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LINE-DIFFERENTIAL STUDIES

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Opinnäytetyön tarkoituksena oli tutkia vanhoja linjadifferentiaali suojareleitä, jotka käyttävät pilottijohtoja analogiseen kommunikointiin ja selvittää onko vanhoille kommunikointilinjoille vielä käyttäjiä, jos uudet releet pystyisivät näitä käyttämään joko analogisesti tai digitaalisesti.

Aluksi työssä tehtiin asiakastutkimus koskien pilottijohtojen tulevaisuuden käyttötarpeita. Seuraavaksi tutkittiin teoriatasolla Solkor-releiden toimintatapa, sekä releiden kommunikointivaihtoehdot. Lisäksi työssä syvennyttiin jo markkinoilla oleviin kommunikaatio konverttereihin. Vanhaa relepari testataan tarkoituksena selvittää sen toiminta-aika, tarkkuus ja herkkyys kuorman heilahduksille.

Asiakastutkimuksen analysointi jää liitteisiin. Markkinoilla olevien kommunikaatiokonverttereiden käytännön toiminta jäi epäselväksi, koska sellaisia ei saatu testeihin mukaan. Solkor-releen testauksen perusteella laite on tarkka, mutta nopeudessa ei ole uusien sukupolvien veroinen.

Avainsanat differentiaalisuoja, pilottijohto, Solkor, kommunikaatio konvertteri

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ABSTRACT

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The purpose of the thesis work was to study old line-differential protection relays that utilize pilot wires for analogy communication and determine if there still are customers that would use old communication lines if the new relays could utilize them either analogically or digitally.

At first, a customer survey was carried out concerning customers' plans for pilot wires. Next it was studied how the Solkor relays are working in theory and then what the communication options for relays are. Existing communication converters on markets were also investigated. A pair of old relays were tested with a purpose of determining its operation time, accuracy, and sensitivity to load swings.

The results and analysis of the customer survey are given in appendices which are not included in this thesis. The functionality of existing communication converters remains unclear because devices were hard to get for tests. After the Solkor relay testing it can be said that it is accurate when it comes to measuring currents, but the new generation relays are better in operating time.

Keywords	Differential protection, pilot wire, Solkor, and communication converter

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LIST OF ABBREVIATIONS

HMI	Human Machine Interface
IED	Intelligent Electronic Device
IEC-61850	International standard of communication protocols for IED
rms	root mean square, effective value
PC	personal computer
kbps	kilobits per second
Mbps	Megabits per second
MUX	multiplex, telecommunication or computer network that include several devices.
DSL	digital subscriber line
SHDSL	Single-pair high-speed digital subscriber line
EMC	Electromagnetic compatibility

1 INTRODUCTION

The purpose of this thesis is to pre-study old pilot wire and serial communication line differential relays found in markets now and study the defined markets' commercial potential. The aim is also to go through different communication protocols that are in use with above mentioned devices. The main focus is on Reyrolle Solkor line-differential protection relays. This thesis is good knowledge base for future line-differential relay engineering.

1.1 Company Presentation

Arcteq Relays Oy was founded 2010, in Vaasa Finland. Arcteq is known for making the most accurate protection relays in the world and it is the pioneer in arc flash protection. The headquarters and manufacturing facilities are located in Vaasa. Arcteq moved to new facilities in 2020. The research and development centres are in Vaasa and Poland. Over the past decade, Arcteq have had global presence in about 50 countries throughout the world. In addition to high-quality products, Arcteq commits to providing industry-leading support and service to customers. Arcteq's mission is to promote the safe and reliable supply of energy by enhancing power grid protection and control. Arcteq is the only global, independent, and focused protection relay manufacturer.

1.2 Research Problem

The first thing was to determine if there are markets for new generation pilot wire relays. Therefore, a customer survey was made. The survey is presented in Chapter 4.1.

The second problem was to find out the operating principle and characteristics of the pilot wire relays. For this problem, the Solkor R/Rf relays were studied to figure out how they work. The principles are presented in Chapter 4.2. The following chapter presents Solkor N which is more intelligent device compared to Solkor R/Rf. Solkor N can use the pilot wire lines via a modem like new protection relays, but the device is nearly as old as Solkor R/Rf. Solkor R/Rf is one of very few analogy relays that are still in markets and our assumption is that it is still widely in use.

2 LINE-DIFFERENTIAL PROTECTION

Line-differential protection relay is a device that protects feeder lines between circuit breakers. The area between circuit breakers is the protection zone. The line-differential or current differential protection principle is based on Kirchhoff's current law which stated that the current entering and leaving the protection zone is equal. Every current transformer and relay is located at the end of the protection zone. Line-differences can be detected when the feeder line is broken between those current transformers. Line-differential protection cannot detect faults that are not in the protection zone if definitions are made correctly. The protection zone is accurately delineated when it does not require synchronization with other protection functions or additional delay.

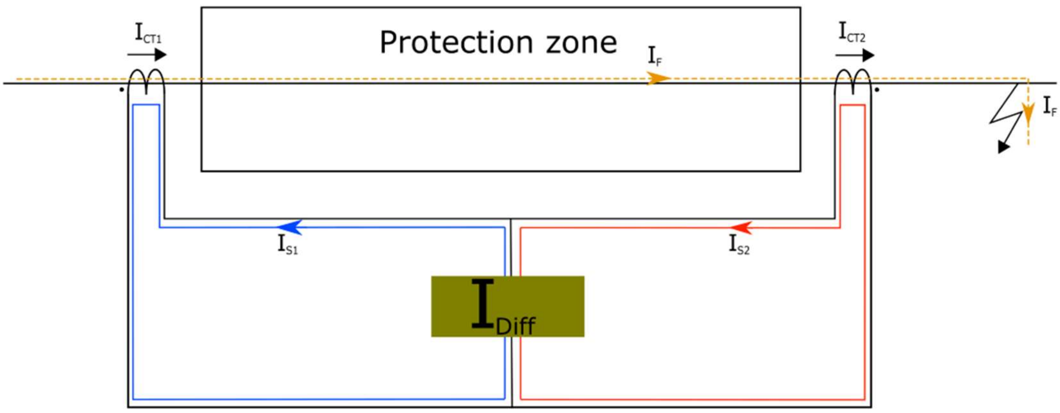


Figure 1. Fault outside of protection zone /1/

In Figure 1 above shows that it is insignificant if there is fault or not. The current is flowing in the same way through both current transformers. Current transformers are however connected mirroring each other so the I_F is measured negative in I_{CT2}. To make it simple we assume the rate of transformers is one to one, then:

$I_{CT1} = I_F$

$I_{CT2} = -I_F$

$I_{Diff} = I_{CT1} + I_{CT2} = I_F - I_F = 0$ => Relays does not trip.

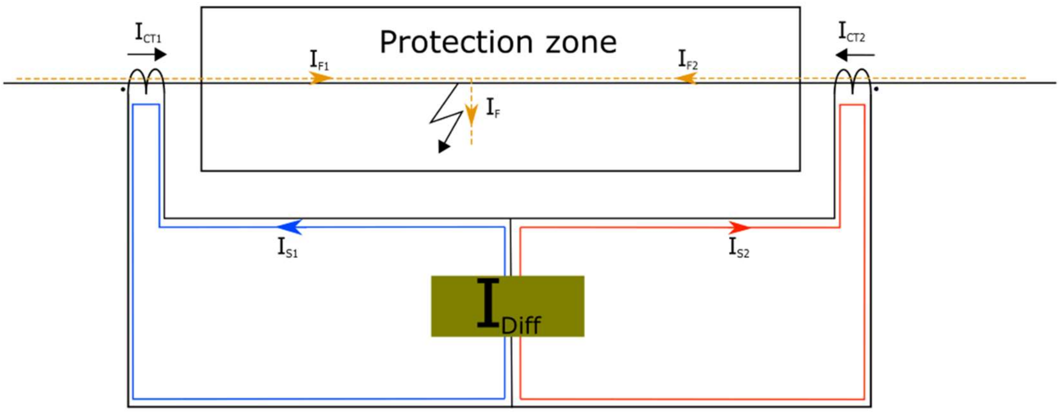


Figure 2. Fault inside of protection zone /1/

Figure 2 shows how currents flow when the fault is detectable. Inside the fault the mathematics will go with the same frame as earlier shown. To simplify the mathematics, we have the same assumption that current transformer ratios are one to one and assume that fault currents are equally sized from both directions then:

$I_{CT1} = I_F$

$I_{CT2} = I_F$

$I_{Diff} = I_{CT1} + I_{CT2} = I_F + I_F > 0$ => Relay do trip.

