay, the model designed in MATLAB Simulink. The test includes apply fault and draw the fault locus on the quadrilateral relay characteristics. The three-phase fault set in distance 35km, 70km, 100 km, The distance protection designed to divide the high voltage transmission line to the zones, each zone contains part of the high voltage transmission line, and the zone 1 set to 80 percent of the first part of the line. The setting of the distance protection considers the line impedance which is the major parameter to design this protection.

4.1 POWER SYSTEM AND CT TRANSFORMER BY SIMULINK

The model consists of two sources, 100 km transmission line and load, current trans-former block which includes the influence of current saturation on power system and distance protection [15].This chapter explains the impact of CT saturation on the distance protection. As we mentioned above the power system simulation contains first of all the source then the CT block. Inside this block there is current transformer also the saturation parameters for this specific system. After the CT block the current signal is moved to the distance protection block which uses this signal with many functions starting from the filter, sampled values and discrete fourier transformer [15]. The current waveform as shown in figure 4.3 illustrates fault current and healthy phase currents.The fault was started from 0.2s and at 0.5s the phase A current comes back to steady state.

DISTANCE PROTECTION BLOCK

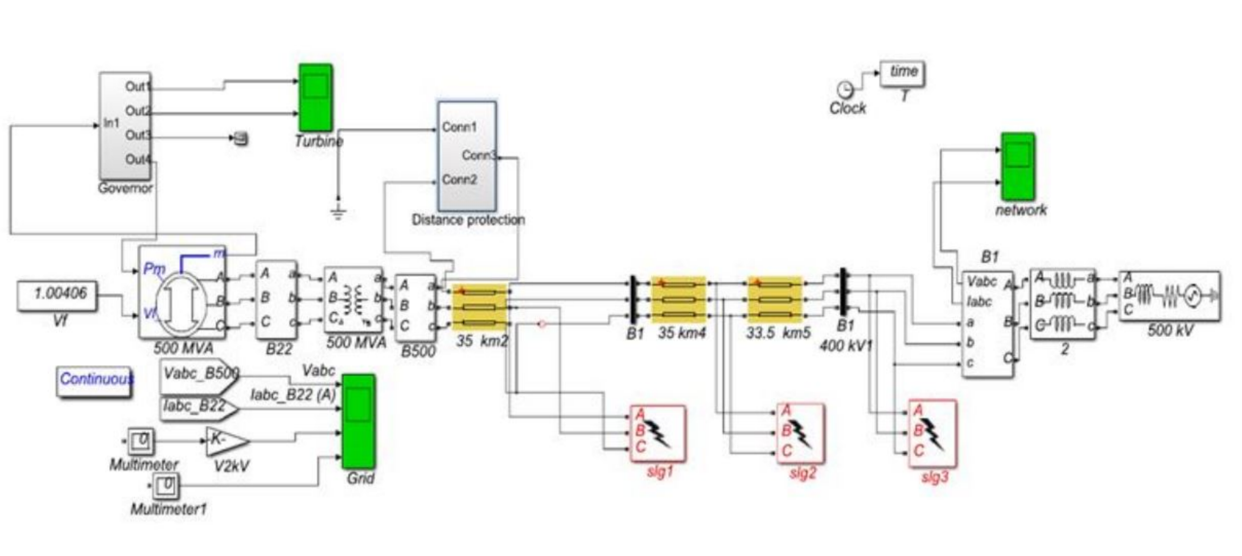
The distance protection is designed to detect the faults which occur in the transmission line. The distance relay divides the transmission line impedance to the zones, every zone covers part of the line [7]. The algorithm is used in the distance protection as shown in eq (4.1.1). This algorithm calculates the impedance of single phase fault, however, the saturation impact on the protection algorithm had resulted on calculation of the fault impedance [14].
Figure 4.3 explains the secondary current under the impact of the current saturation. Current waveform is used in protection block with signal processing.
Single phase fault can be calculated as:

$$\overline{Z}_{slg} = \frac{\overline{V}_A}{\overline{I}_A + 3 \cdot k \cdot \overline{I}_0} \tag{4.1.1}$$

where
V_A and I_A are voltage and current phase respectively.
I_0 is zero sequence current.
k is a residual compensation factor.

4.1.1 SYSTEM MODEL

The model consists of a synchronous machine (generator) 500 MVA operating at 20 kV line to line rating voltage, 500 MVA transformer connected D/Y, primary 20 kV, secondary 400 kV, three phase 400 kV, 50 Hz power system and 150 km transmission line are splatted to three 50 km lines connected between three buses as shown in figure 4.1.1.



Obr. 4.1.1: The power system model in MATLAB simulation

4.1.2 THREE PHASE FAULT IN QUADRILATERAL DISTANCE RELAY

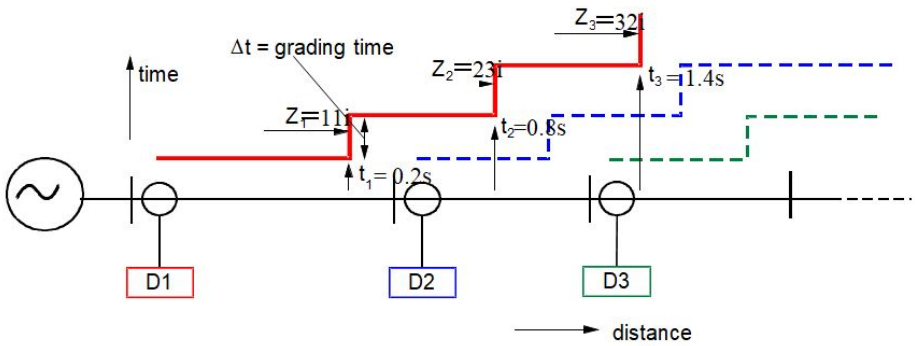
Traditionally, the distance relay zones have been set according to simple rules. The non-traditional options can be grouped according to their conceptual basics: based on expert systems, mathematical optimization, adaptive protection or probabilistic methods [7,9]. The final stage of the model is to develop the quadrilateral characteristics of the distance relay. This step helps to understand and figure out how the distance relay works. Three phase faults were set at distance 35 km, 70 km, and 110 km to check the behavior of quadrilateral characteristics distance relay of this type of near to generator fault. The most important thing to excess distance protection to clear faults immediately which can reduce the negative influence of the fault on the substation devices. Analog input module is a filter and processes the secondary currents and voltages which supplies distance protection relay then analog input module provides immediate sampled values to the internal digital bus. After that inputs of protection can be taken from outputs of the measurement elements [10].
Quadrilateral characteristics with their availability to be increased only in one direction (R

or X) are used to overcome the problem of high resistance fault. For each stage of distance relay, the characteristics can be extended only in R direction with a fixed X setting [11].

- The criterion used for zone 1 reactive reach. The first criterion states that zone 1 only has to operate for faults on the line since this zone is instantaneous. Zone 1 should not operate for faults at the remote bus, by selectivity. Zone 1 reactive reach ($XR1$) will be set to 80% of the reactance of the protected line ($XL+$): $XR1 =$ 80%XL+.

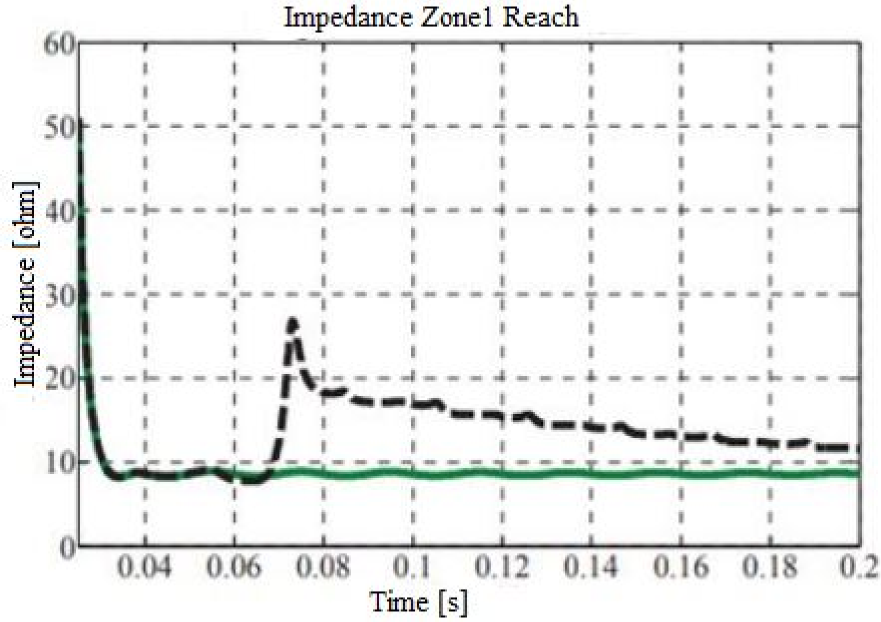
- The criterion used for zone 2 reactive reach. It will be considered that the main objective of zone 2 is to cover the sector of the line that is not covered by the zone 1. This implies that the reactive reach should be set to cover more than 100% of the protected line impedance, in order to guaranty sensitivity for internal faults.

- The criterion used for zone 3 reactive reach. It will be assumed that the main objective of zone 3 is to operate as backup protection for faults in adjacent lines, however, selectivity between zones 3 of different lines will have priority because zone 3 is the faster backup function.

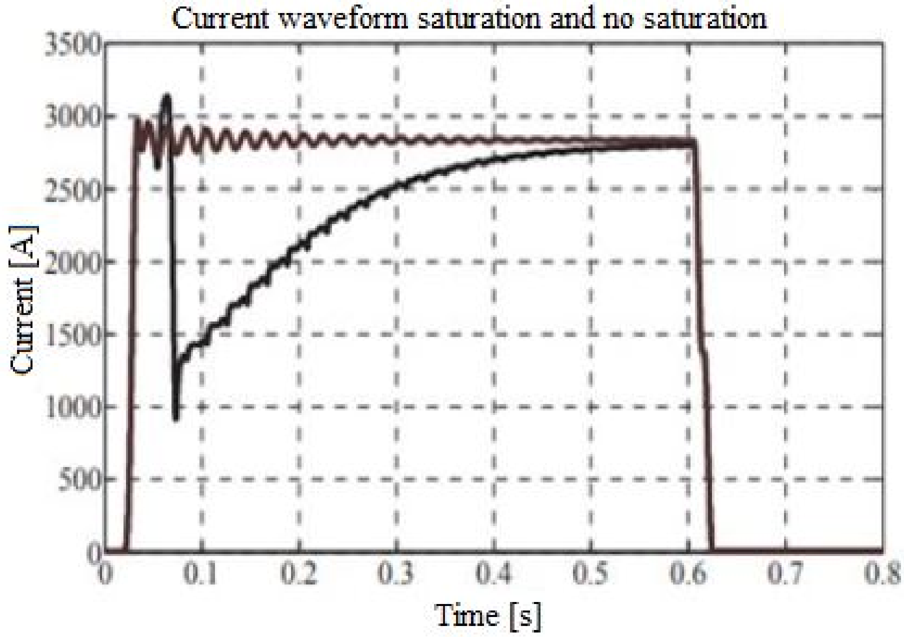


Obr. 4.1.2: Grading time of relay zones

Discrete Fourier Transform (DFT) is used to obtain magnitude and phase components in the time domain of input signal. The Fourier block can programed to calculate the magnitude and phase of the fundamental, the DC component and any harmonic component of the input signal. As shown in figure 4.1.3 green line it's the impedance without saturation and black one the impedance with saturation.
The Fourier block is used to extract the fundamental frequency components from the distorted fault signals by eliminating decaying DC components. Figure 4.1.4 shows the magnitude waveform obtained for current signal with/out saturation. The brown line is the current without saturation and the black one with saturation.



