

# **Generator Shaft Current Protection With ABB REX640 Protection Relay**

Jesse Parviainen

Degree Thesis for Bachelor of Engineering

Degree Programme in Electrical Automation Engineering

Vaasa 2022

# 1 Acknowledgements

Firstly, I would like to thank my teacher Ronnie Sundsten, who provided me with helpful guidance throughout my academic journey.

I would also like to express my sincere appreciation to my colleagues at ABB Energy Industries who have been an integral part of my professional journey. To my supervisor Tapio Karppi, who entrusted and motivated me to write this thesis work. To Akseli Juslin, who provided me with helpful guidance in writing the thesis work. To Jukka Prusti and Owe Bäck, who provided the expertise and knowledge to help me with the thesis work. To Henri Hämäläinen from ABB who provided me with the testing gear and helpful advice.

To my classmates, thank you for the fun we have had during our studies and for the friendships made. I am grateful for your invaluable contributions to my growth and development, and I look forward to continuing our friendship in the years ahead.

**BACHELOR'S THESIS**

Author: Jesse Parviainen  
Degree Programme: Electrical Engineering and Automation, Vaasa  
Specialisation: Automation Technology  
Supervisor(s): Ronnie Sundsten, Novia and Tapio Karppi, ABB

Title: Generator Shaft Current Protection With ABB REX640 Protection Relay

---

Date: 27.04.2023    Number of pages: 63    Appendices: 0

---

**Abstract**

This thesis work has been written for ABB, for the Energy Industries department in Vaasa. The thesis work helps the constant product development within ABB.

Shaft current protection plays a vital role in preserving the good working conditions of a generator. The bearings might get damaged due to Electronic Discharge Machining (EDM) that occurs when shaft currents are flowing in the generator. If the generator is not well protected against shaft currents, the generator might fail only after a few months from the start, resulting in major financial losses.

This thesis work will implement measurements and protection against high shaft currents in the generator shaft. Previously the RARIC protection relay and the ILDD current transformer were used for the purpose of shaft current protection. However, a new solution was necessary since manufacturing has stopped for the RARIC. This will be done by presenting the theoretical background for shaft voltages and currents, solutions and the tests and results for the REX640.

The measuring arrangements and PCM600 settings were first planned before the thesis work was put into practice. The test arrangements include the Rogowski coil with an integrator box, a Knick amplifier, FREJA relay testing system for the shaft current simulations, and the REX640 protection relay.

The tests will include the necessary parameter settings, the different harmonics, and the generated disturbance records from said tests.

---

Language: english

Key words: shaft current protection, generator, Rogowski Coil, Protection Relay

**EXAMENSARBETE**

Författare: Jesse Parviainen  
Utbildning och ort: EI- och automationsteknik, Vasa  
Inriktning: Automationsteknik  
Handledare: Ronnie Sundsten, Novia och Tapio Karppi, ABB

Titel: Axelströmsskydd med Rogowskispole och REX640 skyddsrelä

---

Datum: 27.04.2023 Sidantal: 63 Bilagor: 0

---

**Abstrakt**

Detta examensarbete har skrivits för ABB, för Energy Industries avdelningen i Vasa. Examensarbetet hjälper till med den konstanta produktutvecklingen inom ABB.

Skydd mot axelströmmar spelar en viktig roll för att bevara de goda arbetsförhållandena för en generator. Lagren kan skadas på grund av axelströmmar som flyter i generatoren på grund av Gnistbearbetning (EDM). Om generatoren inte är väl skyddad mot axelströmmar kan generatoren förstöras bara några månader efter start, vilket resulterar i stora ekonomiska förluster.

I detta examensarbete kommer mätning och skydd att implementeras mot höga axelströmmar som uppstår i generatorns axel. Tidigare användes RARIC-skyddet tillsammans med ILDD-strömtransformatorn för syftet med axelströmsskydd, men eftersom tillverkningen har upphört för RARIC var en ny lösning nödvändig. Detta kommer att göras genom att presentera den teoretiska bakgrunden för axelspänningar och strömmar, lösningar samt test och resultat för REX640.

Mätarrangemangen tillsammans med PCM600-inställningarna planerades först innan examensarbetet sattes i praktik. Testarrangemangen inkluderar Rogowski-spolen med integrationsbox, en Knick-förstärkare, FREJA-relätestsystemet för simuleringen av axelströmmen och REX640-skyddsreläet.

Testerna kommer att inkludera de nödvändiga parameterinställningarna, de olika harmoniska vågorna och de genererade störningsinspelningarna från testerna som utförts.

---

Språk: engelska

Nyckelord: axelströmsskydd, generatorskydd, skyddsrelä, Rogowskispole

## Table of Contents

|       |   |    |
|-------|---|----|
| 1     | Acknowledgements.....   | 1  |
| 2     | List of Figures.....  | 5  |
| 3     | List of Tables .....  | 7  |
| 4     | Introduction .....  | 8  |
| 5     | Theory.....   | 11 |
| 5.1   | Generator Working Principle.....                              | 11 |
| 5.2   | Shaft Current and Voltage Theory .....                        | 14 |
| 5.3   | Shaft Current Protection.....                                 | 16 |
| 5.4   | Damages Due to Shaft Currents .....                           | 18 |
| 5.5   | Mitigation Methods .....                                      | 20 |
| 5.5.1 | Bearing Insulation .....                                      | 20 |
| 5.5.2 | Shaft Grounding .....   | 20 |
| 5.5.3 | Measuring Shaft Currents.....                                 | 21 |
| 5.6   | REX640 Protection Relay .....                                 | 25 |
| 5.7   | Configuring an ABB REX640 Protection Relay .....              | 29 |
| 5.7.1 | PCM600 Software .....   | 30 |
| 5.7.2 | Configuring the ABB REX640 Protection Relay With PCM600 ..... | 32 |
| 6     | Technical Data .....  | 33 |
| 6.1   | Rogowski Coil.....  | 33 |
| 6.2   | Knick Amplifier.....  | 35 |
| 6.3   | FREJA Relay Test System.....                                  | 37 |
| 7     | Function specification for Shaft Current Protection.....      | 39 |
| 8     | Testing the New GSLPTOC Function.....                         | 42 |
| 8.1   | Measurement Function .....                                    | 46 |
| 8.2   | Harmonic Selector.....  | 46 |
| 8.3   | Tests with Fundamental Harmonic.....                          | 47 |
| 8.4   | Tests with Third Harmonic .....                               | 52 |
| 8.5   | Tests with Fifth Harmonic .....                               | 53 |
| 8.6   | Trip Time Tests .....   | 55 |
| 9     | Conclusions .....   | 58 |
| 10    | Bibliography .....  | 60 |