Detectable faults are phase to phase faults which means that two or three phases are short-circuited with each other. Phase- to- ground faults meaning that one or several phases are short-circuited with ground potential can also be detected. Line-differential relays can also detect if all or some of cables have broken off but in case like that it is usually either of above-mentioned faults is involved.

Line-differential protection function needs two current transformers and that means that it usually needs two relays, too. These relays are in different locations depending on their communication with each other from a few meters to two hundred kilometres from each other. There can be more than just two line-differential relays. In case there are three relays in the same communication surface, one of the relays has two protection zones. It is possible to use only one relay in case there are intelligent current transformers or sensors in use.

New modern line-differential relays incudes other protections than only current differential protection. New relays have IED capabilities such as voltage measurements, controls, communications, and they use IEC 61850 communication protocols. /2/

Line-differential protection devices monitor the condition of current transformers to have accurate data in differential function. The current flow in each phase of the current transformer is monitored with current transformer supervision function. A coil is connected in parallel with the current transformer of each phase terminal. The current transformer supervision function monitors all three phases. Under normal conditions, if the current flow in all three phases is equal, the function becomes inoperative.

3 LINE-DIFFERENTIAL RELAYS COMMUNICATIONS

3.1 Pilot Wire

Pilot wires are two-conductor copper cables between two line-differential relays. Pilot wires are carrying circulating currents between two pilot wire line-differential relays. Pilot lines are named with the voltage insulation level that they have. For example, 5kV pilot lines means that the insulating level of those lines are 5kV rms. The maximum peak voltage applied under fault conditions is 450V. The maximum currents that circulate through the pilot wires under fault conditions are 250mA. With the maximum currents is this little, there is no need for big diameter cables. /3/

In future pilot wires can be used as analogy signal transferring as they have been used already many decades. Analogous signals can be transferred even up to twenty kilometres. Pilot wires can also be used for digital signal transferring. Digital signals can be hard to transfer as long distances as analogue signals, so better way for digital signal transferring is to use a converter that converts the digital signal to analogue signal.

3.1.1 Pure Analogous

Analogous communication is based on current that cycles in pilot wires. Analogous communication is not communication network, it is more like a feeder line than a communication interface, because it does not transfer data on pilot wires. That is why one pair of pilot wires can be connected only to two relays at the time. /1/

When the feeder line is in good condition, it means that in both measuring points the current is flowing to the same direction and equally sized. Summation currents that circulate in the pilot wires are equally sized as well, from both relays. Currents in the pilot wires, however, are directed opposite. Because currents are opposite from each other, the relays will interpret pilot wire currents as zero and do not operate.

When the feeder line is in fault the summation currents are not equally sized. The worst-case scenario is that all feeder lines are broken and relays measuring coils are measuring current from opposite directions. In those kinds of situations both relays can send the same amount of current in the pilot lines and it will be directed same direction. Relays will interpret pilot wire currents double in amount and operates.

In case the pilot wires themselves break the problem will be that relays still detects pilot wire current to add up zero. Therefore, relays will not operate in case the feeder line breaks. This kind of malfunctions can be fixed with a pilot supervisor that detects if pilot wires are not functioning. The supervisor will send information to the relay, and the relay operates whether the feeder line is functioning or not.

3.1.2 Digital Modem

A digital modem is in use with relays that use only a digital communication protocol. Pilot wire modems use serial communication. It is used to increase the distance between line-differential relays. Nowadays it is used only if the existing wires are not changed.

Pilot wires are the same type of cables than normal analogue relays use. Serial communication is used when the modem is in the same station with the relay. The length of the serial cable between the relay and the modem can be only from zero to two meters. The digital modem might have fibre optic to pilot wire conversion. Optic cables allow modems assembly further away from relays. Optical modems can be used also between two separate pilot wire lines. This solution allows to double the distance of pilot wire relays from each other.

3.2 Digital Communication

Digital communication-based relays communicate with each other’s digital signals and can communicate with several relays at the same time. Digital communication has possibilities to send and receive information with a

PC. Current transformers still need their own relays and line differential protection function needs as many devises as analogue. Digital communication between devices can be send over a fibre optic or metal wires. Metal wires need to be protected against high voltage lines in case there is a possibility to indicate currents from powerlines to data transferring lines.

Serial communication uses metal wires and it most usually uses the RS-232 or RS-485 communication protocol. Both RS communications use the same kind of connectors, but the pin orientation of the connectors and communication protocol is different. The RS-232 communication has an ability to transfer data only for several meters and the transmission rate is low, the maximum data rate being 19,2 kbps. That is why RS-232 is usually used to transfer data between the relay and the converter. RS-232 can handle only two devices at the time, the sending and receiving ends. Converters can be from RS-232 to fibre optic, RS-232 to ethernet or RS-232 to pilot wire. The RS-485 communication can be used up to a few kilometres. RS-485 is used straight relay- to- relay or relay- to MUX- communication. In relay- to- relay use, RS-485 has also two devices in the communication network. In the MUX communication each relay is connected to the same network and with RS-485 the maximum number of devices can be thirty-two. The maximum data rate with RS-485 is 10Mbps, which is over five hundred times more than RS-232. /4/

Fibre optic communication is based on flexible transparent fibre that transfers light signals inside. The fibre is usually made from glass or plastic. The function of fibre optic cable is based on light signals travelling through a transparent fibre. The length of the optical cable can be hundreds of kilometres. A long distance consumes the data rate speed compared to a short distance optical cable.

3.3 Communication Interfaces vie Telecom Network

3.3.1 G.703 64kbit/s (E0)

G.703 is an encoding standard developed by the International Telecommunication Union for interfacing data communications equipment with digital high-speed synchronous communication services. G.703 64kbit/s is a co-directional interface type. This type of communication is performed via 2*2 wire isolated galvanic type interface. The protection device is connected to a multiplexer or gateway which is responsible for protocol/speed conversion. The impedance over cables is 120Ω and the cable length up to 50m. /5/

3.3.2 C37.94 Nx64kbit/s

The IEEE C37.94 standard defines the rules to interconnect tele protection and multiplexer devices from different manufacturers using optical fibres. The IEEE C37.94 standard describes the N times 64kbit/s optical fibre interface between the protection device and multiplexer equipment. The data rate can be 1-12*64kbit/s with 64kbit/s steps. C37.94 uses fibre optic cables, and its wavelength is 850 nm. /5/

3.3.3 G.703 2.048Mbit/s (E1)

Communication takes places via telecom networks like G.703 64kbit/s but the data rate is higher, 2.048 Mbit/s. /5/

3.3.4 G.991.2

G991.2 is an SHDSL protocol that allows high-speed full duplex communication over one pair of copper wires. The data rate is 192 kbit/s to 15304 kbit/s depending on the communication distance. /11/

4 PRE-STUDY

4.1 Customer Survey

The purpose of the customer survey was to evaluate if it is possible to develop business opportunity for pilot wire replacement. The survey was directed to Arcteq Relays Oy resellers. In the survey we were interested in which resellers have pilot wire relays installed in their region and how many pilot wire applications they have currently in use. Valuable information was also how and in what time the customers of our resellers are going to upgrade their pilot wire relays.