Obr. 4.1.3: Impedance plot for zone 1 reach



Obr. 4.1.4: Current signal magnitude from FFT

Chapter 5

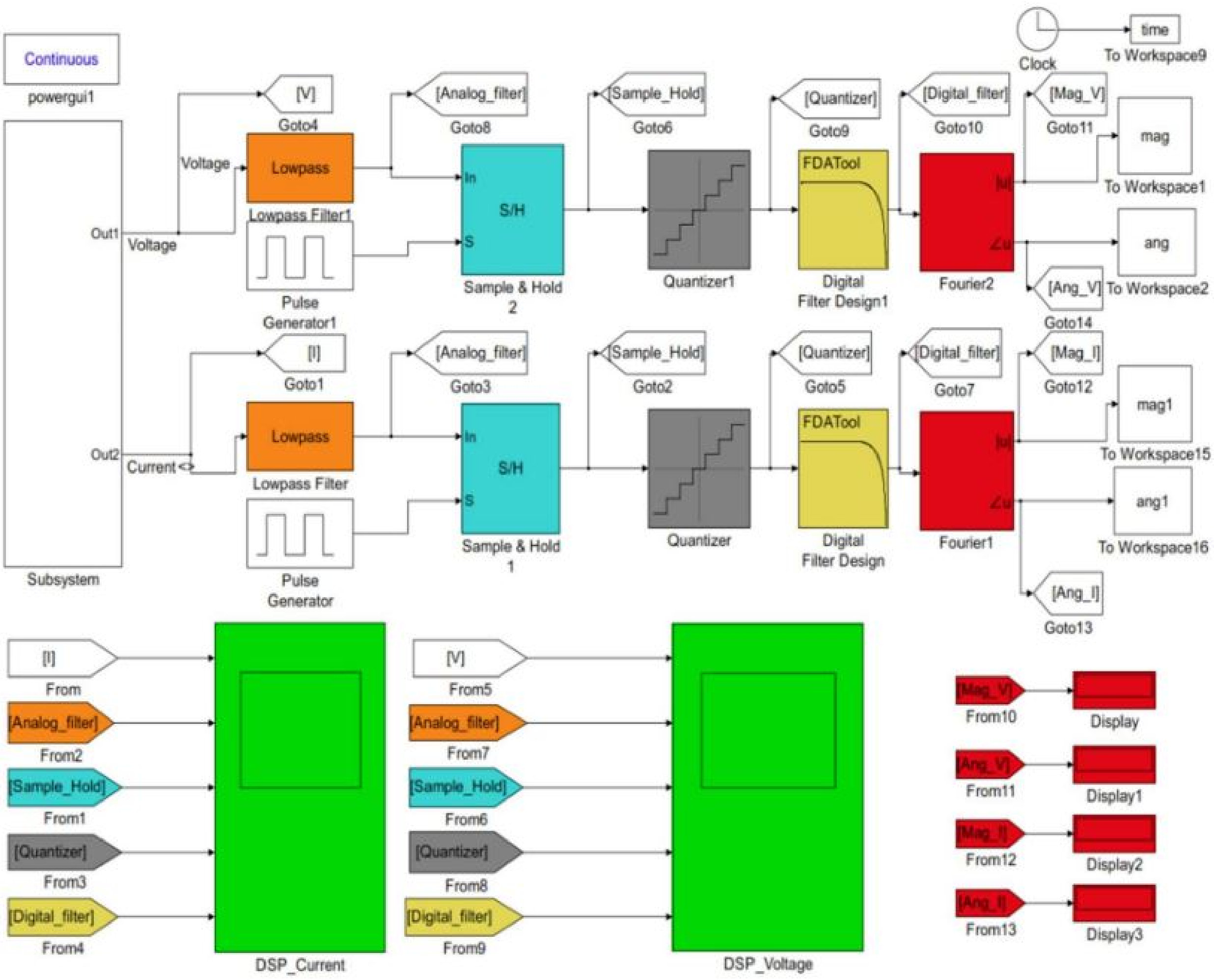
EVALUATION OF HARMONICS IMPACT ON DIGITAL RELAYS

This chapter explains part of the digital signal processing in a power system. Moreover, the chapter provides different methods to compare the relay algorithm which can be used in a power system based on the impact of harmonics once they are injected in high values. The implementation of the test requires analyzing the occurrence of events in the power system. Each event contained in the input signals can be imported to MATLAB via a Comtrade reader which reads the selected event. Digital relays are limited because they can only respond to changes in the magnitude of the fundamental current or voltage. Regarding overcurrent relays, a low level of harmonic distortion may not affect their operation, however, concerning distance relays, while the relay's ability to find faults away from zone's limit may still be reliable, when it comes to faults located near the limit of the zone, there is a possibility for the distance relay to be misguided as to the location of the fault.
Protective relays implement different techniques to measure the current and voltage. The microprocessor relays use a digital filter to take out the fundamental component. Filtering techniques were developed to accommodate a wide variety of harmonic influences. Antialiasing provides the ability to remove the frequencies higher than the Nyquist frequency; filter techniques should be implemented to reduce the harmonic level from the power system measurements.

5.1 DESCRIPTION OF MATHEMATICAL MODEL

The model is a suggested method of processing the voltage and current signals similar to the process that takes place in relays, precisely for the frequency variations and the number of samples per cycle. To ensure the validity of the test for this model, a comparison was made between the output of the model and the output of the physical relay located in the laboratory. The simulator generated signals for the voltage and current of a single phase fault (a short circuit) with the accompanying of these signals. These signals have been sent to the physical relay and have been recorded and changed the format to Comtrade (Common Format for Transient Data Exchange for power systems); after that the signals have been sent to the model. Comtrade is a file format for status data related to a transient power system and storing signals. In addition to blocks that simulate these physical elements, the model also contains a display and calculation blocks for graphic representation of the results of simulated scenarios. The model presents the simulation and modeling of communication based digital relay using MATLAB, the model tested under abnormal conditions (short circuit) and under various fault types, the parameters of the derived model is based on the physical relay. The behavior of the model can be monitored and compared with the real

protection relay by using the enerlyzer in omicron which can able to record voltage and current signals. The model reads the recorded signals by using Comtrade reader and the model offers the analysis of signals as shown in figure 5.1.1.
The model designed in the MATLAB Simulink programming environment (figure 5.1.1) using elements of the SimPower Systems library. The first step is to get the current and voltage signals from the current and voltage transformer sides and apply some functions to them. The digital processing signal is the process of modifying a signal to improve the performance of the relay, to eliminate the high frequency components, and to avoid the phenomenon of the aliasing from a fault signal; low pass antialiasing analog filters with suitable cutoff frequency are used. Holding and sampling the signal is the second block of the signal process which converts the analog signal to the sample. The quantizer converts the smooth signal into a stair step output. Fast fourier transform (FFT) is a faster version of the discrete fourier transform (DFT) which is used to find the fundamental frequency and higher frequencies contained in the input signal [12,13].



Obr. 5.1.1: Model for current/voltage signal processing (DSP)

subsectionFOURIER BLOCK The fourier block offers the calculation the amplitude and phase of the input signal (current and voltage), total harmonic distortion. The block offers analysis of the signal components as a percentage of the fundamental signal.

- Recall that a signal *f(t)* can be expressed by a Fourier series of the form:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n cos(nwt) + b_n sin(nwt) \tag{5.1.1}$$

- where n represents the rank of the harmonics. ($n = 1$ corresponds to the fundamental component). The magnitude and phase of the selected harmonic component are calculated by these equations:

$$\mid H_n \mid = \sqrt[2]{a_n^2 + b_n^2} \tag{5.1.2}$$

where

$$a_n = \frac{2}{T}\int_{t-T}^{t} f(t)cos(nwt)dt \tag{5.1.3}$$

$$b_n = \frac{2}{T}\int_{t-T}^{t} f(t)sin(nwt)dt \tag{5.1.4}$$

$$T = \frac{1}{f_1} \tag{5.1.5}$$

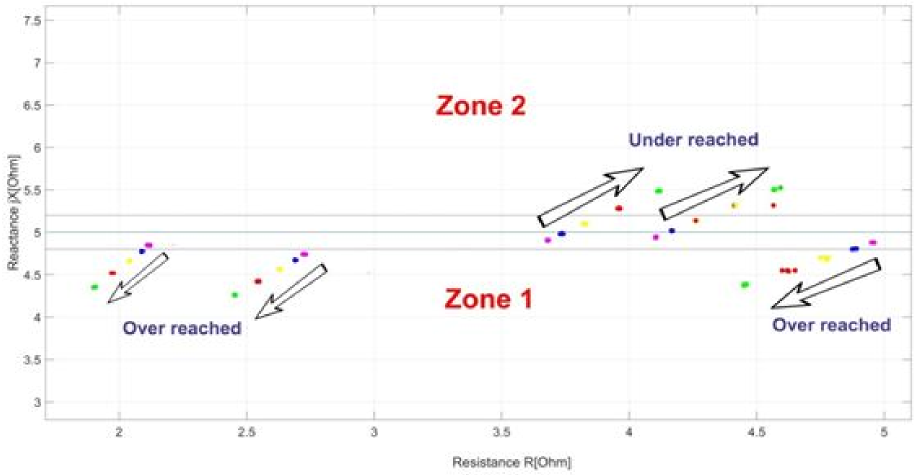
f_1: Fundamental frequency.