## 2 List of Figures

|   |    |
|---|----|
| Figure 4.1 Motor with a single shaft extension [2] .....  | 9  |
| Figure 4.2 Shaft current protection relay RARIC [9] .....   | 10 |
| Figure 5.1 Example of Turbo generators [4] .....  | 12 |
| Figure 5.2 Details for hydroelectric power plants [5] .....   | 12 |
| Figure 5.3 Hydraulic turbine connected to a generator [5] .....   | 13 |
| Figure 5.4 Shaft Voltage production by Yoke Flux in a 4-pole machine [6] .....                                      | 14 |
| Figure 5.5 RARIC installations in turbo generators [9] .....  | 16 |
| Figure 5.6 Mounting of the ILDD shaft current transformer on hydro generators [9] .....                             | 17 |
| Figure 5.7 Frosting, Spark Tracks and Pitting [33] [34] .....   | 19 |
| Figure 5.8 Bearing damage due to fluting, note the grooved pattern in the bearing<br>raceway [15] .....             | 19 |
| Figure 5.9 ILDD Shaft Current Transformer with diameter D up to 2000 mm. [9] .....                                  | 22 |
| Figure 5.10 - Recommended installation for shaft grounding and monitoring with<br>Grounding Brushes [16] [34] ..... | 22 |
| Figure 5.11 Principle of Rogowski Coil Design [20] .....  | 24 |
| Figure 5.12 REX640 Protection Relay [37] .....  | 25 |
| Figure 5.13 REX640 Base Functions [26] .....  | 26 |
| Figure 5.14 LHMI example [26] .....   | 27 |
| Figure 5.15 SHMI example [26] .....   | 28 |
| Figure 5.16 WHMI Overview [37] .....  | 28 |
| Figure 5.17 WHMI example [26] .....   | 29 |
| Figure 5.18 PCM600 Graphic Interface [36] .....   | 30 |
| Figure 6.1 The mounting of a Rogowski coil below a shaft CT [22] .....  | 33 |
| Figure 6.2 LFR Current Probe with integrator box and power supply [25] .....  | 34 |
| Figure 6.3 P27000 DIP-switch setting and connection terminals [27] .....  | 36 |
| Figure 6.4 Input Value Knick Amplifier [29] .....   | 37 |
| Figure 6.5 Output Signal from Amplifier [29] .....  | 37 |
| Figure 6.6 FREJA 300 Relay Test System .....  | 38 |
| Figure 7.1 Symbol for the shaft current protection function [25] .....  | 39 |
| Figure 7.2 Module diagram for the shaft current protection function [25] .....                                      | 39 |
| Figure 7.3 Measuring Arrangement for Current Transformer [25] .....   | 41 |
| Figure 7.4 Measurement Arrangement for Rogowski Coil [25] .....   | 41 |
| Figure 8.1 Connection diagram of the measurement arrangement [31] .....   | 42 |
| Figure 8.2 Measurement Arrangement Current Transformer [31] .....   | 44 |
| Figure 8.3 WHMI Overview from REX640 .....  | 45 |
| Figure 8.4 WHMI Trip Events .....   | 45 |
| Figure 8.5 Application Configuration for GSLPTOC .....  | 46 |
| Figure 8.6 Harmonic Selector GSLPTOC .....  | 47 |
| Figure 8.7 Application for Fault Simulation .....   | 47 |
| Figure 8.8 Verifying the Fundamental Frequency .....  | 48 |
| Figure 8.9 WHMI Monitored Data .....  | 48 |
| Figure 8.10 Alarm, Start and Operate signals tripped .....  | 49 |
| Figure 8.11 Disturbance Recorder Parameter Settings .....   | 50 |
| Figure 8.12 Disturbance records in PCM600 .....   | 50 |
| Figure 8.13 Disturbance recording from Alarm tripped in Wavewin32 .....   | 51 |
| Figure 8.14 Disturbance record for OPERATE and START .....  | 51 |
| Figure 8.15 WHMI Third Harmonic Data Monitoring .....   | 52 |
| Figure 8.16 Wavewin32 Disturbance Record for Alarm trip in the Third Harmonic ..                                    | 52 |

|   |    |
|---|----|
| Figure 8.17 Wavewin32 Disturbance record for Start and Operate in the Third Harmonic..... | 53 |
| Figure 8.18 FREJA set to Fifth Fundamental (250Hz) .....                                  | 53 |
| Figure 8.19 WHMI GLSPTOC Monitored Data for Fifth Harmonic.....                           | 54 |
| Figure 8.20 Wavewin32 Alarm tripped with Fifth Harmonic .....                             | 54 |
| Figure 8.21 Wavewin32 disturbance record of Start and Operate with Fifth Harmonic .....   | 55 |
| Figure 8.22 Binary Outputs in the Application Configuration .....                         | 55 |
| Figure 8.23 REX640 Binary Output connections.....   | 56 |
| Figure 8.24 FREJA Trip Time.....  | 57 |

### 3 List of Tables

|  |    |
|--|----|
| Table 5.1 Advantages and disadvantages for the Rogowski Coil .....             | 23 |
| Table 6.1 LFR Characteristics.....   | 35 |
| Table 8.1 Components used in a Generator application using Rogowski coil ..... | 43 |
| Table 8.2 Retrofit Current Transformer measurement arrangement [31] .....      | 44 |
| Table 8.3 Trip Times.....  | 57 |

## 4 Introduction

The objective of the thesis work is to develop and modernize the shaft current protection for generators with ABB's REX640 protection relay. This thesis work will include the planning, designing, and implementation of said objective and the testing of the final product. The thesis work was commissioned by the Energy Industries department in ABB, Vaasa.

