APPLICATION OF SENSORS AND DIGITALIZATION BASED ON IEC 61850 IN MEDIUM VOLTAGE NETWORKS AND SWITCHGEARS

DOCTORAL THESIS – SHORT VERSION

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# TABLE OF CONTENTS

TABLE OF CONTENTS ................................................................. 3

1 TARGETS OF THE DOCTORAL THESIS ................................................................. 5

2 INFLUENCE OF EXTERNAL FACTORS ON SENSORS ACCURACY ......................... 6
   2.1 General introduction and assumptions .................................................................. 6
   2.2 Conclusions on applications of Rogowski coil, resistive and capacitive divider in MV networks and switchgears................................................................. 7

3 Calculation of residual current, APPLICATION OF ROGOWSKI COIL ...................... 10
   3.1 General arrangements and rational of the measurement ....................................... 10
   3.2 Results and conclusions from the laboratory tests ............................................. 12
   3.3 Results and conclusions from testing on primary network model ....................... 13
   3.4 Overall collusions of the Rogowski coil application for earth fault protection .......... 14

4 NEW ARCHITECTURE OF MV AIR INSULATED SWITCHGEAR AND SUBSTATION .......... 16
   4.1 Definition of the gap ......................................................................................... 16
   4.2 Architecture of the MV air insulated switchgear with sensors and process bus ........... 17
      4.2.1 First step – definition of the standard feeders ............................................. 18
      4.2.2 Third step - Calculation of communication bandwidth ................................... 19
      4.2.3 Fourth step - Selection of communication architecture and redundancy principle .... 20
      4.2.4 Reliability study of PRP and HSR redundant communication architectures .......... 21

5 CONCLUSIONS AND CLOSINGS .............................................................................. 23

REFERENCES 27

CURICULUM VITAE ................................................................................................. 29

ABSTRAKT 30
1 TARGETS OF THE DOCTORAL THESIS

This thesis will focus to exploration of the application of two technologies - measuring of currents and voltages by Rogowski coil and voltage dividers and communication bus using IEC 61850-9-2 in MV switchgears. Both technologies as such, have been independently subject of the investigations and explorations in many papers and publications. This thesis will propose and verify simultaneous combination of both technologies implemented and practically verified in MV Switchgear. It will offer clear view, why both technologies deployed hand in hand will create a new opportunities how to protect and control MV switchgears and networks in a different manner. Further target is to explain why Rogowski coil and voltage dividers are better alternative to well-known inductive transformers for current and voltage measurements in MV switchgear. Additional target is to offer technical arguments of what is the next step is architecture of MV switchgears. Thesis offers a system view on MV switchgear, it will explain how to connect loose well known components: sensors – IEDs – digital bus to one seamless architecture and it will demonstrate how this integration will impact MV switchgear engineering and design approach.

The first part of the thesis will be focused to detailed investigation of possible measurement accuracy influence by external factors in indoor substation environment. Based on the experimental measurements thesis will investigate how good is immunity of the Rogowski coil and voltage dividers against external factors that influence accuracy of the measurement.

The second part will propose alternative approach in residual current measurement by Rogowski coil and IED processing in comparison to existing practice of the residual current measurement by core balance transformer. It will analyze applicability of the alternative measurement and processing of residual current in insulated and directly grounded networks.

The third part will define new system architecture of the MV air insulated switchgear with seamless integration of the sensors, IEDs and digital bus in the switchgear and substation. It will propose new typical layouts of the MV feeders needed to design MV substation. It will investigate how the new typical layouts can change engineering approach. Important aspects of communication network reliability and availability will be verified for proposed architecture.
2 INFLUENCE OF EXTERNAL FACTORS ON SENSORS ACCURACY

2.1 General introduction and assumptions

Every measuring device has certain measuring error given by its physical principle of the measurement. This error is however not the final error. There are many external factors which may influence total measurement accuracy of any instrumental device for the measurement, including Rogowski coil and voltage dividers. External factors influencing measuring error of the sensors can be divided into three categories.

I. External factors that can be eliminated by proper design

II. External factors given by the application environment

III. External factors generated by the architecture of the measuring system

Ad I. External factors that can be eliminated by proper design.

These factors were not investigated within this thesis taken into account assumption that design of the final product eliminates them. This category includes following external factors.

- High dielectric fields
- High magnetic fields (magnetic cross-talks)
- Eddy currents
- Vibrations, shock and tilting
- Altitude

Ad II. External factors given by the application environment

There are two general environmental application in MV networks defined by IEC 62271-1 outdoor and indoor. This thesis is focused to investigation of temperature influence on total measuring error since this variable has major influence in indoor MV applications. Other environmental factors that can influence measurement accuracy when outdoor conditions are considered are following.