One question considers pilot wire line-differential relays which are analogous communicating relays. The purpose on that question was specifically give us the knowledge what customers are going to do with those kinds of relays. In following question purpose is to give information on what customers are going to do with serial communication line-differential relays that utilize pilot wires for communication over the converters.

One of the questions was mapping which manufacturer relays the customers have in use. This information is valuable when we are starting to produce a possible compatible product. Compatible product would let customers to change only one end of the line-differential protection. We think that would be a market trump especially when customers are also changing the other end, maybe after few years, and we have our modern IED device already assembled at the first end.

A few questions were mapping how big the annual opening in the market is and how much customers are ready to pay for new generation relays, that may come available.

The last question was free comment in case the above questions and response options were not covering some customer needs.

The survey was made using Microsoft Forms and it was sent to resellers straight from there. Arcteq has a licence to Microsoft 365 which includes Forms. This was considered the easiest way to produce this kind of survey.

4.2 Requirements for Communication Converter

The main requirement is a ten-kilometre radius for communication. For Arcteq it would be beneficial if the converter uses ethernet port for the converter- to- device communication. When the information is transmitted via copper cables between converters, it is important to have protection against other electromagnetic interfaces. The device should comply with CISPR 32, FCC Part 15B standard, which is part of EMC Directive 2014/30/EU. This means that the device can disturb the surrounding devices with its own magnetic fields, which also means that it can better handle other magnetic fields around it. The CISPR 32 standard can be used only when device frequency is in range of 9 kHz to 400 GHz. /6/

4.3 Existing Communication Converters

4.3.1 Siemens 7XV5662-0AC00 / 7XV5662-0AC01

The communication converter copper (CC-CO) is a peripheral device linked to the protection device which enables interference-free data transfer between the CC-CO and the protection unit. The converter uses optical interface with a protection relay and converts that serial data into a frequency-modulated signal. The distance between the converter and the relay can be 0 to 1,5 km. Converters use 5 kV isolated pilot wires for communication with each other. The maximum length of pilot wires with synchronous operation is 15 km and the data rate up to 128 kbit/s. Asynchronous operation allows baud rate for protection unit to 38,4 kbit/s. The maximum loop resistance of the pilot wire is 1400 Ω which means that in 15 km distance the maximum resistance is 46,5 Ω/km. The power consumption is approximately 2,5 W or 9,5VA. The converter has internal power supply with two-pole screw-type terminal 24 to 250V DC or 115 to 230 V AC. /7/

4.3.2 Siemens 7XV5662-0AA00

The communication converter CC-XG for coupling to a communication network is a peripheral device linked to the protection device via fibre optic cables which enables serial data exchange between two protection relays. The electrical interfaces in the CC-XG for the access to the communication device are selectable as X.21 (64 kbit/s, 128 kbit/s, 256 kbit/s or 512 kbit/s) or G.703.1 (64 kbit/s). At the opposite side, the data are converted by second communication converter so that they can be read by the second device. The power consumption is approximately 2,5 W or 9,5VA. The converter has internal power supply with two-pole screw-type terminal 24 to 250V DC or 115 to 230 V AC. /8/

4.3.3 Siemens 7XV5662-0AD00

This converter can use RS232 or fibre optic interface for communication with the protection relay. For communication between converters, they can use fibreoptic or four wire G703 interface. The power consumption is approximately 2,5W or 9,5VA. The converter has internal power supply with two-pole screw-type terminal 24 to 250V DC or 115 to 230 V AC. /9/

4.3.4 ABB RPW600

ABB RPW600 is a pilot wire modem. There is always need for two variants of RPW600, master and follower which always need to be used as counterparts in a pilot wire communication link. A typical line length between the devices is 8 km. Protection device- to- modem communication is fibre optic based. Communication between modems is implemented with a twisted pair wire. Pilot wires are 5 kV isolated from electronics. The average power consumption is 4,8 to 5,5 watts. The modem has a DC power supply of 24 to 110 volts. /10/

4.3.5 Westermo DDW-120

Westermo DDW-120 is ethernet to DSL, end to end, converter. Communication between the device and the converter is made with a CAT5 ethernet cable. The line between converters is one pair of twisted copper wires with the IEEE G.991.2 interface. The distance between converters is promised up to 15 km depending on wire size and condition. The data rate is from 192 kbit/s to 15Mbit/s. DDW-120 has a 2.5 mm jack as a service port. The average power consumption is 2,88 watts. The DC power supply is from 12 to 48 volts. /11/

4.3.6 Phoenix Contact SHDSL/SERIAL

Phoenix Contact SHDSL/SERIAL-modem is a serial- to- DSL converter. Communication between converters is done with the IEEE G.991.2 interface. Converters can be located up to 20 km from each other and there is a possibility to use one or two pair of twisted copper cables. With one pair the data rate is from 32 kbit/s to 15Mbit/s and with two pairs the data rate is double that. Communication can be done with RS-232, RS-422 or RS-485 interface. The power consumption is approximately 36 watts. The DC power supply is 24 V. /12/

4.4 Solkor R/Rf

Solkor R/Rf is completely analogue pilot wire line-differential relay. It does not need an external power source to operate. Relays are powered from current transformers from measurement currents. Solkor R/Rf's requirement for current transformer as follows:

$U_k = \frac{50}{I_n} + \frac{I_F}{N}(R_{CT} + 2R_L)$, where:

U_k = Knee point voltage of the current transformer

I_n = Rated current of Solkor R/Rf relay.

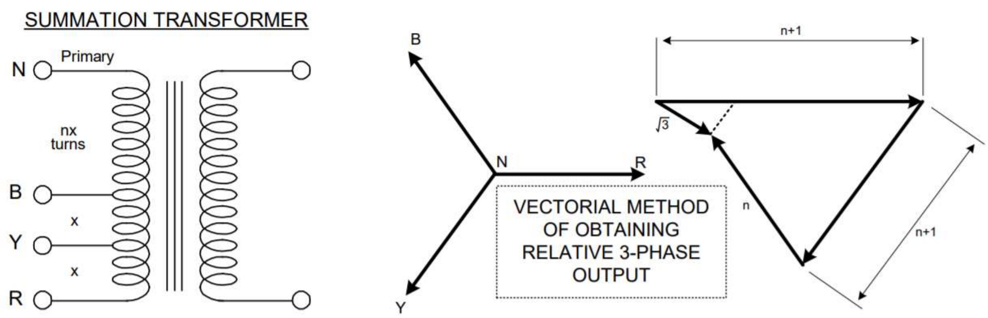
I_F = Primary current under maximum steady state through fault conditions.

N = Current Transformer ratio.