In electrification and automation, ABB is considered a technology leader, further enabling more sustainability and a resource-efficient future. ABB was merged by two companies in 1988, they were the Swedish company ASEA AB and the Swiss company BBC Brown Boveri & Cie. The new group had their headquarters in Zurich, Switzerland, and started operations on the 5th of January 1988. At that time ABB had \$17 billion in revenues and 160 000 employees around the world. The company has since grown and developed and currently is operating in over 100 countries with about 105 000 employees, ABB had 29 billion USD in revenue in 2022. [1]

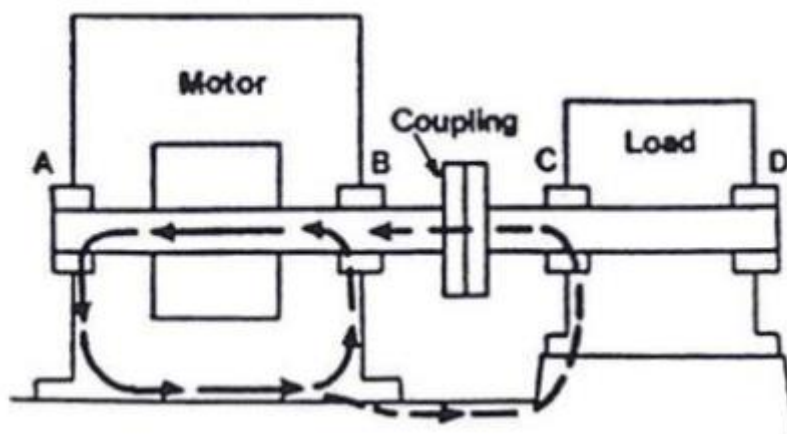
ABB has operated in the power plant industry for more than 125 years, and they have one of the largest installed equipment bases in power plant and automation solutions. The department for which the thesis work was made, is Energy Industries. Energy Industries are located in the KT-building in Strömberg park, Vaasa. Globally, ABB's Energy Industries employs more than 3000 people, approximately 80 experts work in Finland, with most of them in Vaasa. [1]

Energy Industries in Vaasa designs and delivers electrical-, automation-, instrumentation- and control systems and supporting services for these systems on a turnkey basis. The offer also includes system analyses as well as maintenance services, which map ways to improve the performance and reliability of power plants. These power plants include several types of turbines, such as hydro, gas, steam, and diesel engines. [1]

Shaft current protection has an important role in preserving the good working condition of a generator. Currents that flow in the generator could potentially damage the bearings in the generator that can shorten the operating time and cause major financial issues. It is crucial to stop the generator from running while high shaft currents are present. A

generator without a proper protection against shaft currents might result in early failure within a few months of the installation. Shaft current protection is well known within generator protection and since the products surrounding the electrical and automation industries constantly evolve and change, new innovative work is necessary. ABB has previously used a combination of the current transformer, ILDD, and the shaft current relay, RARIC, for measuring shaft currents.

Dissymmetries in the magnetic pathways through the stator and rotor iron are what lead to shaft circulating currents. Small variations in the magnetic reluctance (also known as magnetic resistance) of the core components produce voltages between the ends of the shaft as the rotor rotates inside the stator and as the stator's magnetic field rotates. These currents can break through sleeve bearing oil films or jump across the ball bearings gaps which damages the bearings in various ways which are presented in Chapter 5.4. Figure 4.1 demonstrates a normal motor with a single shaft extension. Bearing A is to be insulated to break the current path through the entire circuit. Only insulating bearing B does not necessarily stop currents from damaging bearing A and C. [2]



**Figure 4.1 Motor with a single shaft extension [2]**

The purpose of the thesis work is to implement shaft current protection with ABB REX640 protection relay and Rogowski Coil that trips the unit if high shaft currents are present. The previous solution that ABB offered, which included the RARIC protection relay (Figure 4.2) and the ILDD Current transformer is no longer possible due to the components stopping manufacturing. Additionally, the shaft current protection can be implemented with the Current transformer ILDD and the REX640, depending on the customer's specifications.



**Figure 4.2 Shaft current protection relay RARIC [9]**

Prior to the REX640, alternative protection relays could not be configured to detect current at the same levels as the RARIC. The operating value can be set from 0,5 mA to 2 mA and an RC circuit is included in the current input circuit, which has an 82 ohm resistance and suppresses high-frequency disturbance signals.

## 5 Theory

Shaft current protection plays an important role in preserving optimal working conditions in a generator. Without the proper protection against shaft currents flowing in the generator, the bearings could take damage which leads to shorter operating times causing economical setbacks. To understand how shaft currents occur and what mitigation methods are available, we must take a closer look into the generator and the theories behind shaft currents and voltages.

### 5.1 Generator Working Principle

A generator is a machine that converts mechanical energy to electrical energy through various sources of energy. These sources include gas turbines, water turbines, and wind turbines. As we depend on energy for almost everything in modern life and a reduction in power generation might have negative effects on society, the generator is a crucial piece of equipment.

A **turbo generator** is a turbine and generator coupled together, which converts mechanical energy from a moving fluid, such as liquid water, steam, natural gas, or air, into electricity. Figure 5.1 shows the working principle of two turbo generators connected to the grid. The turbo generator consists of a moving part, which is the rotor, and a stationary part, which is the stator. Electromagnets are used to cover the rotor's outer layer, while coils of copper wire are used to line the stator's inside wall. A revolving magnetic field produced by the rotor's rotation causes an alternating current in the stator. A transformer then raises the voltage of the produced electricity to the necessary level for usage in the power transmission system. [3] [4]

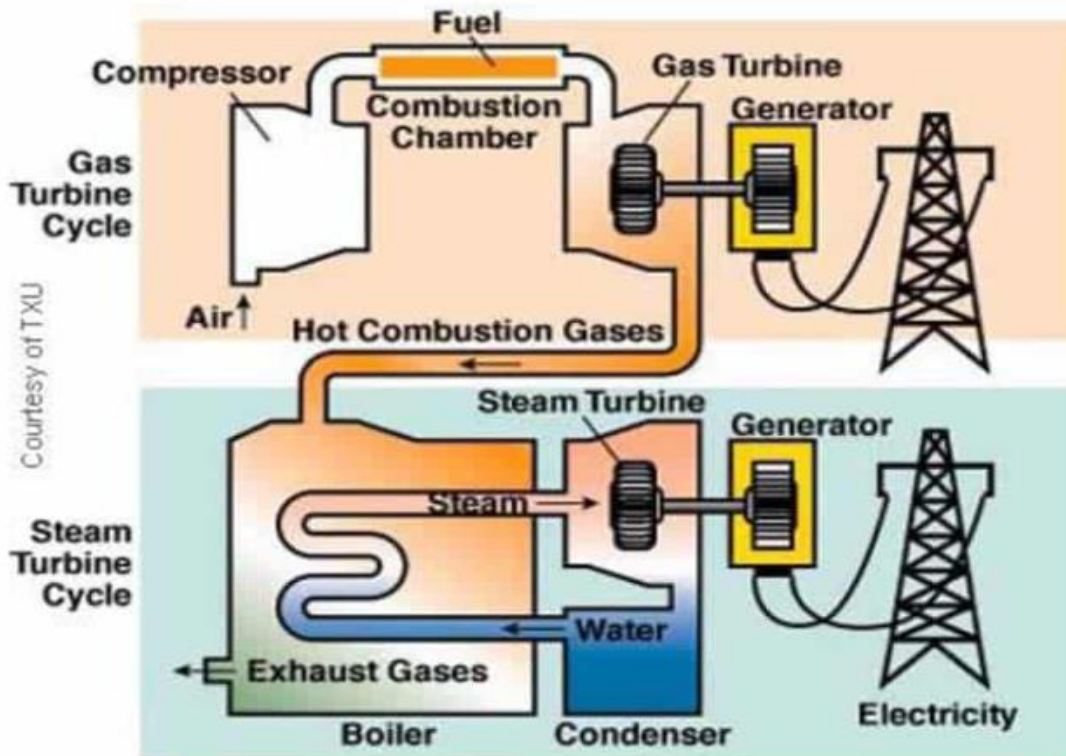


Figure 5.1 Example of Turbo generators [4]