- Humidity
- Pollution
- UVA & UVB

Ad III. External factors generated by the architecture of the measuring system

The third category includes factors generated by the architecture of the measuring system. The current view about requirement of accuracy class measurement in MV applications is generally limited to accuracy class of sensing element (instrument transformer or sensor). This view is however not correct, because total measurement error is sum of errors contribution of each and every element in measuring chain. Complete measuring chain is clearly explained in IEC 60044-8 and can be seen from Fig. 2-1.
Picture above defines measurement accuracy chain applicable both for MV and HV applications. There is no need to use primary and secondary active converter in MV applications due to the limited distance between primary sensor and relay. Transmission system represented by the cable between primary sensor and the relay is however element where it is very important to understand its possible influence on measuring accuracy. Finally also analog input of the relay, its nominal burden and design has influence on the measuring accuracy. Each manufacturer of the relay has analog inputs board optimized for the signals generated by the particular sensors. For the purpose of this thesis, ABB relay REF 615 was used, where analog input board is designed taking into account character of the signal sensors specified below in this chapter. All measurements were done by use of Ethernet communication cable CAT6 which represents transmission system on Fig. 2-1.

Accuracy and the measurement quality of the sensors can be influenced by the design, manufacturing and assembly methods, therefore all results are relevant only for ABB sensors used for the purpose of this thesis. However, combination of sensor – IED – AIS architecture coming from different manufacturers could be investigated in an identical way. All investigations and measurements were done on following three types of ABB sensors: KEVCD 24 AE3 – parameters are specified in Appendix 1, KEVA 24 C21 – parameters are specified in Appendix 2 and KEVCR 17.5 CA1 – parameters are specified in Appendix 4.

2.2 Conclusions on applications of Rogowski coil, resistive and capacitive divider in MV networks and switchgears

Rogowski coil

Accuracy is acceptable for the application in MV networks and switchgears. Contribution error generated by environmental temperature typical in MV applications does not influence results of overall accuracy neither in amplitude nor in phase displacement. Cable length between Rogowski coil and IED has very small impact on measurement accuracy, therefore use of Rogowski coil for current measuring in case protected object is up to 100 m from IED (e.g. Transformer, Motor) is possible. Frequency response of Rogowski coil for protection purposes fully meets requirements of high harmonics accuracy measurements for protection purposes. When using Rogowski coil for measuring of high harmonics for power quality purposes where high accuracy of the high harmonics measurements is required, Rogowski coil must be placed as close as possible to IED. Cable length between Rogowski coil and measuring device which does not exceed 6.5 m transfer high harmonics
up to 25th with satisfactory accuracy. Very important conclusion is that all contributing errors across measured ranges of temperatures, cable length or frequencies shows constant pattern. This allows to set correction factors in IEDs and offset any measurement error close to zero. If the correction factor is properly defined and set in IED, assumption of having current measured with no measuring error for processing in IED can be made. Results are summarized in Tab.2-1.

Tab. 2-1 : Rogowski coil meas. errors influence by external fac.

<table>
<thead>
<tr>
<th>Temperature -40°C - 115°C</th>
<th>Rogowski Coil Errors Influence by External Fac.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude error</td>
<td>0.02% ... 0.04%</td>
</tr>
<tr>
<td>Phase dis. Error</td>
<td>Constant</td>
</tr>
<tr>
<td>Distance to IED 6.5 m - 100 m</td>
<td></td>
</tr>
<tr>
<td>Amplitude error</td>
<td>0.12° ... 0.5°</td>
</tr>
<tr>
<td>Phase dis. Error</td>
<td>Constant</td>
</tr>
<tr>
<td>Frequency response 50Hz - 1500Hz</td>
<td></td>
</tr>
<tr>
<td>Amplitude error Protection (50 - 300Hz)</td>
<td>0.5% ... 1.7%</td>
</tr>
<tr>
<td>Metering (50 - 1500Hz)</td>
<td>0.5% ... 1.6%</td>
</tr>
<tr>
<td>Phase dis. Error Protection (50 - 300Hz)</td>
<td>-90° ... -92°</td>
</tr>
<tr>
<td>Metering (50 - 1500Hz)</td>
<td>-90° ... -92°</td>
</tr>
</tbody>
</table>

Resistive divider

Accuracy is acceptable for the application in MV networks and switchgears. Accuracy of resistive divider is not dependent on temperature. Contribution errors of amplitude and phase displacement errors as function of the temperature can be considered as negligible for the applications in MV networks and switchgears. Cable length between resistive divider and IED is also not limiting factor in MV applications. Cable up to 100m generate small measuring errors of amplitude and phase displacement, both have constant pattern. Depending on application, these errors can be offset by setting correction factor in IED. Accurate measurement of high harmonics by resistive divider has limits of the cable length between resistive divider and measuring electronic. Measurements showed that cable length between resistive divider and IED shall no exceed 20 m for protection purposes and 6.5 m for power quality purposes. In this case measuring error of amplitude and phase displacement stays within the values acceptable in MV applications. Results are summarized in Tab.2-2.
Capacitive divider

Accuracy dependency on external factors, especially temperature makes application of capacitive divider in MV networks questionable. It could be used in application where ambient temperature shall not exceed 40°C. In this case accuracy error of amplitude and phase displacement are within the limits acceptable in MV applications and both have contact pattern which allows to set correction factors in IED and offset measurement error close to zero. Capacitive divider shows excellent performance as far as the accurate high harmonics measurement is concerned. Capacitive divider does not generate any measurement errors of amplitude and phase displacement up to 10 kHz. Results are summarized in Tab.2 -3.