R_{CT} = Secondary resistance of the current transformer

R_L = Lead resistance between the current transformers and the Solkor R/Rf per phase. /3/

The Solkor R/Rf relay consist of summation transformer, short circuit summation transformer, three non-linear resistors, a tapped resistor, three diodes and several opening and closing contactors. The summation transformer ads up the current coming from current transformers and forms a vectorial summation current. As shown in Figure 3, the summation current has a unique form depending on the fault type. The summation current is the current which is compared in short circuit summation transformer to other current that comes from the second relay over pilot wires. When the short circuit summation transformer summation is other than zero amperes, it will send the tripping command to the circuit breaker. /3/



Fault Type	Effective Primary Ampere-turns	Relative Output
R-E	I(nx + x + x) = Ix. (n+2)	n+2
Y-E	I(nx + x) = Ix. (n+1)	n+1
B-E	I(nx) = Ix. (n)	n
R-Y	I(x) = Ix. (1)	1
Y-B	I(x) = Ix. (1)	1
B-R	I(2x) = Ix. (2)	2
3P	I(√3x) = Ix. (√3)	√3

Figure 3. Summation transformer output in different fault types. /3/

The purpose of the non-linear resistor is to limit the appearing voltage across the pilot wires. Using Solkor R mode the peak voltage applied to pilot wires under fault conditions is 300 V when using Rf mode the same voltage is allowed to be 450 V. /3/

The purpose of tapped resistor at both ends is to bring the total resistance of the pilot loop to standard value. The maximum resistance value using R more is 1000 Ω and using the Rf mode it is 2000 Ω. Solkor's tapped resistor has five additional terminals along its length, which are 35, 65, 130, 260 and 500 ohms. The chosen resistance value using R mode should be as near as possible to ½(1000-R_p) ohms, where R_p is the measured or calculated pilot resistance. When using the Rf mode, the chosen resistance value should be as near as possible to ½(2000-R_p) ohms. /3/

With the Rf mode there is an option to use a 15 kV isolating transformer. The tapped resistor value should be chosen as near as possible to ½(SV-R_p)/T ohms, where T is additional isolation transformer tap, SV is maximum pilot loop resistance with each isolating transformer tap and the R_p is the measured or calculated pilot resistance. Table 1 is showing how isolation transformer taps affects maximum pilot loop resistance and peak voltages applied to pilot wires under fault conditions. /3/

Table 1. 15 kV isolation transformer taps. /3/

Number of Pilot cores required 2

	Rf mode with 15kv Transf.		
	Tap 1	Tap 0.5	Tap 0.25
Max. Loop Resistance	1780 Ω	880 Ω	440 Ω
Peak Voltage applied to pilots under fault conditions	450v	330v	225v

Pilot wires circulate the vectorial current between short the circuit summation transformers that comes from the summation transformers. The maximum current flowing over the pilot wires under fault conditions while using the R mode is 200 mA and using the Rf mode the maximum current is 250 mA. The Rf mode when using a 15 kV isolation transformer, the maximum pilot wire current under fault conditions depends on which tap is in use. When tap 1 is in use, the maximum current is 250 mA. Using tap 0,5 the maximum current increases to 380 mA. With tap 0,25 the current rises to half on amper. /3/

The fault type can be determined of the magnitude and direct of the current. When calculating the fault type, it is important to know the number of winding circles, as shown in Figure 3. /3/

Solkor R/Rf connections are simple. There are four inputs for current transformers one for each three phase and one for other ends of the current transformers. For pilot wires Solkor has two connection points. One point to send the tripping command to the circuit breaker. Solkor also has three connection points for external tripping command, for example from the pilot wire supervisor. Above mentioned connectors can be chosen if they are opening or closing contactors. /3/

4.5 Solkor N

Solkor N is a serial communication based, more modern line-differential relay compared to Solkor R/Rf. Solkor N has other protection functions than only line-differential protection. Solkor N has overcurrent protection and high-set and low-set element that can be added for line-differential function. The high- and low-set elements cause tripping if currents are similar from each end, but it is too low or too high after pre-set time. Solkor N has also a few supervision operations. Inter-trip operation ensures tripping at both ends and it is used with external tripping that receives a tripping signal from another device. Solkor can also supervise its own trip circuit condition and the condition of current transformer winding. /4/

Solkor N uses only digital communication protocol, but it has one option to use a pilot wire modem. Communication between the relay and the modem is implemented with RS232 cable that is at maximum 1,9 metres long. Between modems there are one or two twisted pares of pilot wires. /4/

Serial communication with the Solkor N is implemented with four wire RS485 interface. The maximum length of RS485 cable is two kilometres. /4/

Fibre optic communication is also optional for Solkor N. Solkor N has fibre optic communication port for MUX or PC communication and own optical port for communication between relays. With Solkor N the optical cables can be forty-nine kilometres long. /4/

Solkor N has, like Solkor R/Rf, measurement inputs only for phase currents coming from current transformers. Unlike Solkor R/Rf, Solkor N needs an external power supply to maintain its own power and protection functions functionality. /4/

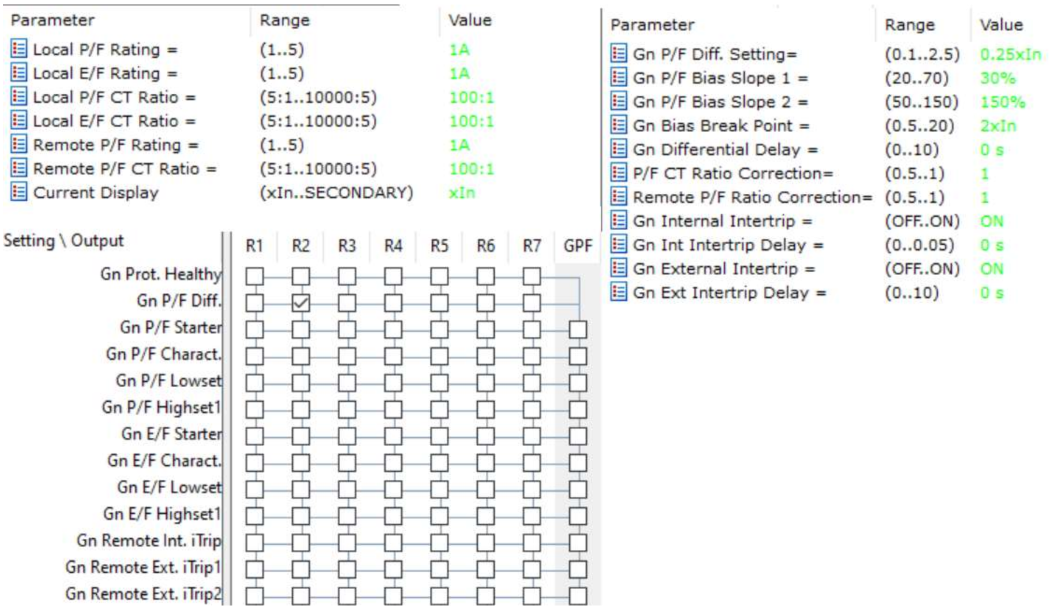
5 TESTING

Due to the delivery times only one pair of Solkor N devices with optical communication interface were tested. The tests focused on measuring the operating time, differential accuracy, inrush current and how sensitive it is to the swings of the load. During the tests, other protection functions were not in use, ensuring that overcurrent, for example, did not cause the trippings.

Two different testing devices were used, Ponovo L336i, where the currents were arraigned manually, and Omicron CMC 356, where fault scenarios were simulated with PSCAD 4.6.1 Professional. Using feature called Advanced TransPlay the Omicron was able to open PSCAD simulation files. Ponovo and Omicron have two sets of three-phase output terminals for current, which were connected straight to the relays 1A current measuring ports. Both devices also have binary inputs for monitoring when the relays are operating.