Hydroelectric power plants produce electricity by using falling water to turn the turbine, which turns the shaft in an electric generator. The hydroelectric plant works in a similar way as a coal-fired power plant with the difference that the coal-fired uses steam to turn the turbine blades instead. Figure 5.2 shows an example of hydroelectric power generation.

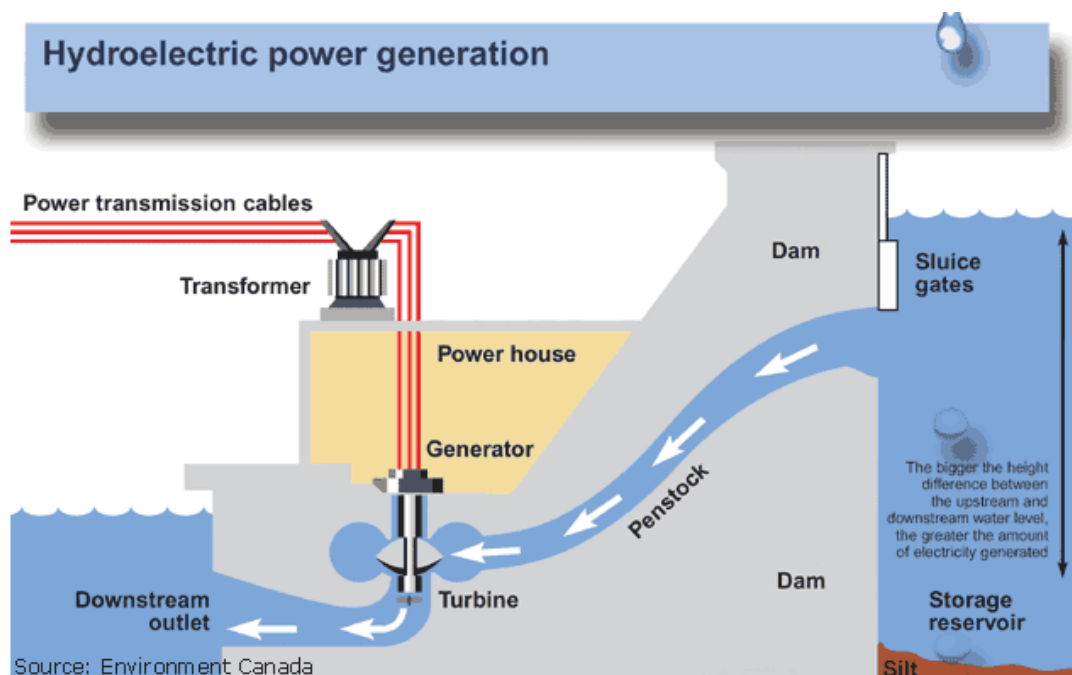
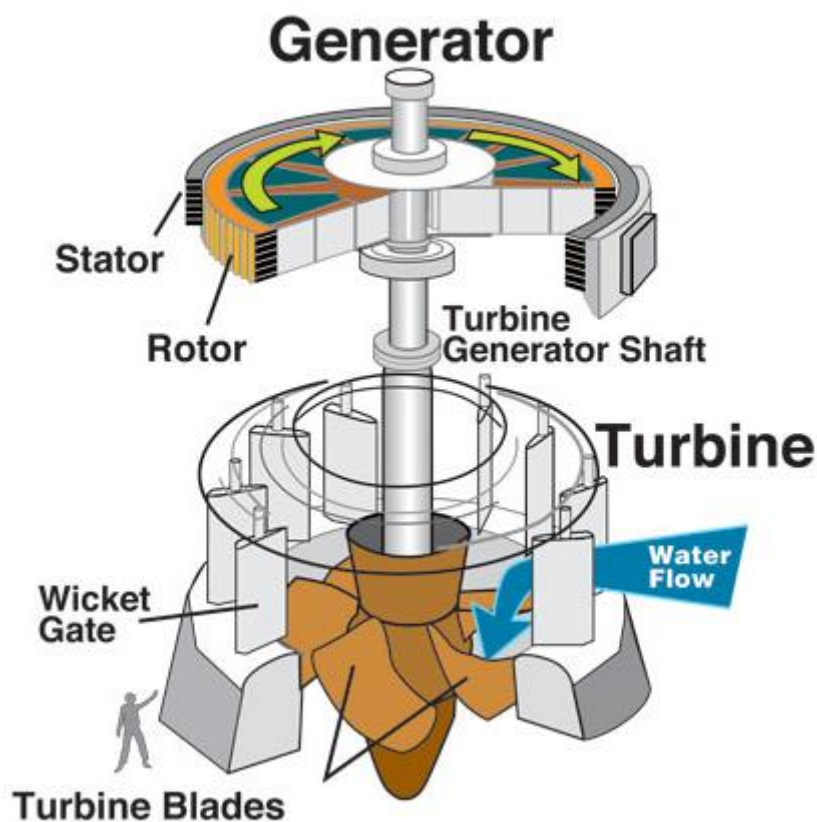


Figure 5.2 Details for hydroelectric power plants [5]

The hydraulic turbine works by converting the flowing water to mechanical energy. The hydroelectric generator then converts said mechanical energy into electricity, this operation was discovered by Faraday who discovered that moving a magnet through a coil result in the flow of electricity. Figure 5.3 Demonstrates the production of electricity in the hydraulic turbine, where water flowing through the turbine blades turns the turbine generator shaft, which in turn produces electricity. This is due to field poles, which are electromagnets that are made up of a wire coil where a current flows through. The field poles are mounted to the rotor's outer edge and cause the flow of electricity when they move past the conductors fixed in the stator while the rotor turns. [5]



**Figure 5.3 Hydraulic turbine connected to a generator [5]**

The turbo generator and the hydro generator are the main types of generators to which this thesis work will apply to. However, since few hydroelectric dams are built nowadays due to social and environmental concerns, more focus is shifted towards turbogenerators.