5.2 RELAY REPORT AND SIMULINK RESULT

The test was conducted at five different fault points and a total harmonic distortion was added to each of these tests. The total harmonic distortion on the current wave added at two points (the arrow direction up) is called an overreach, and the total harmonic distortion was added to the voltage wave at three points, as shown in figure 5.2.1. The total harmonic distortion was added as a percentage of the fundamental signal as follows: 10%, 20%, 30%, 40%, and 50%, and was colored in the following colors, respectively (violet, blue, yellow, red, and green).
Overreach and under-reach of protection relays are common problems in power systems; they cause a maloperation of the protection relays and it is impossible to detect the fault in the correct zone. The overreach of the point of the fault can cause the protection relay to send a maltrip signal, which means that the relay instead of a trip in a delayed time zone 2 will send the tripping signal in zone 1, which is not desired. A harmonic distortion can change the power factor which leads to a change in the measured impedance lower than the actual value. The overreach can be noticed from a distorted voltage waveform, as shown in figure 5.2.1, due to the lagging power factor. Conversely, an under-reach of the point of fault can cause the change of protection relay and the decision to send a maltrip signal; it means that the relay instead of a trip at a delayed time zone 1 will send a tripping signal at zone 2, which is not desired, as shown in figure 5.2.1.

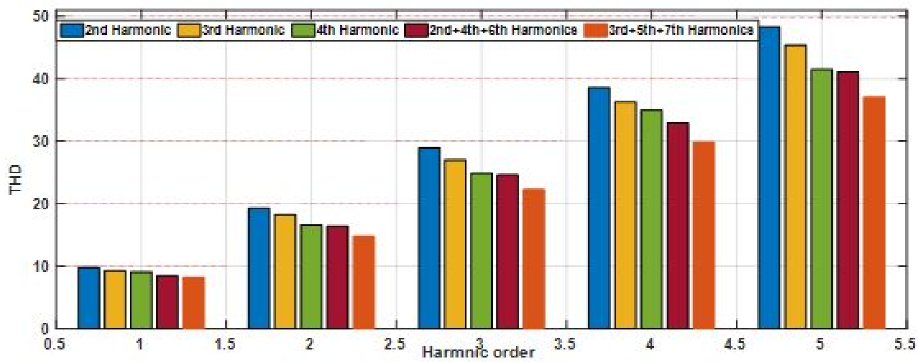
5.3 TOTAL HARMONIC DISTORTION DETECTION IN PHYSICAL RELAY AND MATLAB MODEL

Through the test, the results show that the commercial relay of the harmonic capture ratio is lower than the original harmonic value. The total harmonic distortion is 10%, 20%, 30%, 40%, and 50% of the current signal according to the relay report. Figure 5.3.1 shows the harmonic measurements in a commercial relay. The second, third, and fourth harmonics were added as well as the three harmonics combined (2nd, 4th, 6th) and were added to the 3rd, 5th, and 7th harmonics. We can conclude that the commercial relay measures the THD with a difference of up to 35%, especially when there are three harmonics combined in



Obr. 5.2.1: Quadrilateral characteristic and measured fault impedance locus

the input signal, as shown in figure 5.3.1. The digital relays start function when abnormal conditions occurred as faults. Abnormal events are accompanied by harmonics which are combined with the current and voltage signals.



Obr. 5.3.1: Commercial relay measurement of THD

Figure 5.3.1 shows the measurement of THD in a commercial relay. A harmonic measurement evaluates the error of calculation, and the calculation method described above applies to the steady state fault conditions. The measurements of the third harmonic showed that the error of calculation in the commercial relay increased according to the harmonic percentage of the signal. The error of the calculation of the third harmonic is ca. 7% when the percentage of harmonic is 0–10%. After that, the error of the calculation of the third harmonic is stabilized to 10% when the percentage of harmonic is 10–50%. The highest error of the calculation of the THD can be found in mixed harmonics, as shown in table 5.3.1 and table 5.3.2.
The THD for mixed 3rd, 5th, and 7th harmonics is ca. 10–20% when the harmonic content is 0–10%. After that, the error of the calculation of THD for mixed 3rd, 5th, and 7th harmonics are stabilized to 33% when the percentage of harmonic is 10–50%.

Figure 5.3.2 shows the measurement of THD in the model. The harmonic measurements evaluate the error of calculation. The measurements of the third harmonic show that the error of the calculation in the model is increasing according to the harmonic percentage of the signal and the error of the calculation of the third harmonic is ca. 1% when the harmonic percentage is 0–10%. After that, the error of the calculation of the third harmonic

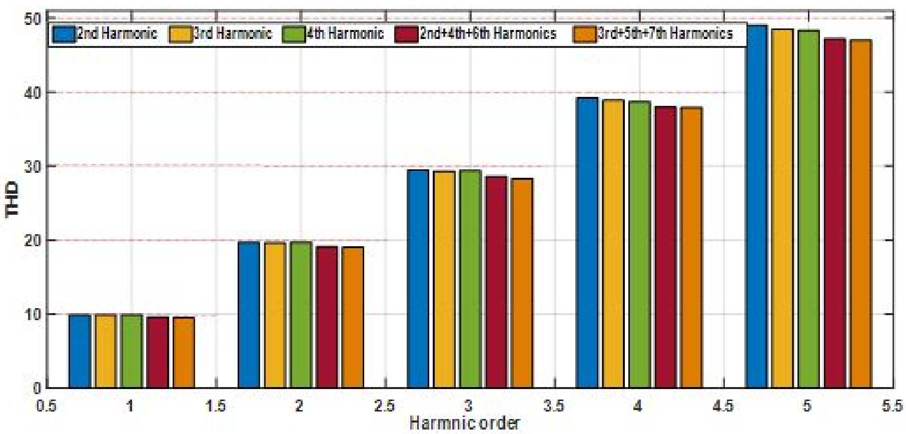
Table 5.3.1: The error of calculation THD for commercial relay

THD	10%	20%	30%	40%	50%
2^{nd}harmonic	2.04	3.62	3.45	3.62	3.52
3^{rd}harmonic	7.526	9.89	10.29	10.19	10.13
4^{th}harmonic	9.89	20.48	20.48	14.28	20.48
$2^{nd}+4^{th}+6^{th}$harmonics	17.56	21.95	21.95	21.58	21.65
$3^{rd}+5^{th}+7^{th}$harmonics	21.95	35.3.1	34.53	34.22	34.77

Table 5.3.2: The error of calculation THD for MATLAB model

THD	10%	20%	30%	40%	50%
2^{nd}harmonic	1	1.52	1.69	2.04	2.04
3^{rd}harmonic	2.045	2.38	2.74	2.827	3.092
4^{th}harmonic	1.01	1.522	2.739	3.359	3.519
$2^{nd}+4^{th}+6^{th}$harmonics	4.16	4.712	4.89	5.26	5.932
$3^{rd}+5^{th}+7^{th}$harmonics	5.266	5.263	6	6.1	6.38

is stabilized to 2% when the harmonic percentage is 10–50%. The highest error in the calculation of THD can be found in mixed harmonics, as shown in figure 5.14 and in table 5.3.2; the THD for the 3rd + 5th + 7th harmonics is around 1–2% when the harmonic percentage is 0–10%. After that, the error in the calculation of the THD for the 3rd + 5th + 7th harmonics is stabilized to 3% when the harmonic percentage is 10–50%.



Obr. 5.3.2: Model measurements of THD

Chapter 6

ANALYSIS OF IEC 61850-9-2LE MEASURED VALUES USING A NEURAL NETWORK

This chapter is all about the analysis of IEC 61850-9-2LE measured value using a natural network. In the substation devices the data is being used for multiple purposes and this data can be measured through intelligent electronic devices. This chapter is divided into multiple sections including time synchronization section, sampled values section, timing analysis of sampled values streams section, GOOSE (generic object oriented substation events) section and the last is machine learning section.

The main goals to implement IEC 61850 are to increase power quality, reduce the copper wire, providing the interoperability, reducing the cost of operation and maintenance, secure and fast data transmission and flexible functionality. To create a better environment to implement IEC some parts of the substation should be replaced as well as to make the huge amount of real time data processing easier. To implement the distribution function there are three rules to follow first of all is the IEC configuration should follow the performance requirements, the communication interface between IEDs and the system should follow the IEC 61850 standard communication fundamentals and the last one is that the establishment of communication between devices by mean transfer data between IEDs and the power system among the SAS. There are some features offered by IEC 61850 which includes the data characterization, communication specifications and the most important is the data structures and the data objects' services.
The specifications of IEC 61850 can be summarized as the definition and determine how to access the data structure, standardizing the output data categorized the sharing of data and the communication implementation of IED and network by using eXtendable Markup Language (XML). This chapter also explains in detail the IEC 61850 information system. There are four main object structures which are Data, Attribute, Logical Nodes and Logical Devices. The time synchronization is an important element in sampled value applications due to the problem that can be caused in case of time synchronization is lost. The relation between the time synchronization and sampled values is called SmpSynch. It gives details about the time source (GPS) and the sampled values source (IED publisher).
Peer to peer (PTP) protocol is also explained in this chapter, this is actually defined as the time synchronized is required to get more accurate measurements and implement PTP protocol. The GPS sends three massages to synchronize the devices these are announce message, synch message and follow up message. The IEC 61850 includes three stages for sampled value testing. First is to send sampled measured values, second is to convert analogue into digital and the third one is to check the values in the software named

SVScout. Simulation of the merging units of the IED publisher is the main task performed for sampled value testing. The software is used for the visualization of sampled values. It can receive, view, process and save sampled values.

This chapter examines the IEC 61850-9-2 standard based on the sampled measured values. It provides different methods to compare the timing analysis between the merging unit of physical protection relay (IED) that converts the current and voltage signals from the conventional transformers into a digital signal and shares it with sampling frequency (4000 samples/second) and the simulated merging unit of an Omicron 256 CMC that is used to publish SMV to the physical relay (IED-subscriber). The implementation and configuration of the test requires two IEDs are applicable to sending and receiving SMV and GOOSE messages according to standard IEC 61850. Modern IEDs are able to publish four current signals and four voltage signals and share the voltage in the power system. GPS is used to synchronize the time and keep all the devices in the same time and without phase offset. In summary, we can conclude the following from the experiments above:

- The IED-subscriber starts to send sampled measured values once the global clock is applied (GPS-time synchronization), conversely, IED-subscriber does not send or publish SMV once the internal clock is applied from the publisher IED.

- The interval time between the samples is 250 μs according to the IEC 61850 standard, and the network analysis tool shows that four MAC addresses are available, in this case (CMC-publisher, IED-publisher- 2x IED-Subscriber) with time synchronization is applied, however, the interval time is around 240 μs with the local clock of the publisher IED or CMC merging unit, and the interval time is around 230 μs with the global clock (GPS) applied.