Before the tests, the relays settings were set identically for both ends. The most important settings are shown in Figure 4. R2 is a binary output in Solkor N which was connected to the binary inputs of the test device. Figure 5 is differential characteristic that shows in theory when the differential relays should trip with settings that was used. Differential currents above the characteristic line should cause a trip and below should not. /4/

I Diff in Figure 5 vertical axel shows the secondary current difference between current transformers. I Bias on the horizontal axis is basically the average secondary current measured in current transformers. /13/



Parameter	Range	Value
Local P/F Rating =	(1..5)	1A
Local E/F Rating =	(1..5)	1A
Local P/F CT Ratio =	(5:1..10000:5)	100:1
Local E/F CT Ratio =	(5:1..10000:5)	100:1
Remote P/F Rating =	(1..5)	1A
Remote P/F CT Ratio =	(5:1..10000:5)	100:1
Current Display	(xIn..SECONDARY)	xIn

Parameter	Range	Value
Gn P/F Diff. Setting=	(0.1..2.5)	0.25xIn
Gn P/F Bias Slope 1 =	(20..70)	30%
Gn P/F Bias Slope 2 =	(50..150)	150%
Gn Bias Break Point =	(0.5..20)	2xIn
Gn Differential Delay =	(0..10)	0 s
P/F CT Ratio Correction=	(0.5..1)	1
Remote P/F Ratio Correction=	(0.5..1)	1
Gn Internal Intertrip =	(OFF..ON)	ON
Gn Int Intertrip Delay =	(0..0.05)	0 s
Gn External Intertrip =	(OFF..ON)	ON
Gn Ext Intertrip Delay =	(0..10)	0 s

Figure 4. Relay settings

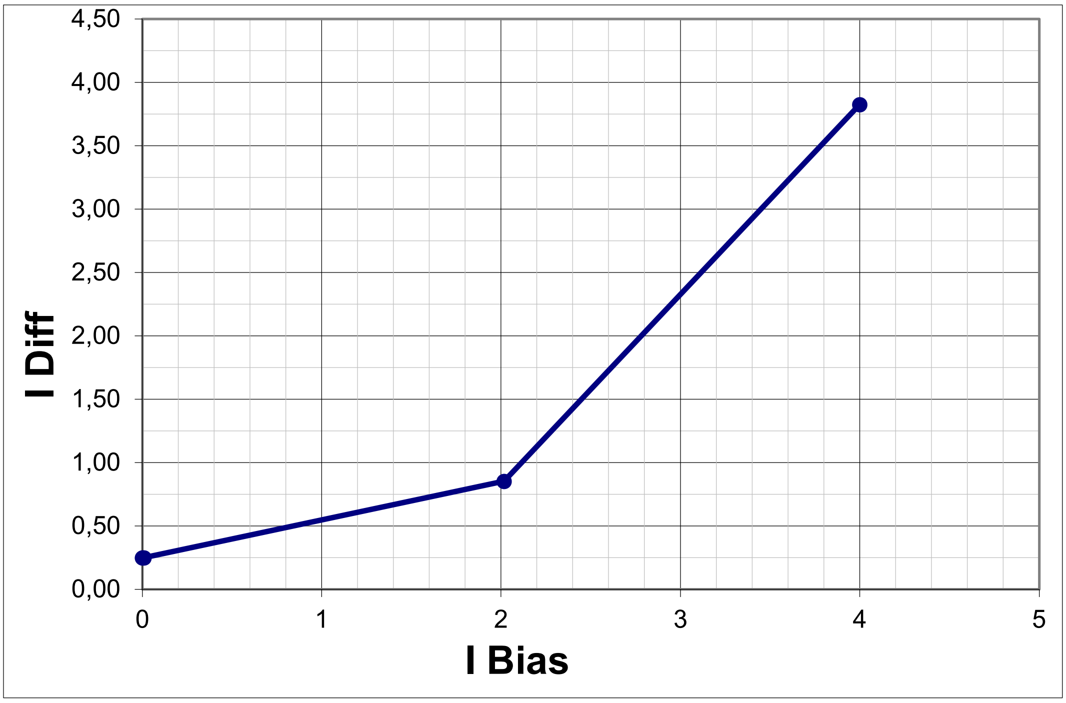


Figure 5. Differential characteristic

Figure 6 shows the simulated network. Unlike in Figures 1 and 2, both current transformers are facing the same direction, that is because relays were manually wired for measuring currents, as it is right in theory. When currents were simulated for different directions, the relays were operating only in scenarios where the fault was outside the protection zone.

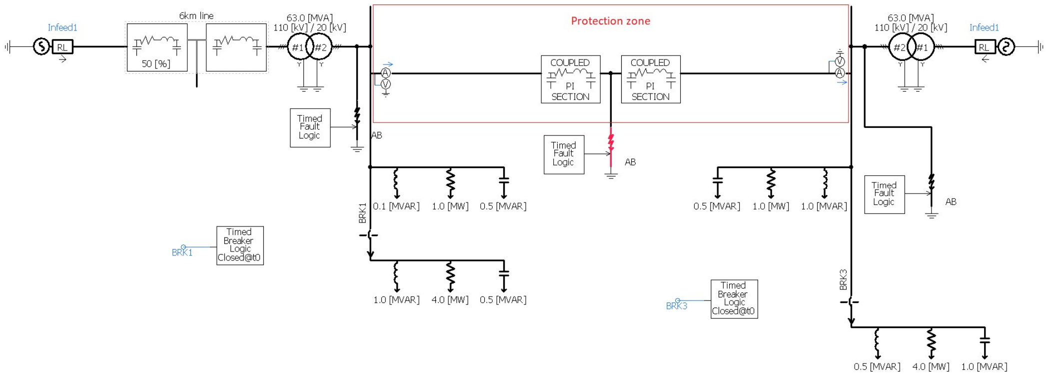


Figure 6. PSCAD simulation network.

The protection zone was simulated to be an 8km long 3-phase line. The line was formed of two similar line components and the fault point had located between them. The location of the fault can be changed for different line lengths, just to ensure that summary on lengths keeps at 8km, for example 4000m – 4000m, 7500m – 500m and 500m – 7500m were the line length used while simulating the faults.

5.1 Operating Time

The operating time is the time from the fault start to point when both relays are operating. The operating time was tested with both testing devices, but the data from Omicron was easier to process, so mainly that data was used.

Overall, sixty documented tests were made with Omicron where both relays were functioning under the fault. A mean distribution figure was made from the results. Figure 7 shows that best operating time was 38,7ms and the worst was 51,1ms. The median operating time was 44,75ms, which is good operating time considering the age of the device. However, Solkor N is not as fast as new relays are, AQ relays promises operating time less than 20ms. The standard deviation is 3,66ms which is eight percent out of the median time. Eight percent deviation is not good accuracy. /2/