## 5.2 Shaft Current and Voltage Theory

Since the turn of the century, scientists have been studying shaft currents in generators. As a result, some information regarding this phenomenon is already available. Possibly the oldest thoroughly explained paper on shaft currents was presented 1923 [6]. Both [6] and [7] stated that asymmetry in the armature field is the most common and important source of shaft currents. This thesis work, therefore, starts from the information based on this source of shaft currents. According to Ong, shaft currents would not exist if it were possible to design a perfectly balanced and symmetrical machine. Flux going through the shaft of a multi-pole machine, such as a synchronous generator, divides into two halves. One part of it moves counter-clockwise, while the other moves clockwise. If those two components are not equal due to magnetic dissimilarities, the resultant flux will circulate around the yoke as seen in Figure 5.4. This voltage will cause the current to cycle through the shaft, through the bearing oil film, through the machine base, and back through the other bearing. The most well-known causes of dissymmetries are sectionalized frames and segmental punchings. The frequency of shaft current generation is determined by the number of poles and joints or segments in the stator core. [7] [8]

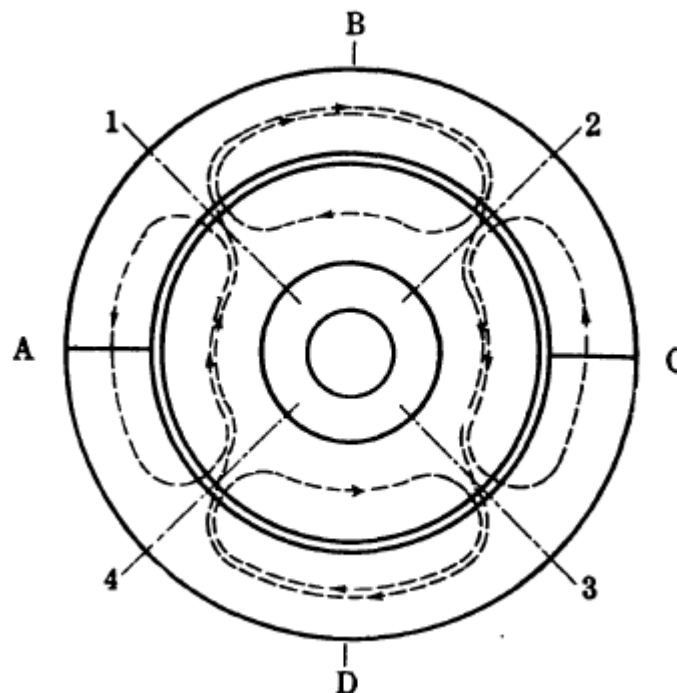


Figure 5.4 Shaft Voltage production by Yoke Flux in a 4-pole machine [6]

Alger & Samson developed a shaft current prediction rule. This rule, which is expressed in equation 5.1, states that if the ratio of twice the number of joints, J, to the number of poles, P, reduced to its lowest term, holds an odd number in the numerator, shaft currents will occur at a frequency equal to  $A * f$ , where f is the line frequency. [6]

( 5.1)

$$\frac{A}{B} = \frac{2 * J}{P}$$

Similar to this, if the ratio of four times the number of segments over the number of poles, expressed as a fraction to its lowest terms, has an odd number for the numerator, shaft currents will occur with a frequency equal to  $A * f$ .

( 5.2)

$$\frac{A}{B} = \frac{4 * S}{P}$$

Ong states that “The number of joints is the number of segments per circle, S, times the number of layers before the pattern repeats, generally 2”. Where A and B are both whole numbers, and B is the lowest common denominator. As a result, it may be written as follows:  $J = 2 \times S$ . This rule is not extended to include spatial and time harmonics or saturation effects, which will only cause negligible currents if nominator A is an even number. Based on the rules described above, it can be determined that if shaft current exists, the frequency of this current will be equal to or odd multiples of the line frequency. [7]

However, it is described and demonstrated by experiment in [7] that the above rule does not take into consideration some effects that may result in magnetic asymmetry. Because of this, harmonics with frequencies multiples of line frequency can be anticipated in shaft currents.

### 5.3 Shaft Current Protection

Shaft current protection is an essential generator protection concern in hydro and turbo generators. Typically, a slip-ring on the prime mover side grounds the turbogenerators' shaft to prevent the rotor from being electrically charged (Figure 5.5). For hydro-generators, a link to the ground is made by the water in the turbine (see Figure 5.6). If the bearing pedestal on the opposite side of the rotor is grounded, voltage is imposed on the bearing. Due to the low impedance of the loop formed by the shaft, bearing, and ground structure, a breakdown of the oil-film insulation may result in a strong current that causes the bearing to be destroyed. Currents under 1 A are not considered severe damage to the bearings but the consequences of higher currents in the shaft are described in Chapter 5.4. Previous solutions that ABB has used for detecting shaft currents that can damage the bearing include the shaft current relay RARIC as well as the current transformer ILDD. Typically, shaft currents are monitored using a shaft current transformer ILDD that is installed between the turbine and the generator in hydro-generators and between the non-insulated bearing and the generator in turbo-generators. The protection relay then measures excessive currents and if those are present, trips the unit based on the delay set on the time relay. [9] [8]