- The number of samples per millisecond of IED-publisher: the number of packets is not constant, the range was between 3 to 5 packets/ms, while with CMC-publisher: the number of packets is almost constant at 5 packets/ms.

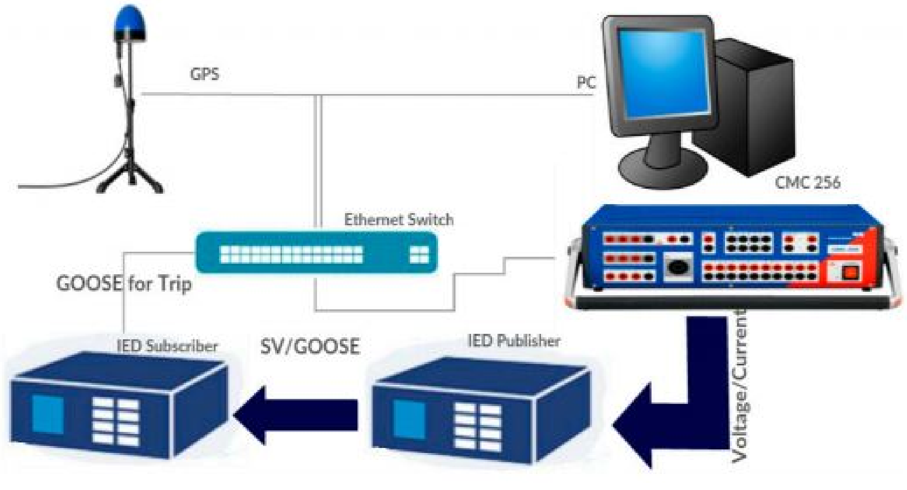
- GOOSE message configuration is implemented to the IEDs (sender-receiver), the GOOSE message is sent to the receiver IED (tripping signal), the signal is duplicated four times with a size of 147 bytes per packet, the average interval time between the packets was practically constant from the first to the fourth packets (278 μs) and the average interval between the fourth and the fifth packet was 102 milliseconds.

- IED-subscriber is subscribing the SMV from the IED-publisher and CMC-publisher equally, IED-subscriber is unable to recognize who is the publisher of the SMV (IED or CMC) due to the fact the CMC-publisher has the same dataset as the IED-publisher (that is, in fact, what happened when CMC-publisher was simulating the IED-publisher). Wherefore, a model is applied to predict if the IED-subscriber would recognize which merging unit is sending the sampled values based on different attributes, to implement the approach, train a classifier using different models and measure the accuracy and compare models, using the classifier for prediction. The preparation data includes two parameters (number of samples/ms - interval time between the packets) for each publisher of SMV (IED or CMC). By using neural net pattern recognition that solves the pattern recognition problem using two layer feed networks (nprtool), the inputs and the target provided to the network and the algorithm break up the data into test sets (training 70%- validation 15%- testing 15%), and the best validation was in the 23rd epoch.

- This method can be used for optimization of testing procedures in substations where IEC 61850-9-2LE are implemented. This method can be used for shorter test preparation, to lower the cost and help support research projects since it allows one to implement better platform and services as well as to integrate different communication protocols when necessary.

6.1 TIME SYNCHRONIZATION OVER A PROCESS BUS

Time synchronization is an important element in sampled value applications due to the problems that can be caused in case the time synchronization is lost due to phase shifts, maloperation or wrong tripping. In the laboratory during implementation the SMV IEDs configuration, the time synchronization can be done by the IEDs- publisher. In this way the IED-subscriber will follow and get the same phase error limit. In case of using several merging units connected together and sharing data among the power system, the time source according to IEC 61869 is required. This time source will be a global area clock, however, a local area clock cannot match the time in the global area clock. There are various methods that can be implemented to achieve the time synchronization in the whole testing system and between the merging units such as master slave architecture for clock distribution (IEEE 1588) precision time protocol (PTP). IEEE 1588 is used to achieve the time synchronization because the IEDs are adaptable to this method and offered high accuracy time synchronization. According to IEC 61869, the GPS or time source is sharing the time over the process bus side by side with sampled values. The configuration of the time synchronization of IEDs is shown in figure 6.1.1. In IEDs, time synchronization is enabled by using synch source (IEEE 1588—slave), IED-subscriber (figure 6.1.1) shows a synch accuracy of 23 ns. More precisely, the sampled values and PTP are using the same.



Obr. 6.1.1: The full scheme of testing the IEC 61850 (SMV-GOOSE)

PTP CLOCK TYPES IN TIME SYNCHRONIZATION

The time synchronized is required to get more accurate measurements and implement the Peer to Peer (PTP) protocol. Grandmaster is synchronized with an external source such as a CMGPS 588 (GPS) controlled time reference. The synchronization unit is an antenna integrated GPS that works as PTP grandmaster clock according to IEEE 1588. Ordinary clock reads can be performed from IEDs or CMC 256 plus. This test requires an advanced Ethernet switch (Hirschmann). Table 6.1.1 lists the GPS status and the timing protocol that was implemented during the experiments (the synch interval between two synchronized messages is 1 s, and announcing the timeout and losing the time synchronization takes 3 s.

Table 6.1.1: PTP time synchronization and settings

CMCGPS 588	CMCGPS 588)	Time Interval	Time Interval
GPS	Locked	Sync interval	1 s
PTP	Master	Announce interval	1 s
NTP	Synchronized	Announce receipt timeout	3 s
Satellites usable	4	Peer mean path delay	85 ns

The GPS sends three messages to synchronize the devices (announce message, synch message and follow up message) and it duplicates them each second, in order to keep all IEDs synchronized as shown in figure 6.1.2.

Obr. 6.1.2: The measured interval time between synchronization announcement messages

6.2 THE TIMING ANALYSIS OF SAMPLED VALUES STREAMS

In order to understand the data acquisition of sampled values, the comparison of sampled values between IED_MU and CMC_MU with no time synchronization of the CMC 256, the measurements of the merging unit are implemented in the laboratory, the CMC 256 is configured to publish the sampled values to simulate the merging unit of the IED merging unit by importing the SCL file of the IED-publisher, thus, the CMC Omicron provides the ability to publish the sampled values and the comparison with the IED merging unite offering a way to analyze the time as shown in figure 6.9. The interval between two packets can be calculated as T = 1/4000 = 250 ms, more than that, the delay time is accompanied by the interval as shown in table 6.2.1. The IED-publisher publishes the sampled values and the time synchronized as the local clock (master clock) of the publisher IED [14].

Table 6.2.1: Time display and time references

Frame Size [bytes]	Round Trip Latency [μs]
128	241
256	292
512	426
1280	645

6.3 MACHINE LEARNING

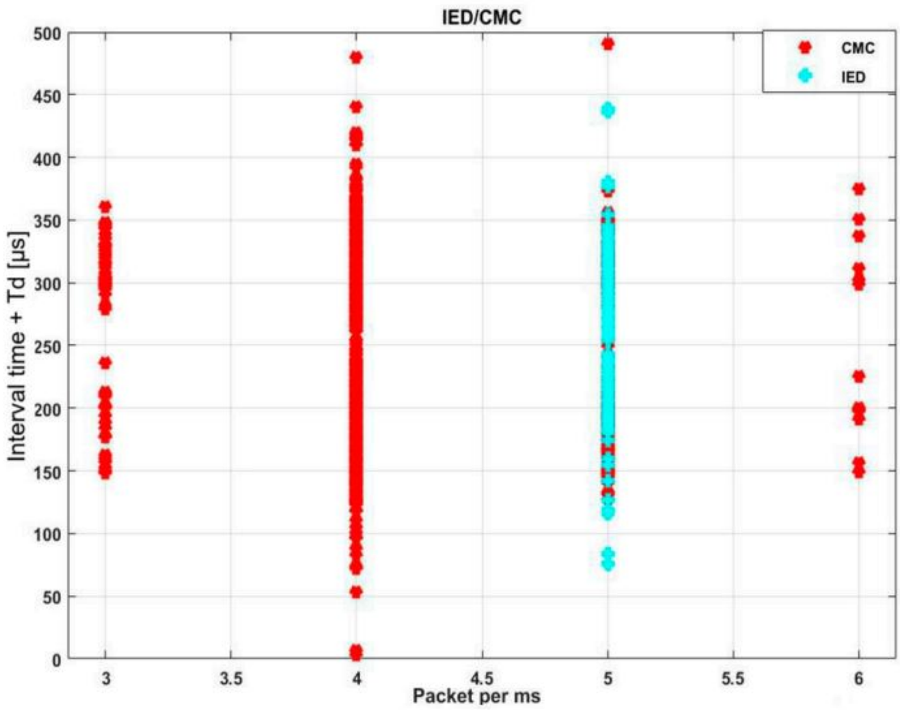
Machine learning techniques are used for power quantity analysis and decision making tasks (accurate forecasting, comparing different machine learning techniques). The data description of the model can be summarized by the IED merging unit and CMC merging unit. A Substation Configuration Language (SCL) file is exported from the IED-publisher to CMC, the data set of the model contains two parameters (interval time between packets, the number of packets per ms), the goal is to find the link between the number of samples and interval time and determine which merging unit is sending the SMV and help the subscriber IED to figure out the correct sender of sampled values. The parameters of both merging units are captured by the network protocol analysis; in figure 6.3.1 and in table 6.3.1 data preparation is added to show the link between the input parameters and the sender of sampled values. The main goal of this test was to determine the source of the sampled values streams.

Table 6.3.1: Data preparation and input array size

Input		Target_Output	
Parameter	IED_Publisher	CMC_ Simulated	IED_Subscriber
4000 × 1	(4000 × 1)	IED	
Number of samples per ms	4000 × 1	4000 × 1	CMC

A few points noticed during the test of sampled values:

- IED-subscriber took time to determine the publisher merging unit, and a delay time to recognize the publisher side. Practical implementation showed that the simulated merging unit of the IED could not subscribe immediately.
- The number of samples is the first input parameter for data preparation; each merging unit includes a number of samples per second.
- Interval time between packets used in this test is the second input parameter for data preparation.
- Measurement of the merging units showed that the quick response of the merging unit subscriber is important in IEC 61850. The data link layer (layer 2) is a lower level addressing structure to be used between end systems and concerned with forwarding packets based on layer addressing scheme and the MAC address of the destination.
- The interval time and the number of samples are parameters used as inputs for this test, using relay protection merging unit and CMC merging unit data to feed the training set and test set.
- By using neural net pattern recognition, we could find the relation between the inputs (number of samples/ms—interval time between the packets) and the source of the data.