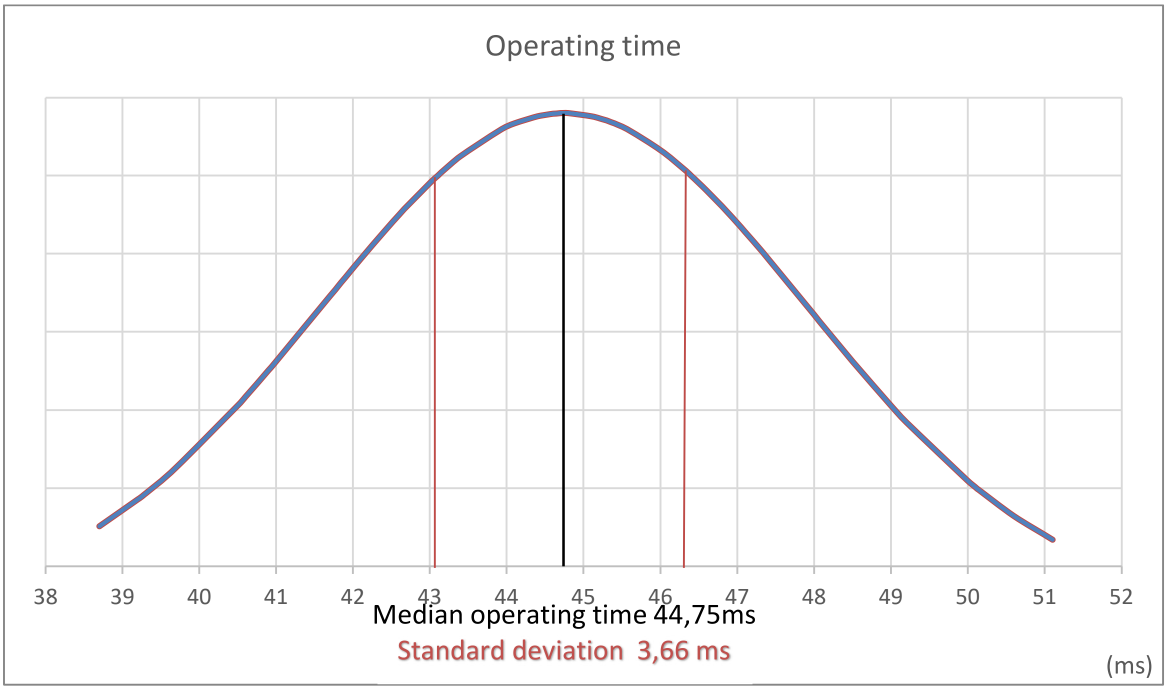
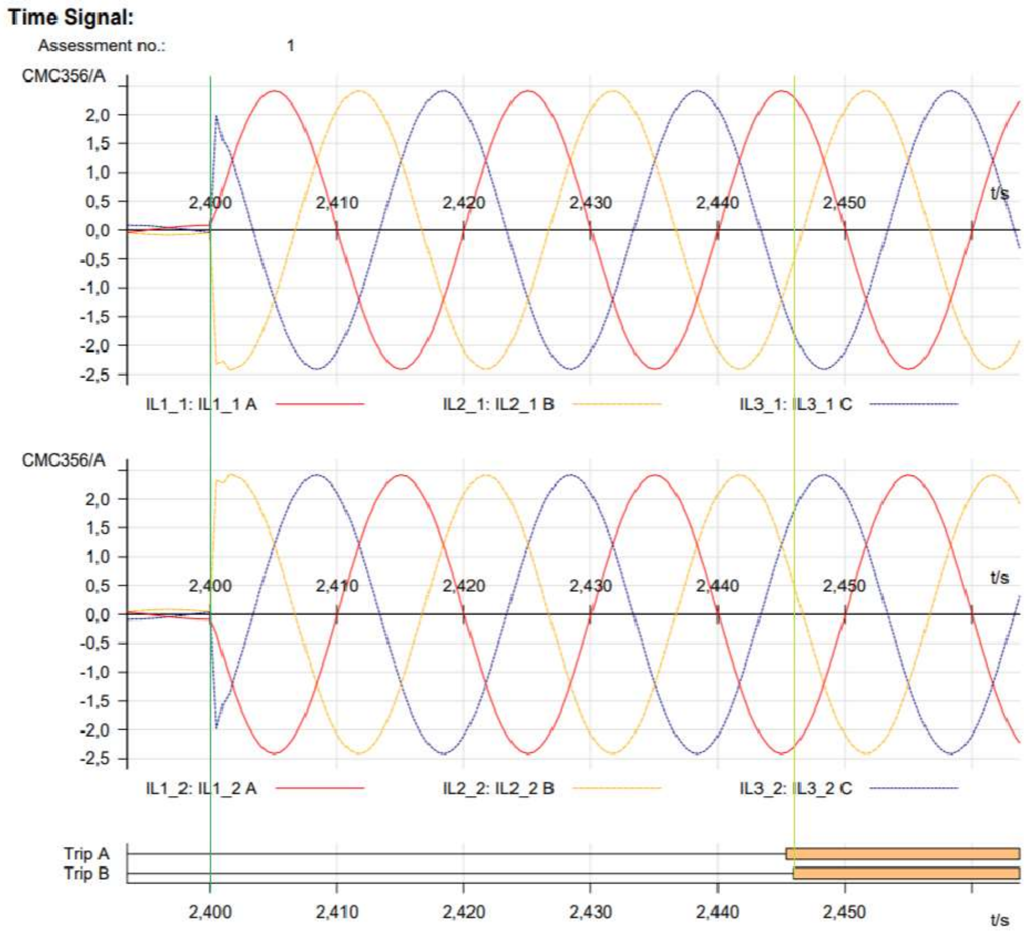


Figure 7. Operating time under fault

Figure 8 shows one fault scenario where a three-phase fault is in the middle of the protection zone. Cursor 1 shows the fault starting point and cursor 2 shows the point where a slower relay is operated that determines the operating time of protection function. Trip A and trip B are previously mentioned binary inputs which are representing the operation of the relay in each end.

In this case the operating time has been 46ms, which is slightly more than median.



Cursor Data

	Time	Signal	Value
Cursor 1	2,400 s	<none>	n/a
Cursor 2	2,446 s	<none>	n/a
C2 - C1	46,00 ms		n/a

Figure 8. Three-phase fault

5.2 Accuracy

In accuracy tests current differential accuracy and the simultaneity of the operation of relays was measured with Ponovo and Omicron.

The differential accuracy was tested with Ponovo. 180 test runs were made with little current steps, 90 with high current and 90 with low current, increasing one to three current over to nominal current median tripping knee point with secondary current difference was 644mA. While lowering the current below the nominal current the median secondary current difference was 475mA.

In low currents the smallest current difference causing the trip was 470mA, after 467mA difference all test cycles caused a trip. Figure 9 shows how many times, out of 15 cycles, each differential current has caused tripping. Figure 9. also shows where the median current difference settles on the curve. Figure 10 shows how above-mentioned currents are setting in differential characteristic.

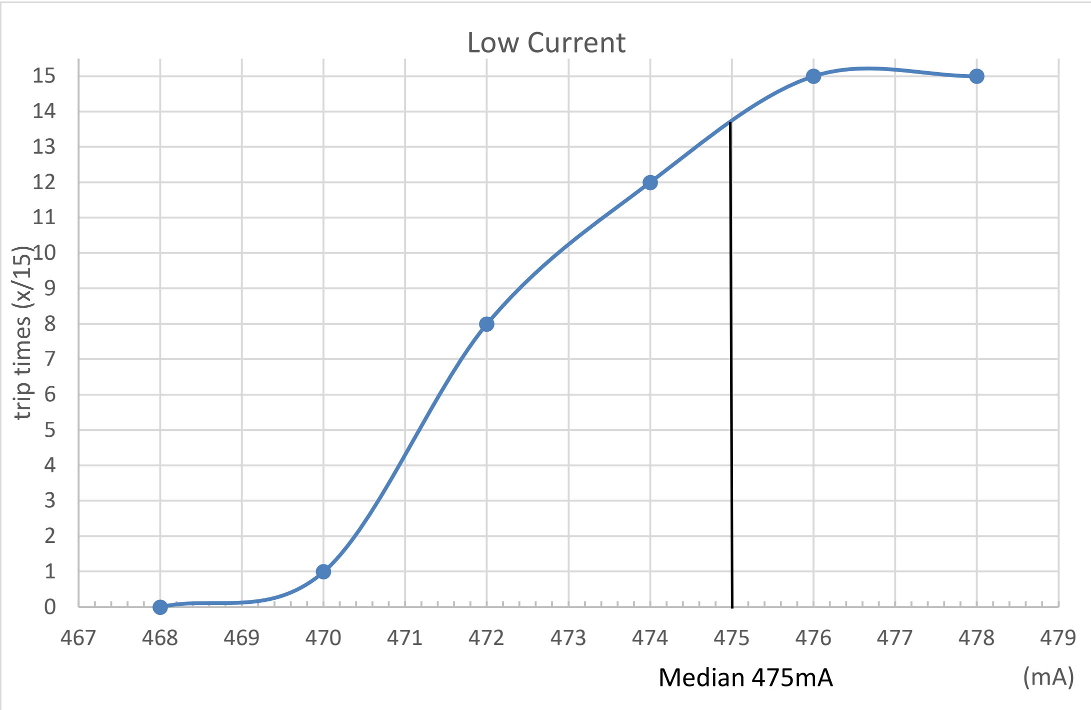


Figure 9. Differential current causing trip (low current)