Further part of this thesis is focused to application of sensors in MV switchgears. Due to the fact that higher operating temperature range is required in MV switchgear applications capacitive divider is not further considered for the purpose of this thesis. This is also the reason why impact of the long cables on voltage measurement by capacitive divider has not been done.
3 Calculation of residual current, APPLICATION OF ROGOWSKI COIL

3.1 General arrangements and rational of the measurement

Current practice in MV application is to use core balance current transformer, which is mounted around all three line cables. This transformer measures vector sum of magnetic fields generated by currents which flows in all three phases. In steady-state conditions, the sum is zero and therefore value of residual current on secondary terminals of the core balance current transformer is zero. In case of unbalance between phase currents caused by earth-faults, an unbalanced magnetic field generates proportional residual current at secondary terminals. Theoretically, the same phenomena could be applied on Rogowski coil, however it would be very expensive to produce Rogowski coil with diameters of several tens of cm. The idea of calculating residual current in IED from measured line currents is of course not new, however experience from residual current calculation in IED by measurement of line currents with Rogowski coils is missing. Especially answers on accuracy of such a measurement across whole metering range is demonstrated in this chapter.

Phase current measurement is always affected by measurement accuracy in certain extend, it has impact also to accuracy of residual current calculation. Due to the phase currents measurement inaccuracy, the apparent residual current $I_{0\text{(ap)}}$ is always generated, example can be seen in Fig.3-1. Generation of the apparent residual current is undesirable however unavoidable.

It is important to understand amplitude value of the $I_{0\text{(ap)}}$ over the whole measuring range which shall lead us to conclusions whether accuracy of residual current calculation in IED can influence overall accuracy of earth fault protection in any type of networks. Fig.3-2 illustrates example of possible relations between real residual current $I_{0\text{(r)}}$ and apparent residual current $I_{0\text{(ap)}}$. Real residual current can be described according Eq.3-1.

$$I_{0\text{(r)}} = I_0 + I_{0\text{(ap)}} \quad (Eq.3-1)$$

It is important to understand whether the $I_{0\text{(ap)}}$ can reach such a value that can generate false pick up of the earth fault protection.
It is also important to understand phase displacement between real residual current $I_0$ and apparent residual current $I_{0(ap)}$, since it might have negative impact on proper detection of earth fault current value and direction in the system. Example of the phase displacement between $I_0$ and $I_{0(ap)}$ can be seen in Fig. 3-3.

For the purpose of residual current calculation by IED from the line currents measured by Rogowski coil, ABB REF 615 IED was used with ABB KEVCD 24 AE3. Six tests were done in order to verify impact of apparent residual current to an overall accuracy of residual current calculations by IED.

1) Laboratory testing – Static tests
   a. Stability of the system characteristic with two different nominal current. The target is to compare sensitivity of the REF 615 current deviation depending on primary nominal current settings.
   b. Earth fault protection tested in 1-phase system. The target of the measurement is to find threshold values of the apparent residual current.

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**Fig. 3-2**: Real residual current $I_0$ and apparent residual current $I_{0(ap)}$ relation

**Fig. 3-3**: Phase disp. - real residual current $I_0$ and apparent residual current $I_{0(ap)}$
generated by sensors systems inaccuracy. Threshold values when asymmetry is detected by the REF 615 and asymmetry which is not yet detected by the REF 615.

(c) Earth fault protection tested in 3-phase system. The target is to verify if residual apparent current naturally created by the different accuracy of the sensors in each phase does not influence proper functionality of the earth fault protection function by means of fault pick up or trip.

2) Testing on primary network model – Dynamic tests
(a) Stability test on inrush current in the network caused by the power transformer. The target of the measurement was to verify possible impact of the generated current unbalanced in the system caused by power transformer inrush current.
(b) Earth fault in system with isolated neutral. The target was to verify sensitivity of earth fault protection with virtually calculated residual current in systems with isolated neutral.
(c) Earth fault in system with high impedance neutral. The target was to verify sensitivity of earth fault protection with virtually calculated residual current in systems with high impedance neutral.

3.2 Results and conclusions from the laboratory tests

The conclusion from static tests performed is that sensors enable more accurate signal transformation comparing with conventional instrument transformers, particularly for very low and very high primary currents. Using of sensors enable setting of earth fault protection for 1% of primary rated current 40 A for low primary currents and 3% of primary rated current 40 A for high primary currents. The measurement with high primary current verified the correct behavior of sensors and their linear non-saturated characteristic.

1) For nominal current $I_{pn} 80$ A ≠ rated primary current of sensor $I_{pr} 80$ A
   It was measured currents from 5% up to 120% of $I_{pr}=80$ A where the nominal current parameter $I_{pn}$ was set to 80 A as well. Mean root-square error of value read from REF615 HMI (in the range 0.060-0.136 A) was slightly higher than mean root-square error of injected current (in the range 0.050-0.098 A).