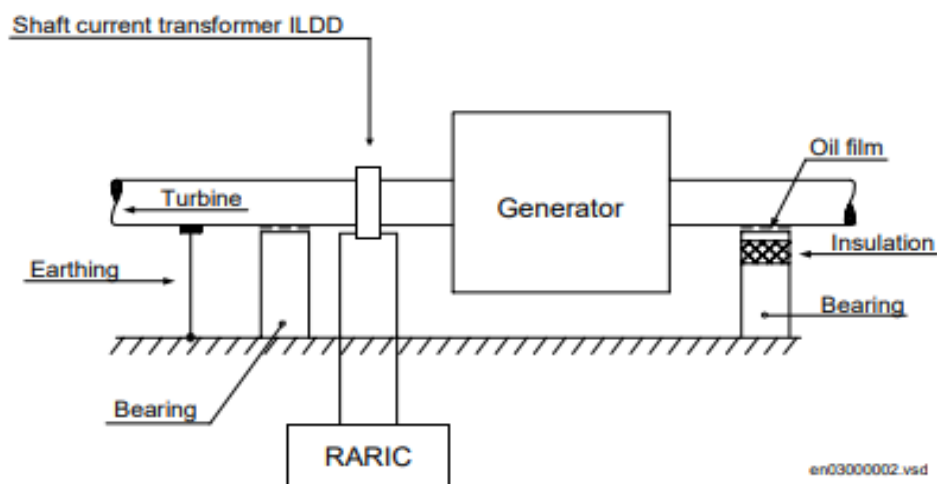
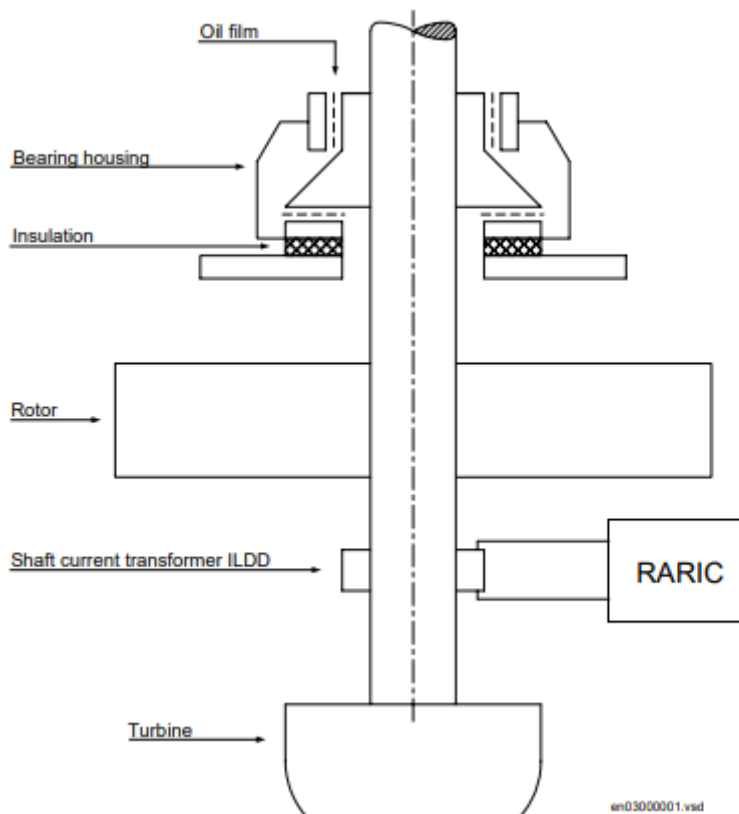


Figure 5.5 RARIC installations in turbo generators [9]

The shaft current relay RARIC has the possibility to be used for generators having a shaft diameter of up to 2960 mm. The minimum operating current is 0,4 to 1,0 amperes, which is dependent on the shaft diameter. [9]



**Figure 5.6 Mounting of the ILDD shaft current transformer on hydro generators [9]**

Shaft current transformers come with a few drawbacks. It is challenging and time-consuming to install such a large, heavy transformer in the cramped area where it is often located. Additionally, it must carefully measure low level primary currents (less than 1 A) in a big conductor that is the shaft. This results in a very low secondary current for the shaft current transformer. The applications with the shaft current relay, RARIC, and the shaft current transformer, ILDD, are shown in Figure 5.5 and Figure 5.6.

The shaft current protection has also been implemented with the ABB REG670 protection relay in addition to a Rogowski coil by ABB. The work using the ABB REG670 showed that the Rogowski coil was a suitable choice for measuring devices since its beneficial electrical and mechanical properties. [8]

#### 5.4 Damages Due to Shaft Currents

This chapter will include the types of damage that bearings might receive due to shaft currents. In the majority of these situations, the first sign of shaft current damage on the bearings are increases in noise and vibration.

Bearing damage can be classified into four types: frosting, pitting, spark tracks, and welding as described in [10]. These four types will be shortly introduced. A fifth type of bearing damage, fluting, which is a type of bearing damage that occurs when pitting damage creates a frosted effect, will also be shortly discussed.

**Frosting** is by far the most frequent kind of shaft current damage. Frosting has the appearance of a sand-blasted surface and is not noticeable to the naked eye if the entire surface is affected. However, when the frosted surface is viewed microscopically, it reveals craters with very round and shiny bottoms. This reflects the melting that had happened. This frosting occurs during electro discharge machining (EDM) and as the EDM occurs, the material is removed. Sometimes, the appearance of a chemical attack is comparable to that of frosting caused by shaft currents. Figure 5.7 shows frosting damage as seen through a 30x microscope.

Figure 5.7 shows **pitting** caused by shaft currents. This differs from frosting as its source is extremely powerful and therefore much larger in size. The number of discharges can sometimes be counted since pitting occurs more randomly and does not cover an entire area as opposed to frosting.

**Spark tracks** are shown in Figure 5.7 in the middle and these tracks initially appear as scratches caused by foreign particles in the lubricating or seal fluid. Spark tracks are highly irregular in character and do not follow direction of rotation. When under magnification, the bottom of the tracks are melted and the corners are sharp.

Great amounts of current (hundreds of amperes) cause **welding**. The human eye can easily notice this damage. Quite often this has to be separated by sledgehammers or other mechanical means.

**Fluting** damage is a result of frosting and pitting which creates a grooved pattern in the bearing raceway similar to a washboard. Even the best bearings experience fluting eventually as the lubrication fails. Fluting damage is shown in Figure 5.8.

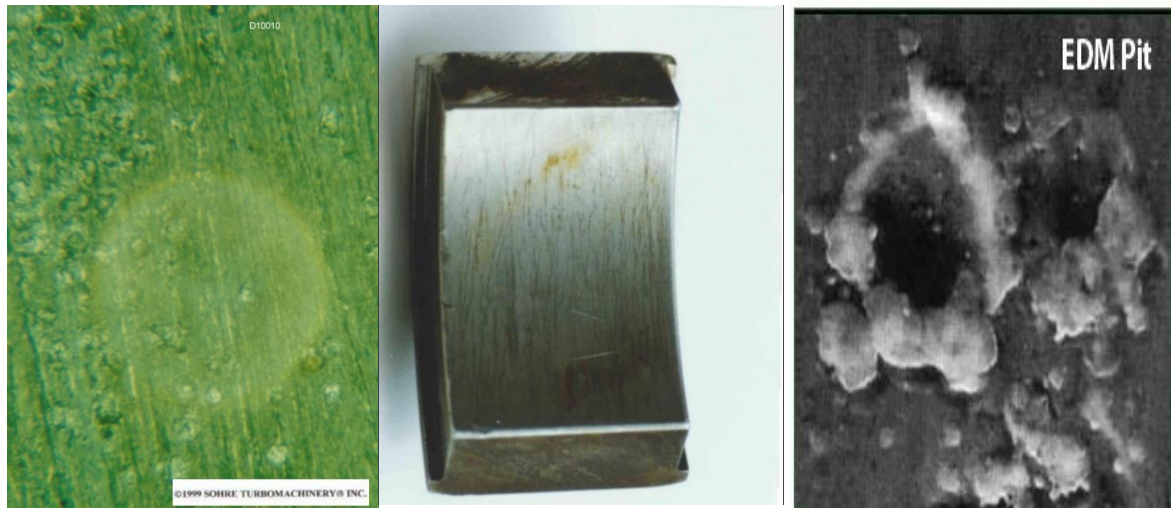


Figure 5.7 Frosting, Spark Tracks and Pitting [33] [34]