Obr. 6.3.1: Data preparation of parameters

- By using this technique, technicians can save time and ensure they are testing the correct merging unit.
- According to our test the subscriber protection relay takes time to respond to the new traffic of sampled values.

The original dataset was divided into test and validation sets. With these settings, the input vectors and targets vectors are randomly divided into three sets as follows:

- The training set is 70%.
- The validation set is 15% to prove that the network stops training before overfitting.
- The testing set is 15% and is used as an independent test of network generalization [15].

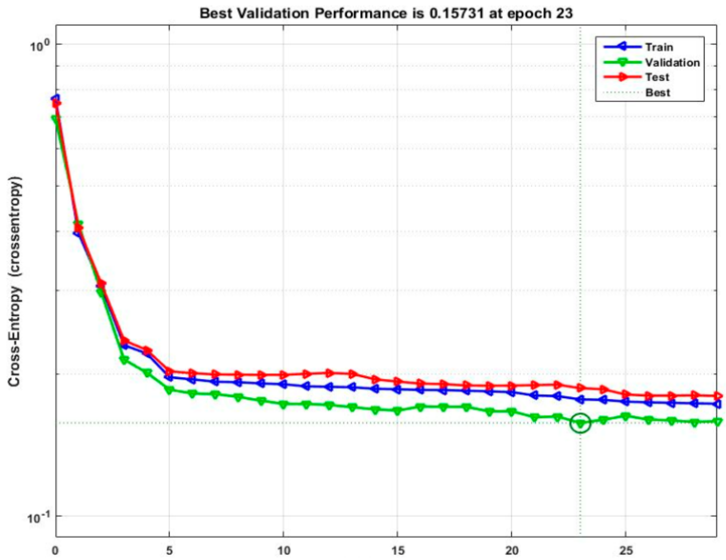
A two layers feedforward network is included in the standard network that is used for pattern recognition, with a sigmoid transfer function in the hidden layer and a softmax transfer function in the output layer. MATLAB uses 10 hidden neurons as the default set, and the number of output neurons is set to 2. Table 6.3.2 shows the number of samples for each merging unit and the test split of the input samples into training and test sets accordingly.

Table 6.3.2: Training set and test set

Training Set			Test Set		
Value	Count	Precent	Value	Count	Precent
CMC	2379	49.55%	CMC	1621	50.66%
IED	2422	50.4%	IED	1579	49.34%

Figure 6.3.2 shows the best validation performance of the network. The plot is used to obtain a plot of training record error values against the number of training epochs, eventually,

the error of training decreases after more epochs and retraining, and the best performance is taken from the epoch (epoch 23) with the lowest validation error.



Obr. 6.3.2: The best validation performance at epoch 23, validation error at the lowest point

Chapter 7

IEC 61850 9-2 LE SAMPLED VALUES TOOL USING MATLAB SOFTWARE

This chapter focuses on a real time application that subscribes the data stream coming from a station near protection laboratory in Brno Unversity of Technology. IEC 61850-9-2 LE SMs are used to transmit the traffic to university laboratory with 16 km of fiber optic cable. The application built using MATLAB and can read the traffic from the ethernet port, the traffic decoded and convert from ASCII to the decimal numbers then draw the current and voltage values. The application developed without using any need for additional hardware, the requirements are the ethernet port RJ45 from the station and pc that is running MATLAB. The benefits and features of the application, easy to use, ability to implement all the distance protection functions, calculation the RMS values of the voltage and current, harmonic distortion, the harmonic components with FTT analysis, distance protection characteristics and fault impedance calculation. All calculations implemented in real time, moreover, in this chapter include sensitivity analysis of MATLAB model in previous chapters. Distance protection functions which discussed in this thesis used the offline model of MATLAB or captured with Comtrade format files. In this chapter will evaluate the protection functions with real time stream from the substation, the application includes the following features:

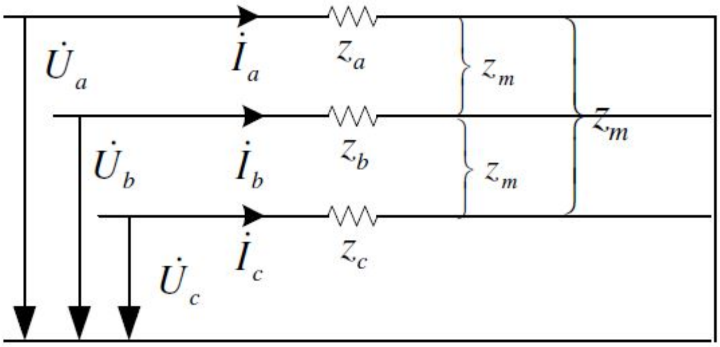
- Instances of voltage and current measurement.
- Harmonic components.
- Fault detection and fault impdance calculations.
- Mho characteristics plot for each type of faults.

7.1 BUILDING GRAPHICAL USER INTERFACE

The final stage of the project is to develop the GUI for the finished model. After completed, this GUI will become an educational tool for the students in enhancing their understanding of distance relay characteristic. This GUI was developed using MATLAB which includes the protection functions (harmonic distortion of the received sampled values traffic from substation using FTT), voltage and current RMS, in output session divided into fault detection (line to ground fault, a line to line fault), frame size (500-4000) frames, network adapter choose the mac address to subscribe the traffic. The second page includes the impedance calculation according to the IEC 61850 9-2 LE such as line parameters (*tx* line length, positive sequence resistance, positive sequence inductance) and impedance plots for each fault type.

7.1.1 RELAY CHARACTERISTICS AND IMPEDANCE DIAGRAM

Line measurement of positive, negative and zero sequence parameters of distribution lines with single inductance used to calculate the fault impedance. For single circuit: In figure



Obr. 7.1.1: The equivalent circuit for single circuit lines

7.1.1, we can get the following equation based on the voltage and current vectors shown as above.

$$\begin{pmatrix} \overline{Ua} \\ \overline{Ub} \\ \overline{Uc} \end{pmatrix} = \begin{pmatrix} \overline{Zaa} & \overline{Zab} & \overline{Zac} \\ \overline{Zab} & \overline{Zbb} & \overline{Zbc} \\ \overline{Zac} & \overline{Zbc} & \overline{Zcc} \end{pmatrix} \begin{pmatrix} \overline{Ia} \\ \overline{Ib} \\ \overline{Ic} \end{pmatrix} \tag{7.1.1}$$

$\overline{Z_{aa}}, \overline{Z_{bb}}, \overline{Z_{cc}}$ is the value of self impedance of three phase respectively. $\overline{Z_{ab}} = \overline{Z_{ba}}$, $\overline{Z_{ac}} = \overline{Z_{ca}}$, $\overline{Z_{bc}} = \overline{Z_{cb}}$ is the mutual impedance between a,b,c phase. (7.4) can be simplified as:

$$\overline{Uabc} = \overline{Zabc} \times \overline{Iabc} \tag{7.1.2}$$

7.1.2 DESCRIPTION OF THE TOOL

It is important to evaluate and test IEC 61850 standard in real time, the real time simulator is expensive and it is not available in every substation, therefore, the need for a cheaper solution came to cheap and affordable application with easy installation and flexible features, nowadays, engineers are using these applications for the industry and educational purposes. The real time simulator commonly used for hardware in the loop testing of protection devices [16].

1. Launch the tool by double clicking the file (SVReceiver.exe).
2. Set the input parameters:
   (a) INPUT General: Here set the (AppID) and the (Network Adapter) fields. The AppID must be in hexadecimal and must match exactly that of the source data stream. Otherwise, no stream will be decoded. To select the right NIC mac address from the (Network Adapter) drop down menu, first, physically connect the source ethernet cable. When you are sure that there's connectivity, then click the (Refresh) button next to the (Network Adapter) input field. At this point, the drop down menu will be populated with the mac addresses of all installed NICs both active and inactive. We can select the MAC which matches the NIC to which the source ethernet cable is connected.

(b) INPUT – Line Parameters: On this tab, set the values of the respective fields. Apart from (Transmission Line Length, Zone 1, Zone 2), the values of the rest of the fields are obtained from the specifications document of the target power line. (Transmission Line Length) is the target protected line length. (Zone 1 , Zone 2) are protection settings.

(c) OUTPUT

i. FAULT DETECTION: When the tool is running and it detects a fault, the indicator(s) light up according to the type of fault detected. The DEA (Differential Equation Algorithm) is the algorithm chosen for this functionality, and it is implemented directly in the c−compiled (svsubscriber.exe) file.

ii. RMS VALUES (MEASUREMENTS): Here the RMS values of the measured instantaneous voltages and currents are displayed in real time.

iii. INSTANTANEOUS MEASUREMENTS: The decoded instantaneous voltage and current values are graphically displayed in real time.

iv. IMPEDANCE CALCULATION PLOTS: The Line to ground and Line to Line impedance, calculated in real time, are displayed graphically.

v. HARMONICS THD: Here the calculated total harmonic distortion (THD) and harmonic contents of the voltage and current are displayed in real time.

3. Click the (Run) button to start running the tool. As it runs, the post processed source payload is displayed in real time.

4. To end the current running session, just click the (Stop) button.

5. If for any reason the source stream is disconnected from the tool while it in (Run) mode, the tool goes into the (idle) mode where the tool is automatically paused after about 1 minute of idle stream activity. When the stream is restored, you can then click (Run) once more to unpause the tool as shown in figure 7.1.2 and figure 7.1.3.