2) For nominal current $I_{pn} 1000$ A ≠ rated primary current of sensor $I_{pr} 80$ A
   It was measured currents from 5% up to 120% of $I_{pr}=80$ A where the nominal current parameter $I_{pn}$ was set to 1000 A. Mean root-square error of value read from REF615 HMI (in the range 0.110-0.544 A) was higher than mean root-square error of injected current (in the range 0.060-0.080 A)

Conclusions of earth fault protection behavior in one phase system showed positive results. Results shows that asymmetrical apparent current as seen by REF 615 has very small values. This values are below typical pick-up values of earth-fault protection so the risk of false operating of the earth-fault protection created by apparent residual current is neglected.
Conclusions of earth fault protection behavior in three phase system showed also very positive results. $I_{o(ap)}$ created as results of unbalanced current between phases due to the different accuracy of the sensors in each phase increases with measured current $I_p$. $I_{o(ap)}$ expresses as percentage value of measured current $I_p$ has exponential character as seen from Fig.3-4. $I_{o(ap)}$ did not reached such value which would initiate pick up stage of REF 615 protection even the settings ware set at most sensitive level. Gap between minimum pick up residual current and residual apparent current gives a sufficient safety margin that allows to make conclusion that calculation of the residual current by the IED for earth fault protection from the line currents measured by Rogowski coil will always work in isolated and directly earthed neutral. Reliable application of residual current calculation by IED in MV networks where neutral is earthed through Petersson coil (compensated networks) requires to make field measurements.

![Fig. 3-4](image)

**Fig. 3-4**: Characteristics of $I_{o(ap)}/I_p = f(I_p)$ [%]

### 3.3 Results and conclusions from testing on primary network model

Additional tests were made on top of the laboratory testing in order to verify proper behavior of the earth fault protection function with virtual residual current calculation in IED. Focus was given on specific situations which may appear in some MV networks such as stability test on inrush current, intermitted earth faults, different earth fault resistances. Measurements are not described with high degree of the details but they can be provided upon request. Overview of the results underlines stabilized measurements of the line currents measured by the Rogowski coil and consequential virtual calculation of the residual current in IED for further processing in IED with focus on proper behavior of the earth fault protection.

Measurements were done on primary network model simulating different type of networks and faults.
3.4 Overall collusions of the Rogowski coil application for earth fault protection

Saturation phenomena of the instrument transformers is well-known constrains that must be taken into account when specifying required parameters of the instrument transformers as a result of the short circuit selectivity study for the particular application. Beside well known linear characteristics of the sensors also accuracy of them measurement across complete dynamic range has positive effect on protection functions behavior. Protection functions algorithms of all IEDs counts with instrument transformer saturation phenomena. It can be concluded that use of sensors and full utilization of their measurement characteristics would require new approach what comes to processing of the measuring signal in IED and its further use for protection functions. Algorithms of the protection function would need to be also reconsidered in order to fully utilize all positive attributes of the current and voltage measurement by the Rogowski coil and voltage divider. The subject of this thesis was not to investigate how the IED architecture could be changed however above assumptions are confirmed by the investigation of earth fault protection behavior with virtual calculation of the residual current in IED from line to neutral currents measured by the Rogowski coil. Detailed measurements were done in order to understand behavior of complete system Rogowski Coil – Cable – IED.

Stability measurement characteristics showed that settings of the nominal value in IED influences deviation of the measurement as seen by the IED in comparison to real current in the system. The lower the nominal value current settings the smaller the deviation is seen.

Examination of the earth fault protection function tested in one phase system showed that naturally created apparent residual current as result of the Rogowski coil inaccuracy, increases with the supplied current, however its values represents such a small fraction of the supplied current that chance of earth fault protection false behavior is very unlike.

Testing of the earth fault protection in three phase system showed that apparent residual current created form the contributions of the Rogowski coils inaccuracy in all three phases increases with supplied primary current, however its value expressed as percentage of the supplied primary current has exponential character. This is very important conclusion, which confirms that false behavior of the earth fault protection due to the natural current unbalanced created by the Rogowski coils is very unlike. Values of the apparent residual current are well below minimum pick up residual currents values of the REF 615 earth fault protection.

When instrument transformers are used, it is generally recommended to not use residual current calculation if there is chance of having earth fault current lower than 10% of the nominal current. Core balance transformers are commonly used in such a cases. Type of the MV network from the neutral grounding principle must be considered as well.

Measurements of the earth fault protection behavior with the line to ground current measurements by the Rogowski coil and consequential calculation of the virtual residual current by IED, showed that above mentioned generally used rules for instrument transformers are not applicable when measuring current by the Rogowski coil. New rules
can be recommended when calculating residual current in IED from the line to ground current measurements by the Rogowski coil.

- MV feeders up to \( I_r = 3150 \text{ A} \) and \( I_k'' = 31.5 \text{ kA} \). Earth fault currents above 1% of the nominal current can be safely calculated by the IED from the line to ground currents measured by the Rogowski coil
- MV feeders up to \( I_r = 4000 \text{ A} \) and \( I_k'' = 50 \text{ kA} \). Earth fault currents above 3% of the nominal current can be safely calculated by the IED from the line to ground currents measured by the Rogowski coil

Above conclusions are applicable for the Rogowski coil ratio settings in the IED 40A / 150 mV. Voltage measuring range of the IED analog input card must be verified when full current dynamic range (up to \( I_k'' \)) is required to be measured.

Additional tests on primary network model showed satisfactory stability of the earth fault protection behavior when calculating residual current from the line to ground currents measured by Rogowski coil. No false trips were registered when simulating

- Power transformer inrush current in the system
- Different resistance of the fault currents in unearthed neutral networks
- Different resistance of the fault currents in high impedance neutral grounded networks

Conclusion of the universal earth fault protection with no need to consider core balance transformer can be made for following networks

- Unearthed neutral MV networks
- Low impedance neutral earthed MV networks

Above conclusion assumes residual current virtual calculation from the line to ground currents measured by the Rogowski coil can be made.