Figure 5.8 Bearing damage due to fluting, note the grooved pattern in the bearing raceway [15]

## 5.5 Mitigation Methods

Shaft currents can be avoided primarily by doing two things. In case of turbo generators, shaft grounding and bearing insulation. As previously described, the failure of bearing insulations results in shaft currents flowing and destroying the bearings.

### 5.5.1 Bearing Insulation

Coated bearings and hybrid bearings make up the majority of insulated bearings available on the market. Two types of bearing insulations that are used to mitigate shaft current damages will be shortly discussed. [11] [12] [8]

Hybrid bearings typically have a steel outer race and rolling elements made of a ceramic material such as silicon nitride, which works as an isolator. Hybrid bearings made of silicon nitride are effective in insulating the housing of AC and DC motors and generators from the shaft due to the excellent insulating properties of the material. This material not only has good isolating qualities but also some other good mechanical qualities like shock resistance, lighter weight (comparing to steel), material strength, etc.

Coated bearings are a type of insulated bearings in which either the outer or inner ring of the bearings is coated with ceramic material. The ceramic layer acts as a barrier against current flow.

### 5.5.2 Shaft Grounding

For the prevention of the rotor being charged electrically, shafts are grounded. Additionally, grounding at the drive end of turbo generators offers a different path for the shaft current. The shaft can be grounded in three ways. This can be done by using grounding brushes, conductive grease in bearings, or grounding rings.

**Shaft Grounding Brushes** provide low impedance path from the rotor to the ground so that the shaft voltage does not build up to the point where it discharges through the bearings. Grounding brushes are effective and economical. However, the brushes are subject to wear because of their contact with the shaft and will eventually need to be replaced.

**Grounding Rings** also mitigate shaft current issues. Where multiple strands of electrically conductive fibres arranged inside a ring go around the shaft. The advantages of the grounding rings are presented in [13]. Surface roughness, unlike grounding brushes, has no effect on the resistance between two conducting materials due to the very small diameter of the fibres. As a result, there is no need to apply pressure to maintain electrical contact, resulting in low friction and negligible wear. Muetze (2007) states that the grounding rings are also resistant to contamination by cutting through oily, greasy, and dusty environments. Another advantage of using a grounding ring that is stated in [13] is "breakdown due to local field emission will occur somewhere along the circumference, thereby reestablishing the electric contact" even if the microfibers lose physical contact with the shaft surface. [14]

Grease in the bearings is the third way to ground the shaft. Such **Electrically Conductive Grease** offers a path without arcing for the current to travel through the bearing. [8] explains that Conductive grease is not shaft grounding per se and that the shaft is only grounded if the pedestal of the bearing is grounded. Willworth and Oh state that since conductive particles could render lubrication useless, this approach has been dropped.

**Turbine Grounding**, the three grounding methods previously discussed were applicable to turbo generators. Water in the turbine provides a good grounding for the shaft in the case of hydro-generators. For this reason, no further grounding is applied to the shaft. [15] [9]

### 5.5.3 Measuring Shaft Currents

Measuring excessive shaft currents can prevent damage to the bearings by halting the unit until the problem is resolved. Currents can be measured in a variety of methods, which are covered in the following sections.

For measuring shaft currents, a **Current Transformer** is the first obvious choice. As a conductor of shaft current, the generator shaft serves as a primary winding with one turn. Around the shaft is a magnetic core with secondary and test windings. The principle of operation of the current transformer will not be discussed further as it is well known. The CT is split up into two or four parts, depending on the size of the shaft. The current transformer ILDD, which was part of the solution that ABB previously used, is shown in Figure 5.9.

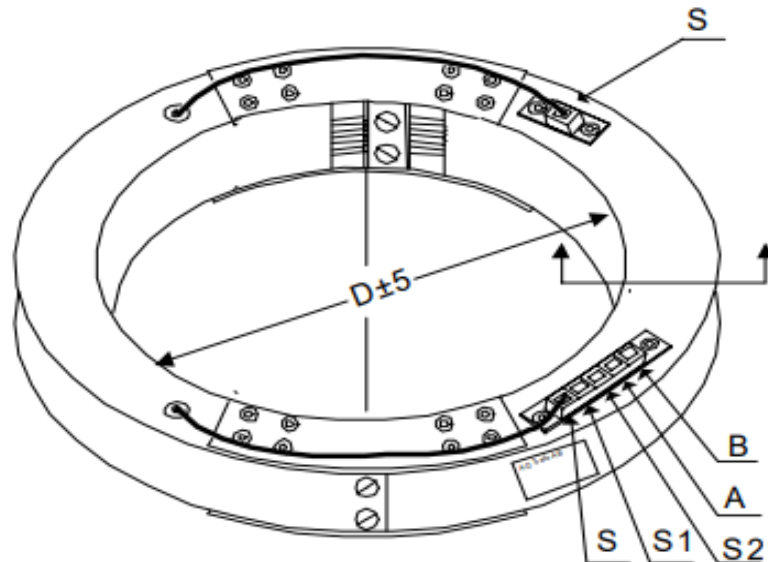


Figure 5.9 ILDD Shaft Current Transformer with diameter  $D$  up to 2000 mm. [9]

The main drawback of ILDD was its limited sensitivity at the desirable trip and alert levels. Furthermore, the Rogowski coil has been found more suitable for shaft current protection applications. [8]

In addition to grounding the shaft, **Shaft Grounding Brushes** can also be used for measuring shaft voltages. [16] is an example of such an attempt. In this example, several brushes at the shaft ends and grounding brushes are used to measure both shaft current and voltage. Recommended installation of complete shaft grounding, monitoring, protection, and warning is shown in Figure 5.10. This installation is best suited for large and critical turbine generators. Furthermore, as previously discussed in earlier sections, brushes have various difficulties that influence not just grounding but also shaft current measurements.