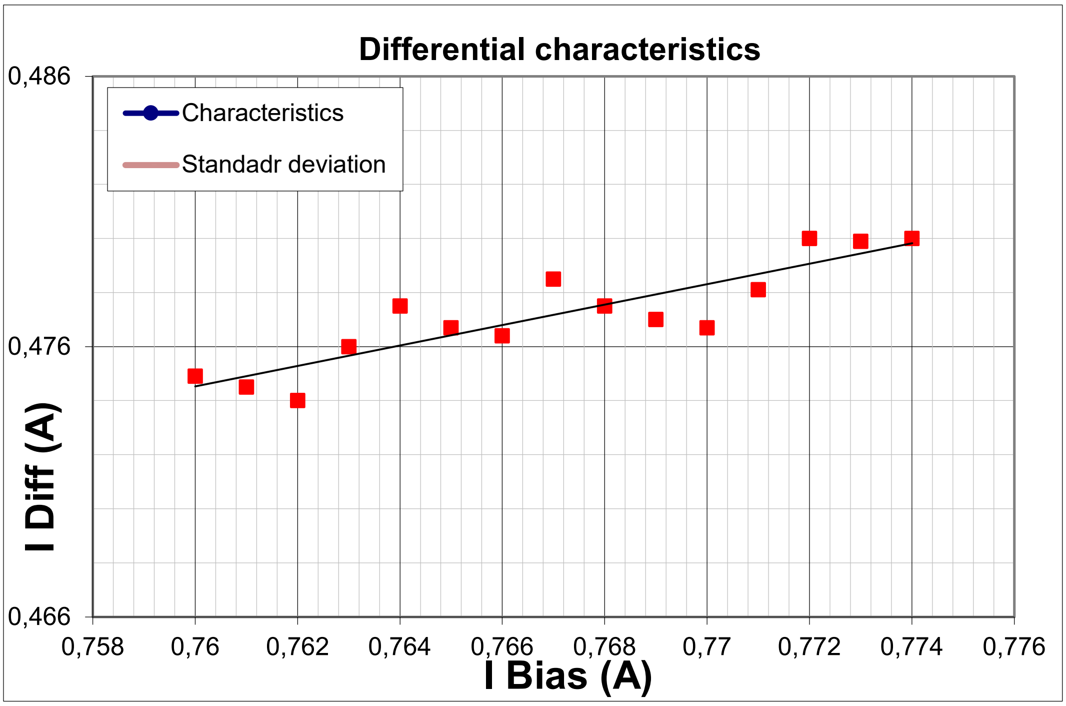


Figure 10. Capture from differential characteristic

In high currents the smallest current difference causing the trip was 641mA, after 645mA difference all test cycles caused a trip. Figure 11 shows how many times, out of 15 cycles, each differential current has caused tripping.

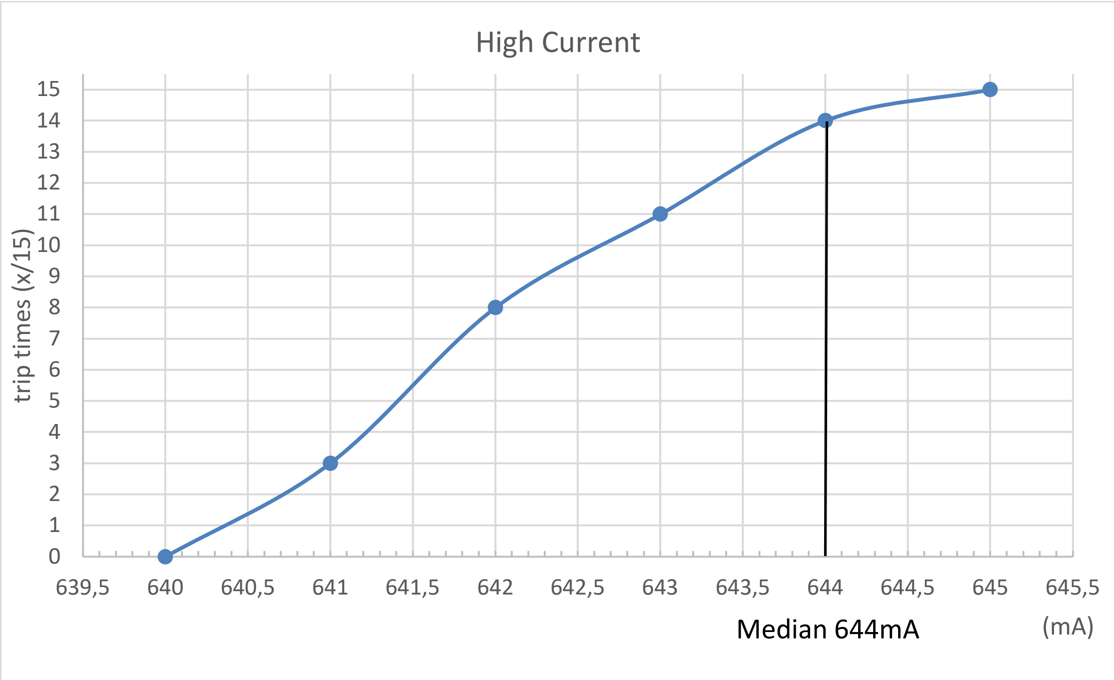


Figure 11. Differential current causing trip (high current)

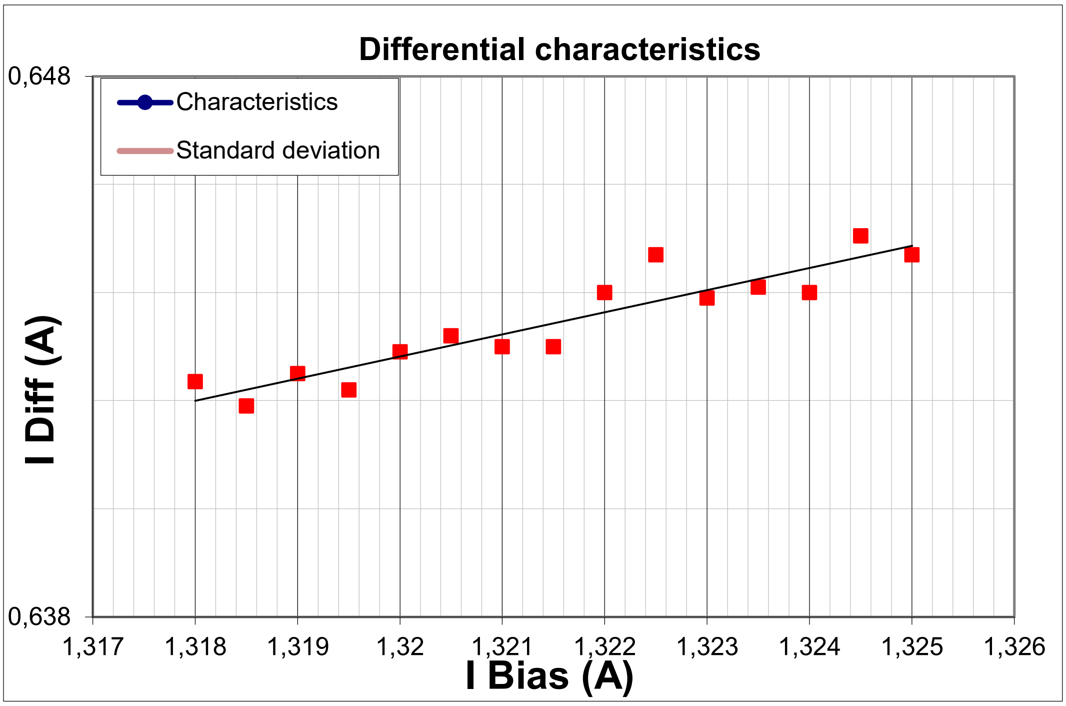


Figure 12. Capture from differential characteristic

Figures 10 and 12 show how the measured values are matching well with theoretical differential characteristic. Red dots are measured values and theoretically every dot should locate between standard deviation lines. Test sampling was narrow, but the accuracy shows to be good. In figure 10 67 percent of measured differential currents were between standard deviation lines. In figure 12 the corresponding result is 73 percent. In both cases the trendline is little steeper than characteristic line, so it can be that the relay is not fully linearly adjusted, or the sampling is just too narrow.