High impedance neutral earthed networks would require further field investigations and tests which is not a subject of this thesis. Results of the measurements and tests presented in Chapter 5 creates high confidence that above conclusion can be extended also for this type of MV network from the neutral earthing principle stand point.
4 NEW ARCHITECTURE OF MV AIR INSULATED SWITCHGEAR AND SUBSTATION

4.1 Definition of the gap
The major technical challenge when considering use of the sensors in MV applications and especially in MV switchgears is simple and efficient distribution of the voltage measurement within substation. Cable length between voltage sensor and IED is not an issue that limits application. In case of voltage transformer application, character of the voltage transformer output signal simple allows to distribute voltage by use of hardwiring within substation. Each IED voltage analog input channel is connected in parallel to voltage transformer where the desired measurement needs to be taken from. Available power output of the voltage transformer is the only limiting factor how many IEDs can be connected with particular voltage transformer in parallel. Simplified voltage measurement distribution within substation when voltage transformers are used can be seen from Fig.4-1.

![Fig. 4-1 : Block diagram - voltage and current distr. with instrument transformers](image)

Current measurement distribution within or outside of the substation does not represent difference between application of the current transformers and the Rogowski coil. Current measurement is connected in series between current measurement source and analog input of an IED. Limiting factor might be the only distance between measuring device and the IED. Relations of cable length between the Rogowski coil and IED is explained in the chapter 4. The best way how to distribute measured values within substation is to digitalize measurements as close as possible to measurement point and transfer sampled measured values over high speed communication bus deployed within substation. There are many techniques and standards for measurements digitalization as well as high number of communication systems architecture that can be theoretically used. This chapter identifies the optimized architecture of the MV air insulate switchgears with sensors and measurement digitalization. IEC 61580 was chosen communication standard for the purpose of this thesis.
4.2 Architecture of the MV air insulated switchgear with sensors and process bus.

Most of the air insulated switchgears are single bus bar systems with two sections where each section includes one incoming feeder and several outgoing feeders. Both sections are horizontally separated with bus coupler element which is typically operated with normally open circuit breaker. Typical single line diagram of such a substation configuration is on Fig.4-2.

![Fig.4-2: Typical substation configuration for MV air insulated switchgears](image)

Each circuit breaker feeder includes an IED. The most elementary task of the IED is to protect particular feeder and load against fault situation and by breaking of the energy by tripping of the circuit breaker limit potential mechanical or thermal damages as consequence of the potential fault preferably to zero level. Measurements of currents and voltages are essential input data for the protection algorithms of IEDs. Majority of the protection functions requires following measurements for their principles of work:

- Line to ground currents
- Incoming feeders line to ground voltages
- Bus bar line to ground voltages
- Residual current
- Residual voltage

Certain protection functions such as differential protection, synchrocheck requires additional or different sets of measurements as input data. This thesis is focused on MV air insulated switchgear architecture limited to use of measurements mentioned above only.

Architecture of the substation where all above mentioned measurements are available to any IED at any time would be very beneficial to use any protection function independently on substation hardware configuration. Assumption of availability of all needed measuring data can decouple configuration and engineering of the measuring hardware from protection application in particular IEDs. The basic precondition to develop such architecture is to use Rogowski coil and voltage divider for current and voltage measurements. This decoupling can create many advantages what comes to engineering activities through entire life cycle of the MV air insulated switchgear.
• Linearity and accuracy of the current measurement by Rogowski coil does not require engineering of its parameters as result of the short circuit selectivity study
• Decision on protection scheme to be finally used in particular feeder can be done any time during project execution
• Additional protection function can be included to protection scheme once switchgear is under operation without need to re-engineer measuring apparatus and changes in substation wiring
• Change of the rated current level during life cycle does not require changes of the current measuring apparatus

Bottom up approach was selected to define new architecture of the MV air insulated switchgear application which would meet above idea of decoupling measuring apparatus specification and engineering from protection application.

1) Definition of the standard feeders
2) Calculation of communication bandwidth
3) Selection of communication architecture and redundancy principle

4.2.1 First step – definition of the standard feeders

Basic elements of every substation are feeders. Typical feeders must be defined in such way that they can all together measure all above mentioned voltage and current measurements. Due to the short distances within one feeder all data between switchgear apparatuses and IED are hardwired and data transmission is always in analog format. IED in every feeder acts as merging unit (MU) in order to publish or subscribe any digital binary signals and sampled measured values needed to be shared within substation.

Four basic feeders type have been proposed:

• Incoming feeder with voltage measurement is the first typical feeder and its standard single line diagram is in the Fig.4-3
• Outgoing feeder with busbar voltage measurement is the second typical feeder and its standard single line diagram is in the Fig.4-3
• The third typical feeder needed to build substation is bus coupler, Fig.4-4
• The fourth and last typical feeder is outgoing feeder. Single line diagram of this feeder is on the Fig.4-4.
4.2.2 Third step - Calculation of communication bandwidth

IEC 61850 uses Ethernet as physical communication layer and TCP/IP as communication protocol. It is very important to understand available communication bandwidth of Ethernet, so the sampled measured values can be transferred without any issues or bottlenecks in communication. Basic assumption is to 100 Mb/s Ethernet. IEC 61850-9-2 LE (light edition) specifically designed for MV applications defines two distinct sampling rates.