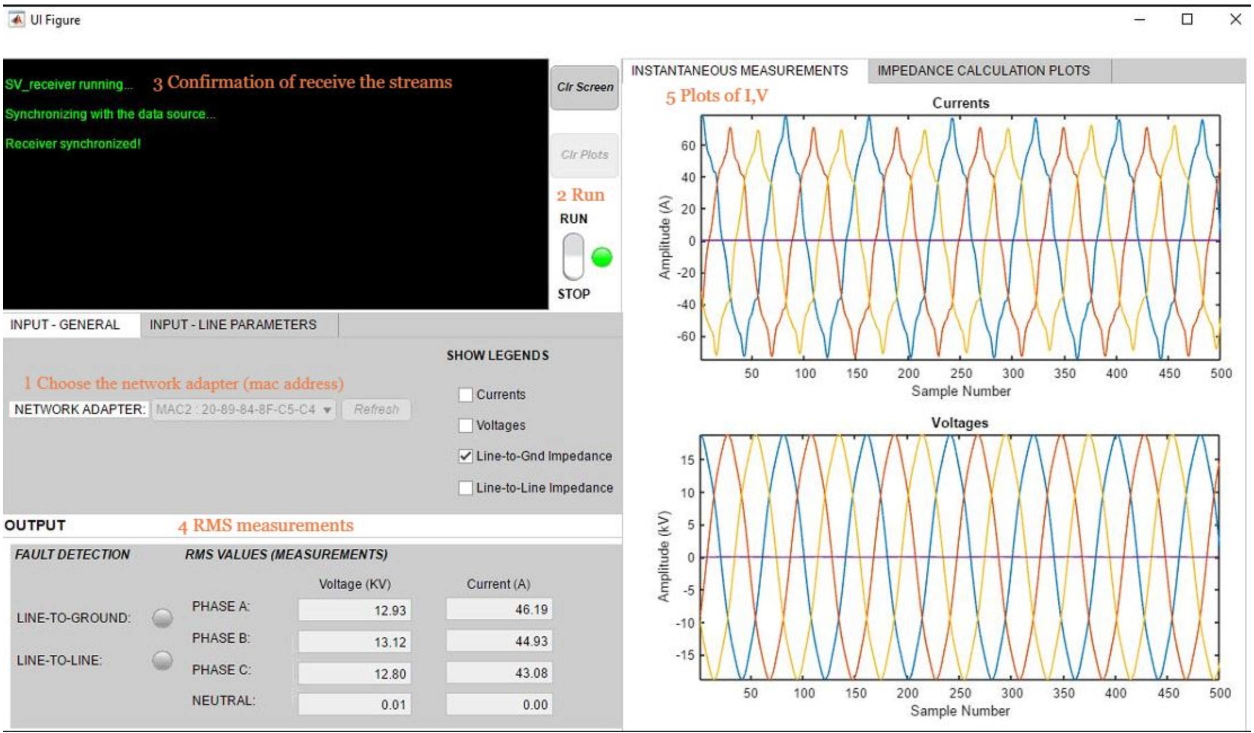
In summary: The tool is developed using MATLAB code to read and subscribe the sampled values from a substation near Brno university of technology according to IEC 61850 9-2 standard. The challenges for developing this tool are the capability to process the sampled values in real time, it has functions (protection characteristics, fault detection, and harmonic components).

7.1.3 IMPEDANCE CALCULATION ALGORITHM FOR MICROPROCESSOR

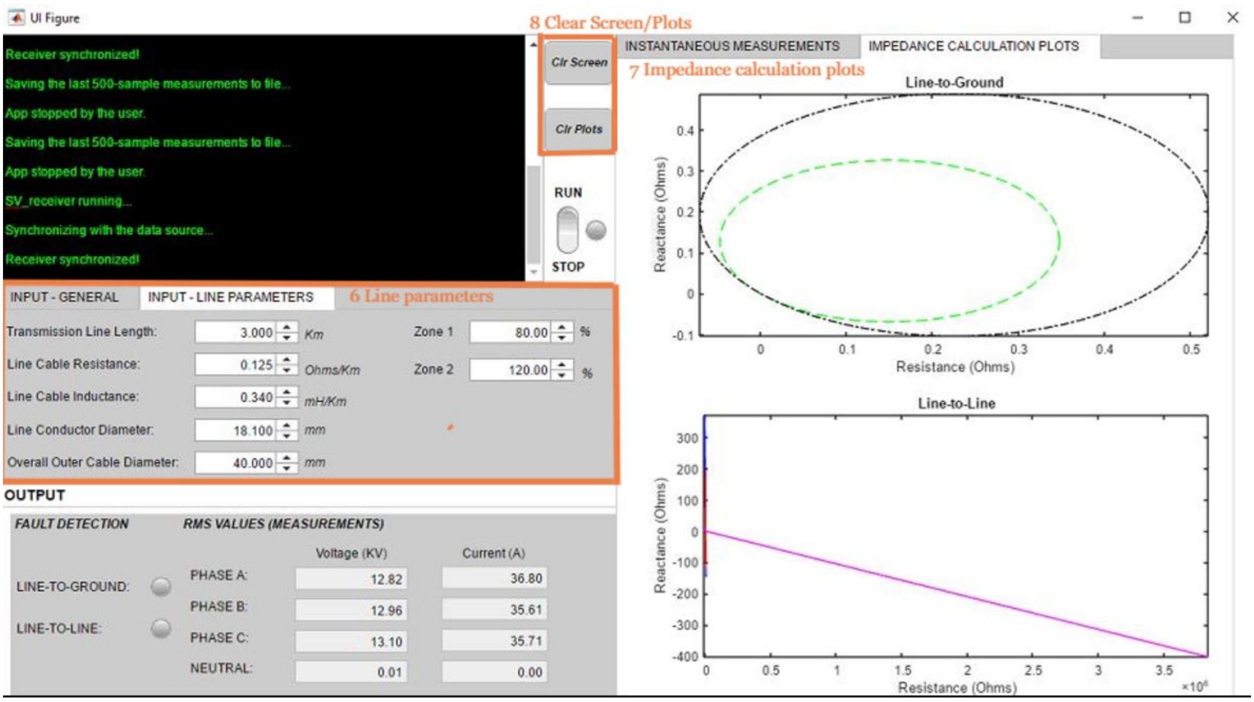
This part explains the used algorithm to calculate the impedance of a transmission line fault in the tool, the impedance is calculated using the differential equation algorithm (DEA) from sampled data. DEA is an alternative method to Fourier transform that can be used to estimate and calculate the fault location and fault impedance. For a fully transposed line it can be assumed that $Lac = Lbc$. Hence, the last term in the previous expression vanishes, giving:

$$V_a - V_b = xR_a(I_a - I_b\frac{R_b}{R_a}) + x(L_a - L_{ab})[((\frac{dI_a}{dt}) + (\frac{L_{ab} - L_b}{L_a - L_{ab}})\frac{dI_b}{dt}])(7.1.3)$$

For a symmetric line, *(Lb - Lab)/(La - Lab)* and *(Rb/Ra)* will be equal to 1 and the



Obr. 7.1.2: Instantaneous current and voltage measurements current and voltage harmonics.



Obr. 7.1.3: Instantaneous current and voltage measurements- Current and voltage harmonics

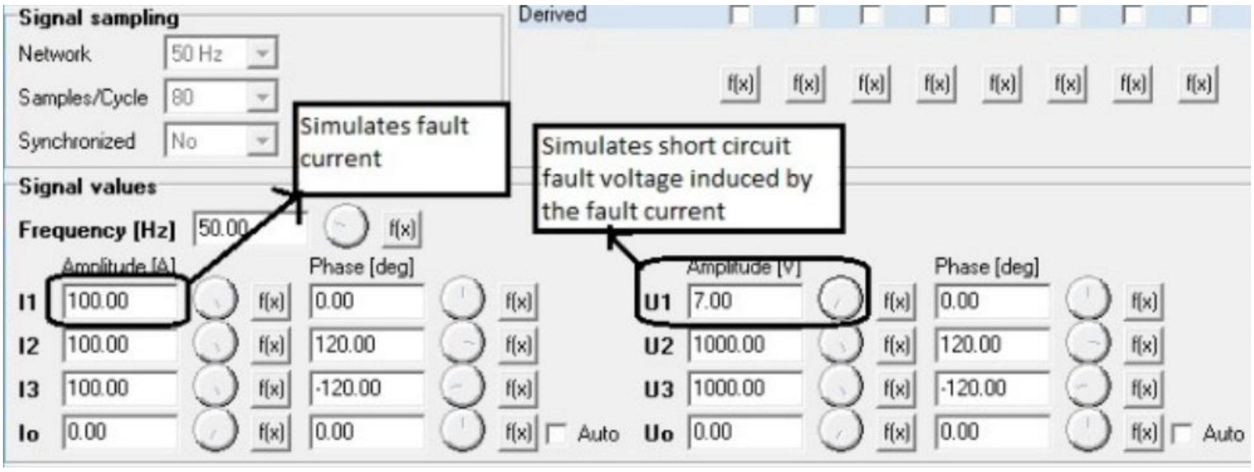
above equation reduces to:

$$V_a - V_b = xR_a(i_a - i_b) + x(L_a - L_{ab})\frac{d(i_a - i_b)}{dt} \tag{7.1.4}$$

The advantage of this method that achieves accurate and efficiency at low voltages, the differential equation algorithm provides flexibility to present the electrical values and simplifies the design of the numerical relay.

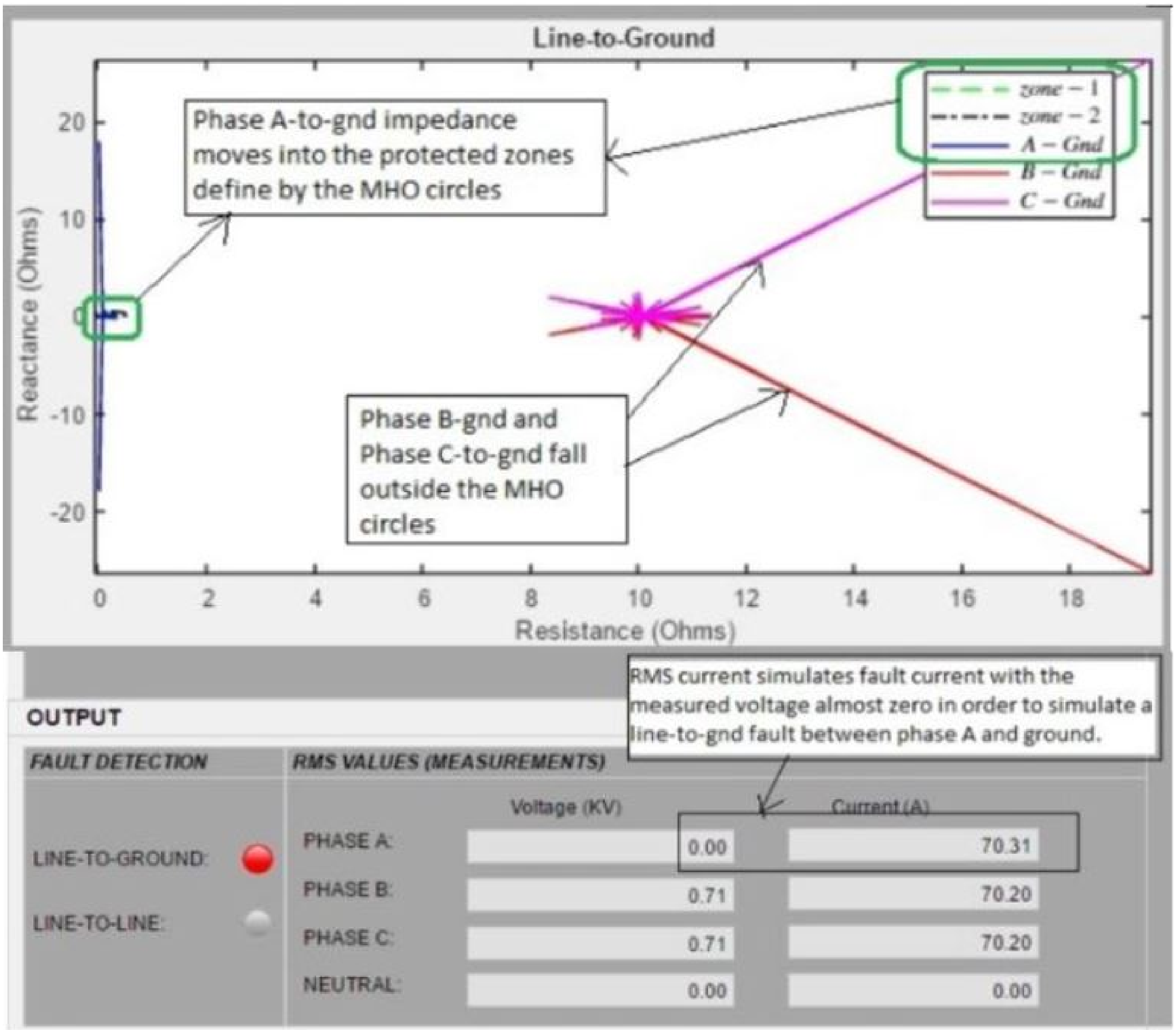
7.1.4 FAULT DETECTION AND IMPEDANCE CALCULATIONS