The simultaneity of the operation of relays means the time between relays have operated under the fault. The best scenario is that both relays are tripping at the same time and that kind of test result were obtained twice. The worst time between relays tripping was 3,52ms. The median time between relays tripping was 1,408ms and Figure 13 shows the normal distribution of tripping time differences. The median time difference is roughly

3% out of median total operating time. Figure 14 demonstrates how time difference was measured from Omicron test reports.

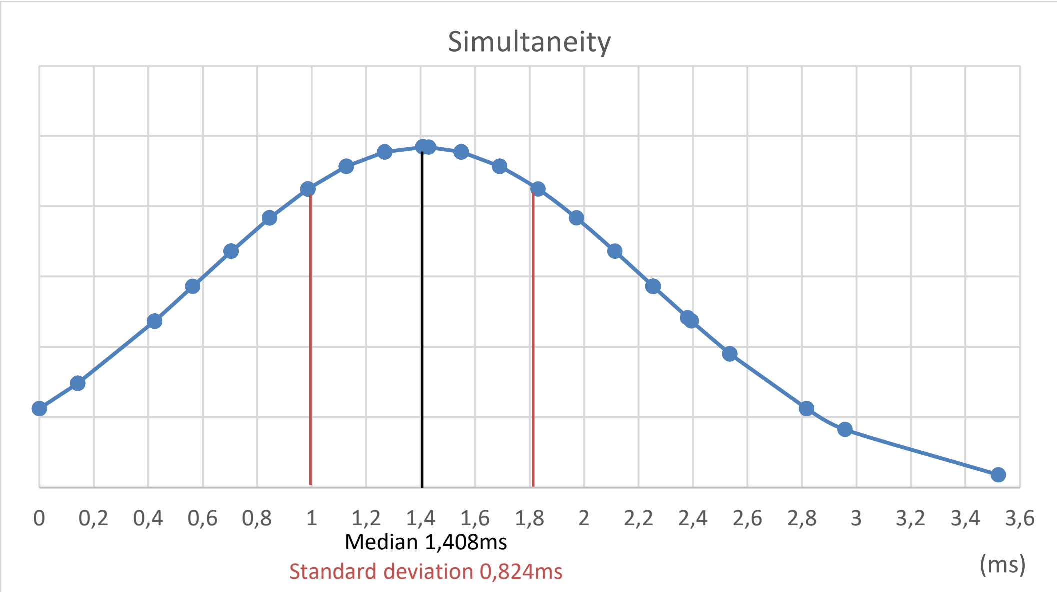
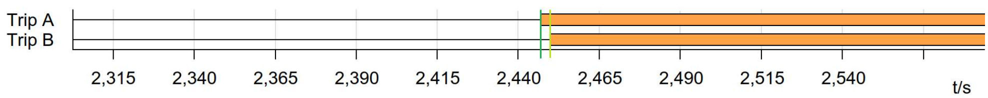


Figure 13. Time difference between tripping



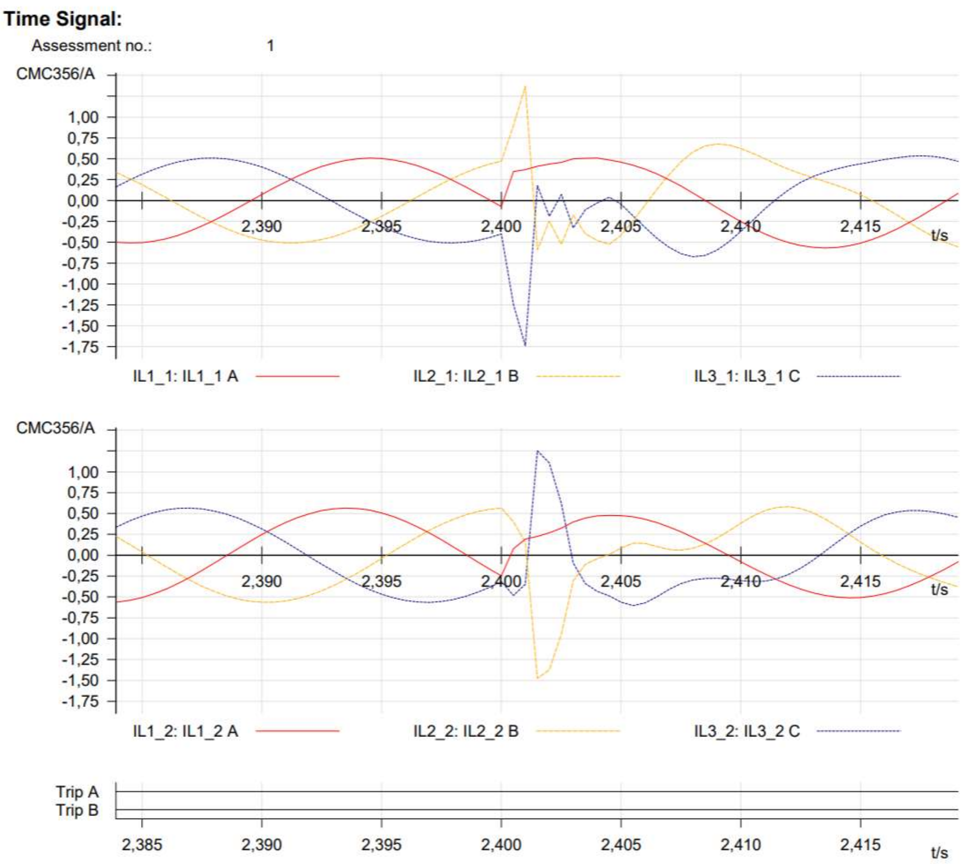
Cursor Data

	Time	Signal	Value
Cursor 1	2,447 s	<none>	n/a
Cursor 2	2,450 s	<none>	n/a
C2 - C1	2,900 ms		n/a

Figure 14. Simultaneity of the operation of relays

5.3 Inrush Current and Load Swing Sensitivity

Solkor N is not sensitive for inrush currents or load swings. When only differential function was in use, Solkor did not react on any current swings if the lines were in good condition. This was tested with several different load addings and cuttings but even adding double sized loads the relay did not trip. Figure 15 shows what happened when double sized load was added at the other end of the line. Even if current momentarily swings and the current different is over 2A relays did not operate because the wave-forms are rapidly returning in symmetric shape. Different currents are ap-pearing only 5ms. When the tripping takes at least 38ms the swinging that short does not cause the tripping.



Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	4,500 s	<none>	n/a
C2 - C1	4,500 s		n/a

Figure 15. Adding load

6 SUMMARY

The next step with the work would be discovering how the hardware and software of converters and AQ relays fit together. This should be done with several manufacturer device to discover which provides the best functionality.

After the best converter has found the next step would be acquiring a pair of communication converters and test how they are functioning with 10km long twisted copper cables. The focus at those tests should be in communication delay and accuracy to ensure that converters do not have a significant negative effect on the characteristics of relays. If possible, also the protection against magnetic fields should be tested.

The last step would be an internal IO card for pilot wires. The internal card would not be considered if time delay and accuracy, with external converter, are at a sufficient level.

For pilot wire applications there are several options that can be added to nearly any protection relay that has a line-differential function. Some theoretically suitable devices might not work as they should. To quote a contact person, who is already using third party communication converter. There have been communication difficulties so they can not safely take guarantee for the modems. When deciding, whether to use a converter, self-made or third party, one needs to be certain the converter is suitable for surroundings the device is located to avoid having with data transmission. /4/

The price is also an essential factor. A line-differential relay with communication converter is significantly more expensive than just a relay. That is why it needs to be clear what kind of markets there are. There are situations where it is smarter to use a converter and situations when it is more profitable to change the pilot wires to optical fibres.

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