- 80 samples per nominal period for protection applications; one set of samples is sent immediately in one SMV message
- 256 samples per nominal period for metering applications; eight sets of samples are sent in one SMV message
General recommendation is to reserve 50 Mb/s it means half of the available 100 Mb/s Ethernet capacity for broadcasting of the substation events so called MMS telegrams between IEDs and SCADA system and GOOSE messages – substation events shared among IEDs for control, blocking and interlocking purposes. Second half of the total available 100 Mb/s Ethernet capacity can be used for SMV data sharing.

Following conclusions can be made what comes to available capacity of 100 Mb/s Ethernet for process bus applications in MV switchgears.

- Single and PRP redundant network architecture
  - Maximum amount of SMV publishers for 50 Hz system = 9
    \[
    \left( \frac{100 \text{ Mb}}{s} \div 2 \right) \div \frac{5.12 \text{ Mb}}{s} = 9.76
    \]
  - Available communication capacity considering two SMV publishers
    - SMV = 12.3 Mb/s
    - GOOSE + MMS = 87.7 Mb/s

- HSR redundant network architecture (principle of the HSR redundancy requires parallel data broadcasting it means half of the 100Mb/s Ethernet can be considered)
  - Maximum amount of SMV publishers for 50 Hz system = 4
    \[
    \left( \frac{50 \text{ Mb}}{s} \div 2 \right) \div \frac{5.12 \text{ Mb}}{s} = 4.88
    \]
  - Available communication capacity considering two SMV publishers
    - SMV = 12.3 Mb/s
    - GOOSE + MMS = 37.7 Mb/s

For the proposed architecture of the MV switchgear with two SMV publishers (sharing of busbar voltage) 100 Mb/s Ethernet using either PRP or HRS communication redundancy principles has sufficient communication capacity to transfer all required data among IEDs and to SCADA system. Other potential future applications with process bus in MV switchgears and networks where higher number of SMV publishers are expected 1 Gb/s Ethernet is highly recommended.

**4.2.3 Fourth step - Selection of communication architecture and redundancy principle**

Reliability of the MV switchgear is one of the most important attribute. All components and systems in the switchgear are expected to work without faults and disruption of energy distribution in steady state conditions. To fulfill the stringent reliability requirements of communication while maintaining the interoperability of IEDs in Substation Automation Systems (SASs), IEC 62439-3 defines two redundancy protocols:

1) Parallel Redundancy Protocol (PRP) (IEC 62439-3 Clause 4)
2) High-availability Seamless Redundancy (HSR) (IEC 62439-3 Clause 5).

Various aspects must be considered when proposing the best communication architecture for the particular application. Comparisons of what is important to be considered for process bus applications communication architecture is summarized in Tab.4-3.
4.2.4 Reliability study of PRP and HSR redundant communication architectures

Reliability is one of the most important aspects of SAS design. IEC 81650-90-4 engineering guidelines describes a number of communication systems for SAS. System can be design in many different ways and therefore it is important to understand reliability pictures of different architectures. Performance of communication in relation to tripping times is also important parameter. Key reliability parameters of the system are:

- Reliability [%]
- Availability [%]
- (MTTF) Mean Time To Failure [years]
- (MTTR) Mean Time To Repair [hours]

Above reliability pictures were calculated by ABB VisualMTTF tool. The tool is designed to consider both elements reliability and system topology for the overall calculation of the system reliability pictures. Elements reliability are MTTF and MTTR data defined by the user for particular component in the system. System topology can be freely defined in graphical editor by instantiation and connections of the substation elements. Final input information is dependency expression which defines information flow.

Results of the reliability calculations for PRP redundancy communication architecture
- Reliability = 99.998368 [%]
- Availability = 96.576878 [%]
- MTTF = 28.71 years
- MTTR = 4.106 hours

Results of the reliability calculations for HSR redundancy communication

- Reliability = 99.998368 [%]
- Availability = 96.921688 [%]
- MTTF = 31.983 years
- MTTR = 4.574 hours

Above results of the reliability pictures calculation shows slightly better results of HSR redundancy principle, however difference in comparison to PRP redundancy principle is so small that conclusion of both redundancy communication principles are suitable for the process bus application in MV switchgears can be made.
5 CONCLUSIONS AND CLOSINGS

It was identified that measuring and sensing part of the switchgear is from the technology aging stand point, the part, where changes by means use of alternative principles other than inductive transformer principle are very likely to happen in the near future.

Feasible alternative for current measuring technology in MV applications is a Rogowski coil and the alternative voltage measuring technology in MV applications are capacitive and resistive dividers. Selected alternative measuring principals alone, would not have been able to create any change in architecture, engineering and design approach of MV air insulated switchgear. Thesis showed that how the application of the selected measuring principles with IEDs and digital bus with IEC 61850 creates new approach in architecture, engineering and design of MV switchgear.

Accuracy of the measurement is the most critical parameter for its further use and processing by IEDs. It is critical to ensure that measuring signal at IED interface is within required accuracy limit and particular application specific factors do not influence accuracy measurement in such way, that required accuracy limits are not met.