Evaluation of the tool during the fault, the substation's sampled values streams are healthy and faults are limited to occur, the best way to test the tool is simulated streams that create faults. figure 7.1.4 shows the generated voltage and current signals, to place a fault and test the tool with a single phase with a ground fault. As shown in the figure, the phase 1 voltage dropped. The next step is testing the function of the tool when a fault occurs, due to the

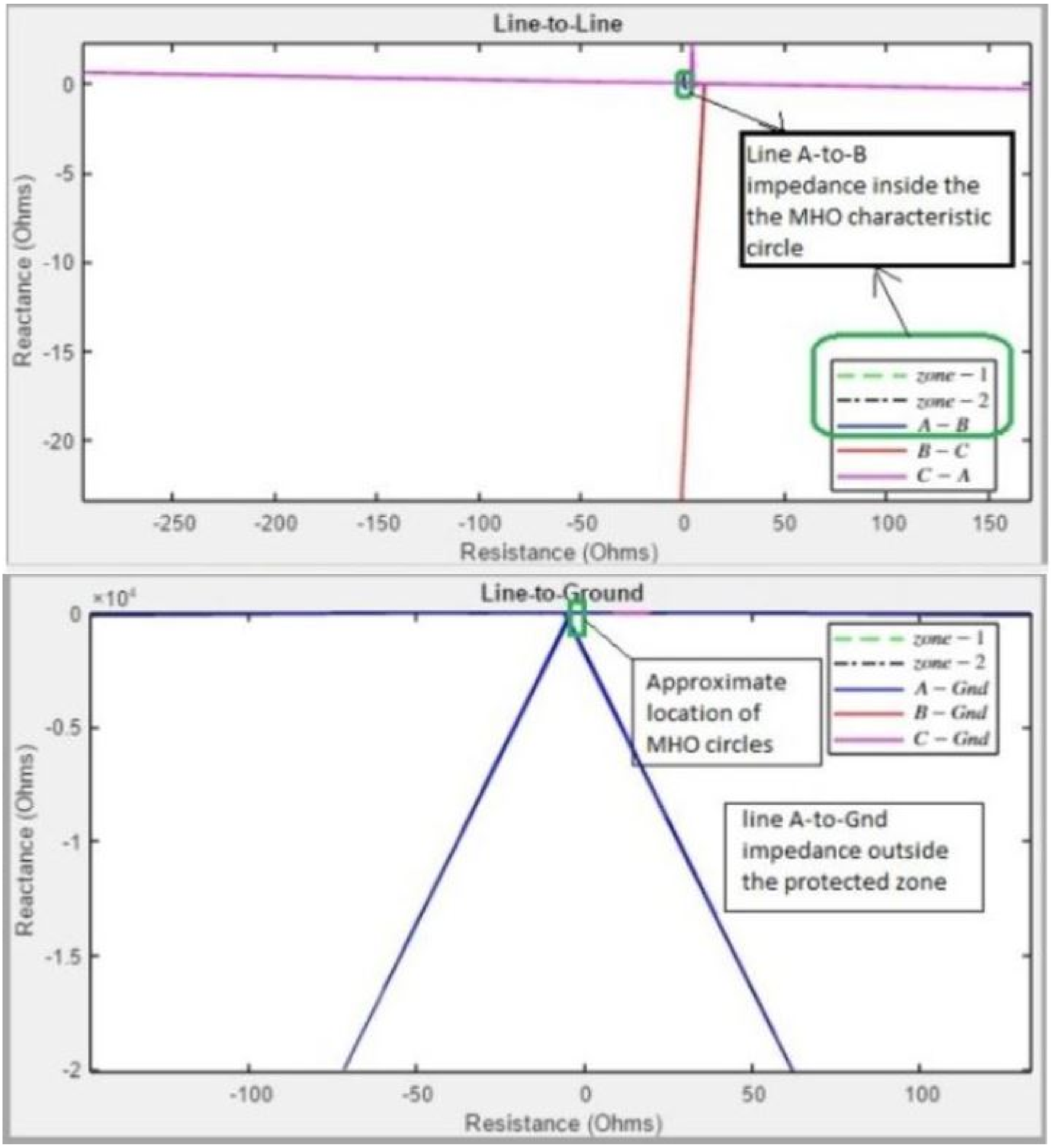


Obr. 7.1.4: Sampled values sender

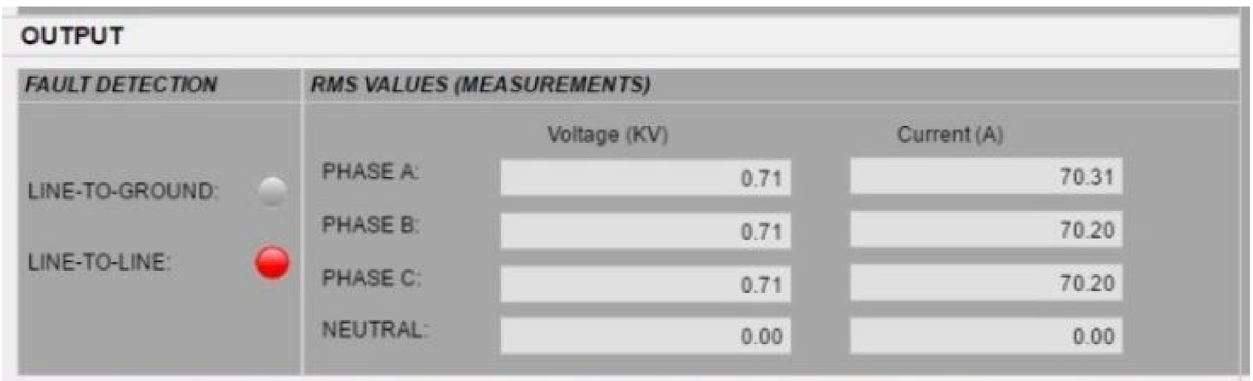
fault does not happen frequently in the protected distribution line under study. Therefore, the tool tested during the fault conditions by using streams coming from another source.
In figure 7.1.5 presents the tool using developed GUI for Mho type distance protection relay. By using GUI, it can study the effect of parameters change on distance relay characteristics such as the effect of fault location and fault resistance. the figure shows fault impedance for phase A to ground, and the line to ground fault detection shows a red alarm. The impedance for phases B and C are showing outside the zone; therefore, the distance protection will not send a trip signal. RMS values show the three-phase values for the voltage and current.
In figure 7.1.6 presents the tool using developed GUI for Mho type distance protection relay. By using GUI, it can study the effect of parameters change on distance relay characteristics such as the effect of fault location and fault resistance. the figure shows fault impedance for line to line (A to B) and the line to ground fault detection shows a red alarm (figure 7.1.7).



Obr. 7.1.5: SLG (phase A) impedance inside outside the zoneV, I RMS during the fault and fault detection alarm (SLG)



Obr. 7.1.6: Line to Line fault



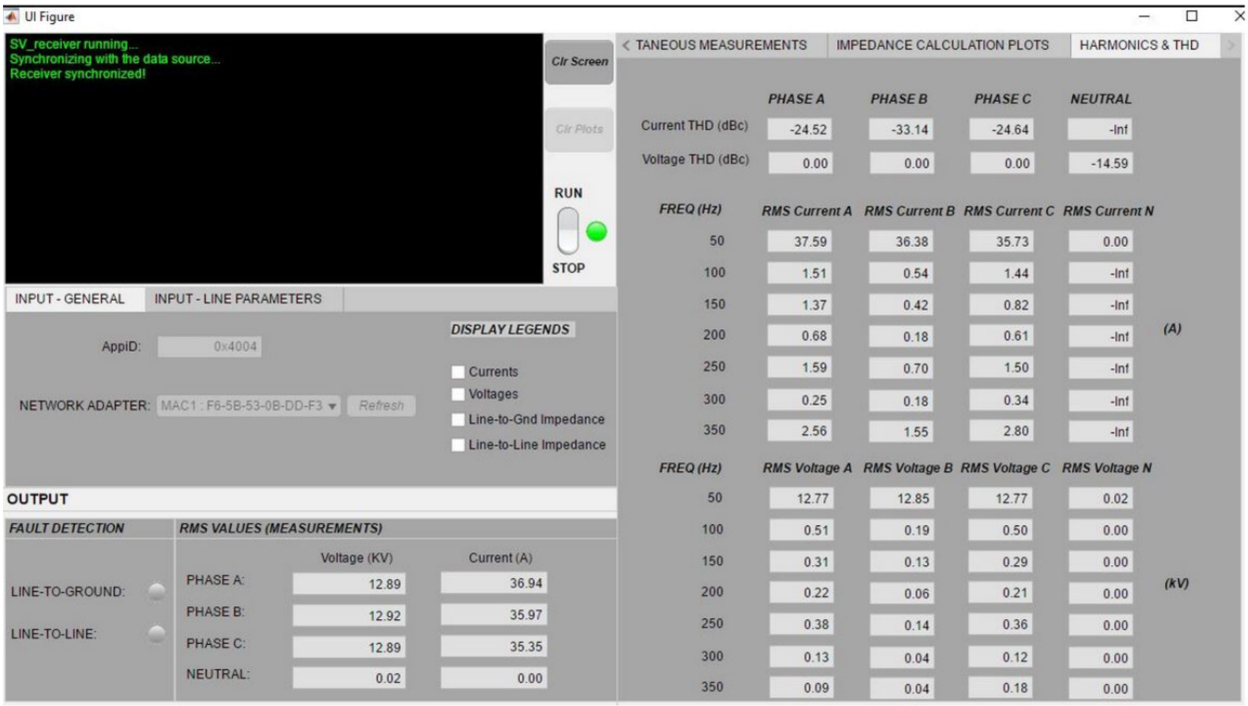
Obr. 7.1.7: Fault detection alarm (Line to Line)

7.2 Harmonic Classification Using FFT Spectrum

The wave analyzer measures the amplitude of each harmonic component. It can be either a frequency domain type, using selective filters or a spectrum analyzer, or a time domain type using digital computation to derive the discrete Fourier transform.
Harmonic distortion: Harmonics can be understood as different frequency periodic components that are superimposed on the main frequency waveform. In power systems, existing harmonics are a mostly odd integer multiple of the power frequency. The 3rd, 5th, 9th, 7th, 11th, and 13th orders can be identified as the most common harmonics. In addition to these common harmonics, it is possible to face signal components that are not integer multiples of the fundamental. Such components are called "inter-harmonics" and they are usually encountered while dealing with non-periodic signals. through the test, the result shows the harmonic capture ratio from the current and voltage waveform.