The first part of the thesis specified what are the most important potential influencing factors in MV air insulated switchgears, which must be analyzed when applying Rogowski coil and voltage dividers. Following external parameters have been identified to be analyzed.

1. Ambient temperature
2. Cable length between sensor and IED
3. Frequency response

All measurements made on ABB Rogowski coil showed acceptable immunity of above listed factors to final accuracy of the measurement and below are most the important founding.

1. Both amplitude and phase displacement errors of the current measurement within whole defined ambient temperature range (-40°C → 115°C) in MV switchgears shows errors within 0.2 accuracy class defined by IEC 60044-8.
2. Examined length of the cable (up to 100 m) between Rogowski coil and IED showed that even 100 m distance fulfills requirement of the accuracy limits for protection purposes defined by IEC 60044-8, however if the accurate measurement of higher frequencies is required distance between Rogowski coil and IED shall not exceed 6.5 m in order to fulfill measuring accuracy limits defined by IEC 60044-8.
3. Frequency response of the Rogowski coil as such is satisfactory and fulfills all accuracy class limits defined by IEC 60044-8. Accuracy measurement however showed that cable length between Rogowski coil and IED limits accuracy of the Rogowski coil frequency response. Same confusion like in previous paragraph is applicable.

In general error pattern of the Rogowski coil always showed constant trend which is important for further possible correction in electronic device.

ABB Resistive divider accuracy explorations showed following results and conclusions.
1. Both amplitude and phase displacement errors of the voltage measurement within whole defined ambient temperature range (-40°C → 115°C) in MV switchgears shows errors within 0.5 accuracy class defined by IEC 60044-7. 

2. Examined distance of the cable (up to 100 m) between resistive divider and IED showed that maximum recommended cable length is 20 m. This cable length fulfills requirement of the class 1 accuracy limits for protection purposes defined by IEC 60044-7. 

3. Frequency response of the resistive divider is depended on cable length to IED. In order to fulfill voltage measuring class 1 defined by IEC 60044-7 for protection purposes cable length shall not exceed 20 m. As far as the metering purposes are concerned, where measurement accuracy up to 1500 Hz is required cable length shall not exceed 20 m in order to meet criteria of the measuring class 1 defined by IEC 60044-7. 

In general error pattern of the resistive divider always showed constant trend which is important for further possible correction in electronic device.

ABB Capacitive divider accuracy explorations showed following results and conclusions. 

1. Amplitude error of the capacitive divider is proportional to ambient temperature increase in such way that both amplitude and phase displacement errors above 40°C exceeds class 3 accuracy limits defined by IEC 60044-7. 

2. Influence of cable length between capacitive divider and IED on measurement accuracy has not been investigated. 

3. Capacitive divider as such showed good performance what comes to frequency response. Accuracy measurement up to 1500 Hz fulfilled criteria of the class 1 defined by IEC 60044-7. 

It can be concluded that capacitive divider is good alternative when high accuracy of high harmonics measurement is required, however it can be used only in environment where ambient temperature does not exceed 40°C. 

The second part of this thesis showed how the application of the Rogowski coil can change approach in protection application area. Target was to explore if the measurement of line currents by the Rogowski coil and further mathematical calculation of residual current by IED can be an alternative to measurement of residual current by core balance transformer. 

The first step was verification of apparent residual current value as function of increased line currents values – stability of the system. The conclusion from static tests performed is that Rogowski coil enables more accurate signal transformation in comparison to inductive based transformers, particularly for very low and very high primary currents. 

The second step was to verify behavior of earth fault protection when residual current is calculated from line currents measured by Rogowski coil. Verification in single phase configuration showed that measured asymmetrical apparent residual current has very small value, which is always safely below typical pick-up values of earth fault protection. Further measurements in three phase configuration confirmed results from single phase configuration. \( I_{o(ap)} \) created as results of unbalanced current between phases due to the different accuracy of the sensors in each phase increases with measured current \( I_p \). \( I_{o(ap)} \) expressed as percentage value of measured current \( I_p \) has exponential character. Gap
between minimum pick up residual current and residual apparent current gives a sufficient safety margin that allows to make conclusion that calculation of the residual current by the IED for earth fault protection from the line currents measured by Rogowski coil will always work in isolated and directly earthed neutral.

The final step was measurement on primary network model where following simulations confirmed no false trip of earth protection when measuring calculating residual current from line currents measured by the Rogowski coil.

- Power transformer inrush current in the system
- Different resistance of the fault currents in isolated neutral networks
- Different resistance of the fault currents in high impedance neutral grounding networks

Based on all measurements done it can be concluded that new rules can be recommended when calculating residual current in IED from the line to ground current measurements by the Rogowski coil. This rules are limited to isolated neutral MV networks and high impedance neutral grounded networks.

- MV feeders up to \( I_r = 3150 \, \text{A} \) and \( I_{k''} = 31.5 \, \text{kA} \). Earth fault currents above 1% of the nominal current can be safely calculate by the IED from the line to ground currents measured by the Rogowski coil
- MV feeders up to \( I_r = 4000 \, \text{A} \) and \( I_{k''} = 50 \, \text{kA} \). Earth fault currents above 3% of the nominal current can be safely calculate by the IED from the line to ground currents measured by the Rogowski coil

The third part of this thesis described seamless integration of sensors and communication bus based on IEC 61850 to medium voltage substation made of air insulated switchgears. Four universal feeders layout were designed in such way that it allows to decouple measuring devices engineering aspects from short circuit selectivity study. This is an important difference to current practice where parameters of inductive based transformers are always given as result of particular short circuit selectivity study. Thesis explained also the limits of communication capacity for 100 Mb/s Ethernet what comes to application of process bus. In general, depending on selected redundancy principle in 50 Hz system, max. 9 IEDs for PRP respectively max. 4 IEDs for HSR can be used as generic SMV publishers when 100 Mb/s Ethernet is used. That means any potential application of process bus requires to check available Ethernet communication bandwidth and decision whether 100 Mb/s or 1 Gb/s shall be used.

Either PRP or HSR redundancy principle must be used for the purpose of SMV share in the substation through the communication. Reliability figures of both redundancy architectures were compared and conclusion if one or the other redundancy principle is better for MV switchgears where SMV are shared in communication bus cannot be made. Both redundancy principles have different pros. & cons. and use of them is application related.
Most important is to stress that transition period from traditional switchgears to switchgears with sensors and digital bus requires flexibility. It means possibility to combine old technology with new technology and search for intersections between what industry and particular customer is ready to accept and where the preference of stay traditional is predominant. This flexibility also allows to collect experience from the real application and helps to understand what the important areas are, as a next focus of the additional testing and development in order to convince industry to use fully digital MV switchgear without traditional technologies. ABB UniGear Digital concept offers this flexibility and that is why it is pioneering product towards to future fully digital MV substations.

My main contributions to the field of energy transmission and distribution and my work and studies in last 6 years about the subject of this thesis can be summarized as follow:

1) Detailed view on Rogowski coil, resistive and capacitive divider accuracy measurement constrains in medium voltage applications. Verification that Rogowski coil and voltage dividers are better alternative for current and voltage measurement in MV application than inductive based instrument transformers.

2) Practical demonstration based on earth fault protection example how the use of the Rogowski coil for current measurement can change today’s practices in residual current measurement and earth fault protection.

3) Definition of standard medium voltage feeders with sensors that allows decoupling of measuring devices engineering aspects from protection and control engineering.

4) New MV substation architecture proposal with seamless integration and utilization of sensors – IEDs – digital communication based on IEC 61850 utility and industry standard.
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SafeGear HD: http://www.abb.com/cawp/seitp202/5f1054466e83c95ac1257c6f004a7369.aspx

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ABSTRAKT

Vzduchem izolované vysokonapěťové rozváděče jsou nedílnou součástí energetického distribučního řetězce a to jak v průmyslovém, tak ve veřejném sektoru. Hlavní funkcí rozváděče je ochrana pracovního personálu, rozpojování/odpojování a spínání, izolování, měření proudů a napětí, chránění a ovládání zatížení a komunikace dat do řídících systémů.

V každé z výše zmíněných funkcí probíhal technologický vývoj v průběhu posledních 40 let. Dnešní rozváděče jsou spolehlivé a elektrickému obloku odolné zařízení, zoptimalizované téměř k fyzikálním limitům dielektrických, elektromagnetických a termodynamických polí. Vakuové vypínače zajišťují stálou a spolehlivou vypínací funkci. Taktéž v oblasti chránění, řízení a komunikace došlo k mnoha technologickým proměnám. Od elektromechanických relé přes zařízení založená na tranzistorech, později na jednoúčelových mikroprocesorech, až po dnešní multifunkční vysoce výkonná mikroprocesorová inteligentní elektronická zařízení. Pouze oblast měření proudů a napětí setrvala z technologického hlediska posledních 40 let beze změny. K dominujícím měřicím technologiím dneška stále ještě patří indukčně založené transformatory proudu a napětí. Byly sice provedeny některé pokusy k obměně technologie měření jako takové, nicméně bez dosažení úspěchu.

Tato disertační práce je zaměřena na poskytnutí nového náhledu na alternativní technologie měření v elektrických sítích a ve vzduchem izolovaných vysokonapěťových rozváděčích, kterou lze využít jak pro měření proudu, tak i napětí. Tato práce vysvětluje, proč Rogowského cívky, odporové a kapacitní dělicí jsou tou správnou volbou a měly by být použity ve vysokonapěťových rozváděčích a podrobně analyzuje přesnost měření a jejich příslušné meze. Dále tato práce popisuje, že pro nasazování nových měřicích technologií musí být postupováno systematicky. Senzory připojené k inteligentním elektronickým přístrojům a schopnosti komunikace založené na IEC 61850 spolu s vysokorychlostní komunikační sběrnici Ethernetu vytvoří systém, který zjednoduší a sjednotí konstrukci rozváděčů a umožní oddělit aspekty projektování měření od studie zkratových selektivit. V práci je také uveden příklad, jak tento nový systém může přinést změny a zjednodušení do oblastí projektování a řízení.

V této práci jsou popsány výsledky několikaletého úsilí při stanovení nových měřicích a digitalizovaných přístupů ve vysokonapěťových rozváděčích pod autorovým vedením. Toto úsilí také vedlo k uvedení nového produktu – UniGear Digital - konceptu od ABB. Závěrečná část práce demonstreuje praktické nasazení všech výsledků v této práci při skutečných aplikacích.