FFT is used to convert time-domain waveform into their frequency components. When the waveform is periodical, the Fourier series can be used to calculate the magnitudes and phases of the fundamental and it's Harmonic components. Harmonic distortion is characterized by the harmonic spectrum of the voltage or current signal obtained by applying the Fourier transform. The spectrum of the distorted signal obtained with power system frequency as –Even harmonic component, odd harmonic component, inter harmonic component, and sub-harmonic component and noise.

Harmonic detection and mitigation is an important task in the power system. This session presents detailed power quality problems, harmonics, and their types, causes of harmonics, effects, and solutions. It proposes the FFT method of harmonics analysis which is most useful to classify harmonics in odd, even, noise, inter harmonics, sub-harmonics, etc. Figure 7.2.1 explains the THD calculation using the FFT spectrum.



Obr. 7.2.1: Current and voltage harmonics

7.3 CONCLUSIONS

This chapter describes the tool of distance relay using Matlab package. Inside the tool, single line to ground (SLG) and double line faults chose to be the fault type and Mho type distance characteristic chose to be the protection scheme. A graphical user interface (GUI) created using a GUI package inside Matlab for the developed tool. Using the sampled values from real substation and analysis in real-time. The tool developed without using any need for additional hardware, the requirements are the ethernet port RJ45 from the substation and pc that is running MATLAB. The benefits and features of the tool, easy to use, ability to implement some the distance protection functions, RMS calculation values of the voltage and current, harmonic distortion, the harmonic components with FTT analysis, distance protection characteristics and fault impedance calculation.

Chapter 8

CONCLUSIONS

- At the beginning of the dissertation, there is an overview of the development of electrical protections from basic electromechanical protections to modern digital protections. The introduction focused on the quadrilateral relay algorithm and improvement of the relay functions. the new measurement method uses sensors to measure current and voltage in the power system and the output signal is a low voltage which transmits through the network over the ethernet cable.
- The main aim of the thesis is to create a model that simulates the distance protection function and algorithm using a digital output from the current and voltage sensors. The dissertation explained the ways to implement IEC 61850 on physical protections with (analog-digital) input data of voltage and current. With the increased interaction between physical devices and communication components, the test proposes a communication analysis for a substation with the conventional method (analog input) and digital method based on the IEC 61850 standard. Moreover, it analyses the merging unit's functions for relays using IEC 61850-9-2LE. The proposed method defines the sampled values source and analysis of the traffic.
- By using neural net pattern recognition that solves the pattern recognition problem, a relation between the inputs (number of samples/ms—interval time between the packets) and the source of the data is found. The benefit of this approach is to reduce the time to test the merging unit by getting the feedback from the merging unit and using the neural network to get the data structure of the publisher IED. Tests examine the GOOSE message and performance using the IEC standard based on a network traffic perspective.
- Chapter 5 presents the concept of the impact of harmonic distortion on a digital protection relay. The aim is to verify and determine the reasons of a maltrip or failure to trip the protection relays; the suggested solution of the harmonic distortion is explained by a mathematical model in the MATLAB Simulink programming environment. The digital relays have been tested under harmonic distortions in order to verify the function of the relay's algorithm under abnormal conditions. The comparison between the protection relay algorithm under abnormal conditions and a mathematical model in the MATLAB Simulink programming environment based on injected harmonics of high values is provided.
- In this dissertation has a theoretical description of protection algorithms and their programming in the MATLAB environment. The model and practice tests provide a new approach to applying digital current and voltage inputs on distance protection. The result of the dissertation shows new possibilities of protection of distribution devices using the IEC 61850 standard. It demonstrates the possibility of the designed

model for real use, whether for the whole substation or groups of panels. The model provides the quadrilateral relay characteristics, determine the fault type, calculate the fault impedance, total harmonic distortion. In this chapter, we developed a tool that can read the currents and voltages traffic stream in real time according to IEC 61850 sampled values (80 samples/second), this tool can get the current and voltage values from the live stream and run it in MATLAB for additional analysis. The tool is divided to 3 stages: First stage, devising a means of capturing the Ethernet packets from the connected LAN network adapter of the host computer. After some researches, we preferred to use t-shark (which is a commandline equivalent of Wireshark). The second stage develops a MATLAB interface or code to import the captured data into the MATLAB environment. The third stage develops a MATLAB GUI to house the display and processing features for the captured data packets. The sampled value sander SAV sender tool was run on a different connected laptop and the ethernet packets were captured using t-shark which is installed on the host laptop. Because of the nature of t-shark (which can only be run from the command line), a MATLAB interface is necessary so that it can be called from within the MATLAB environment. Tshark has both capabilities. In one mode, it can capture live packets directly from the specified ethernet port. In the other mode, it can record the captured packets to Pcap file. This tool gives the possibility to advanced analysis of the digital processing signals, such as FFT, harmonic distortion, fault type, and fault location calculation. It designed to implement for the distance protection getting the signal of the current and voltage signal from the station near the university (Medlanky station), where we install merging units for the currents and voltages and transmit the signals to the protection lab, the tool provides the possibilities for additional analysis of the signals using MATLAB libraries.

THE CONTRIBUTIONS OF THIS DISSERTATION

The dissertation contains theoretical description of algorithms and their programming in the Matlab development environment. The result of the dissertation shows new possibilities of distribution protection devices using the IEC61850 standard. In the tool, the programmed distance protection functions can determine the RMS values of the voltage and current, decode and the streams in real-time and analyze the streams according to IEC61850 standard, It verifies the distribution line under the test (line length, voltage level, and other parameters).

The machine learning used for the optimization of testing procedures in substations where IEC 61850-9-2LE is implemented. This method can be used for shorter test preparation to lower the cost and help support research projects since it allows one to implement better platform and services as well as to integrate different communication protocols when it's necessary.

The proposed tool already deployed in real high-voltage substation and the digitalized data from IEC6185-9-2 SV transmitted via ethernet to protection laboratory.

We explore the applicability of our method to evaluate real-time streams in real-time transmitted over packet-based networks. We selected seven important parameters that have the most impact on the distribution line. These parameters are line length, line resistance, line conductor, overall outer, and zone1,2.

SUMMARY OF RECOMMENDATIONS AND PROPOSAL FOR FURTHER ACTION

We can identify the following steps that should be taken to develop the tool usage and implement the functions presented in this dissertation:

- Analyzing the captured data and compare the measured values during the abnormal conditions.
- The routine test should be carried out to ensure the integrity of the relay scheme as faulty protective devices may also constitute fault and thus affect the integrity of the protection scheme and may lead to loss of supply of electrical energy.
- Identify reliable sources of inputs data and create easy access to inputs.
- In this approach, it is possible to further improve the protection algorithms and work on the principle of distance protection functions.

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Curriculum Vitae

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Education

2006 – 2009	Bachelor in Electrical engineering at Faculty of Electrical Engineering, Damascus University of Technology. Topic of bachelor thesis: Amendment to the AC bus distributor
2009 – 2011	Master in Electrical engineering at Faculty of Electrical Engineering, Damascus University of Technology. Topic of bachelor thesis: Modeling and simulation of the photovoltaic system is connected with the electric grid.
2011 – 2018	Ph.D. studies at Faculty of Electrical Engineering and Communication, Brno University of Technology. Topic of Ph.D. thesis: Distance Protection Design Using Digital Input Data.
2019	Course of real time simulator OPAL-RT, Paris France.

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2013 – 2016	Teaching of seminars at BUT
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Other skills

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Abstract

IEC 61850-9-2 specifies that the transmission of sampled measured values (SMVs) over an Ethernet network, using sampled values generated by merging units of IEDs or individual merging units, instrument transformers.

The implementation of IEC 61850-9-2 depends on the dataset specifications such as time synchronization, sample counts, and interval time.

The dissertation is focused on protection algorithms and analyses the impact of IEC 61850-9-2LE on physical protections with (analog-digital) input data of voltage and current. With the increased interaction between physical devices and communication components, the test proposes a communication analysis for a substation with the conventional method (analog input) and digital method based on the IEC 61850 standard. The thesis analyses the merging unit's functions for relays using IEC 61850-9-2LE. The proposed method defines the sampled measured values source and analysis of the traffic.

Further, the thesis deals with the programming of protection function algorithms in Matlab. The model evaluated the harmonics impact on digital relays and the impact of current transformer saturation on distance protection.

In the end, the thesis deals with the assessment of the benefits of IEC 61850-9-2LE using a neural network.

The last chapter focuses on a real-time application that subscribes the data stream coming from a substation near the protection laboratory in Brno University of Technology. IEC 61850-9-2 LE SMVs are used to transmit the traffic to a university laboratory with 16 km of fiber optic cable. The application built using Matlab and can read the traffic from the ethernet port, the traffic decoded and convert from ASCII to the decimal numbers then draw the current and voltage values. The application developed without using any need for additional hardware, the requirements are the ethernet port RJ45 from the station and pc that is running Matlab. The benefits and features of the application, easy to use, ability to implement all the distance protection functions, calculation of the RMS values of the voltage and current, harmonic distortion, the harmonic components with FTT analysis, distance protection characteristics and fault impedance calculation. All calculations implemented in real-time, moreover, in this chapter include sensitivity analysis of the Matlab model in previous chapters. Distance protection functions discussed in this thesis used the offline model of Matlab or captured with Comtrade format files.