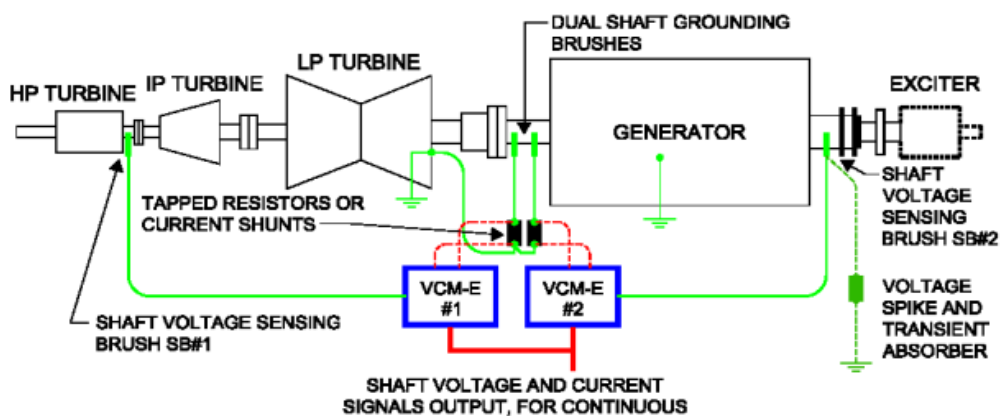


Figure 5.10 - Recommended installation for shaft grounding and monitoring with Grounding Brushes [16] [34]

The **Rogowski Coil** is named after German scientist Walter Rogowski. It has been used since the beginning of the 1900s. However, due to the low-energy coil output and the fact that it monitors the derivative of the input current, it was impracticable for use with the common electromechanical relay technology at the time. A Rogowski coil operates similarly to conventional current transformers (CTs). The main distinction between CTs and Rogowski Coils is that the Rogowski Coil windings are wound over an air core rather than an iron core. Since the air core cannot saturate, Rogowski Coils are linear as a result. [17] [18] [8].

The operating principle (see Figure 5.11) is well known and has been described in a number of works, and a review detailing the said operation is provided in [19]. Some of the main advantages and disadvantages of the Rogowski Coil are described in table 5.1.

**Table 5.1 Advantages and disadvantages for the Rogowski Coil**

| <b>Advantages</b>   | <b>Disadvantages</b>                                  |
|---|---|
| Adaptable and easy to mount                               | Does not measure DC currents                          |
| Low cost  | Output voltage is low                                 |
| Nonintrusive nature, does not disturb the primary circuit | Significantly influenced by the termination impedance |
| Withstanding large overloads without harm                 | Dependent on an integrator circuit                    |
| No saturation because of the air core                     |   |

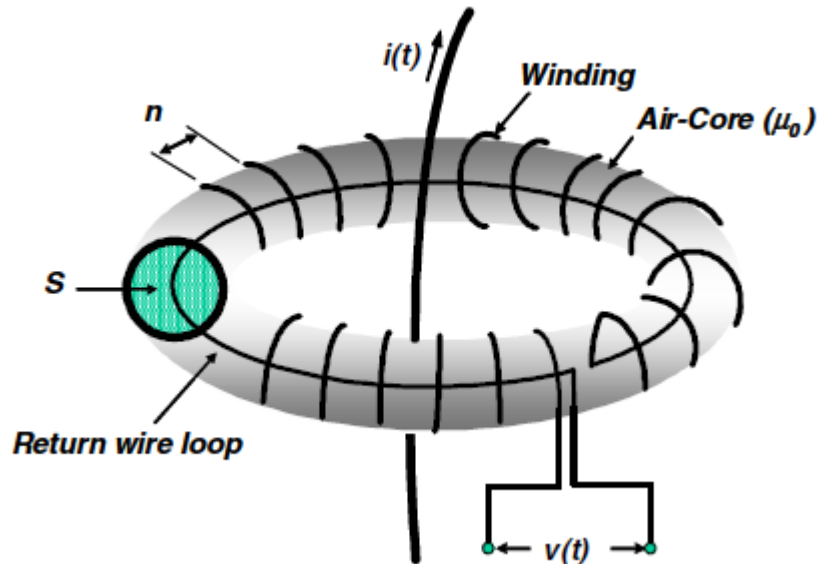


Figure 5.11 Principle of Rogowski Coil Design [20]

The Ampere's law states that the relationship between the current flowing through the Rogowski coil and the intuitional magnetic along the axis of the torus is written as follows:

( 5.3)

$$I(t) = \frac{1}{\mu_0} \oint \vec{B}(t) * \vec{ds}$$

As per Equation 5.3, integrating magnetic flux density,  $B(t)$ , around a closed contour results in a current,  $I(t)$ , flowing inside the closed contour.  $\mu_0$  is the permeability of free space which is also known as the magnetic constant, and  $s$  is the distance along the torus.

Additionally, following Faraday's law, a change in magnetic flux passing through turns in a Rogowski coil will induce voltage. This is expressed as in equation 5.4.

( 5.4)

$$u(t) = N \frac{d\Phi}{dt}$$

The next equation depicts a combination of both laws stated in equation 5.3 and equation 5.4.

( 5.5)

$$u(t) = N \int \vec{B} d\vec{A} = N \frac{A}{S} * \mu_0 * I(t)$$

Where  $s$  is the coil length,  $A$  is the area covered by a single turn and  $N$  is the number of turns in the Rogowski coil. Equation 5.5 expresses the relation between the measured current and the voltage created in the Rogowski coil. The integrator box is required to get the waveform, since the coil generates a voltage proportionate to the rate of change of the measured current. Ray and Hewson review several methods for performing integration, each with their own advantages and disadvantages. The circuit integrations and the issues associated with them were the reason that Rogowski coils were not used that frequently in the beginning. Crotti, Giordano, and Morando analyze the Rogowski coil operating under non-ideal measurement conditions such as influence from external field sources, non/uniform distribution of the coil turns, and positions of the power conductor. The measurement accuracy that the Rogowski coil provides was compared to the former IEEE standard 112-1991 measurement techniques and concluded that the Rogowski coil measurement technique is the better alternative. The Rogowski coil can be taken into account for purposes with numerical relays. [20] [21] [22] [23]

## 5.6 REX640 Protection Relay

The high-performance ABB REX640 protection relays are designed to safeguard electrical systems against a wide range of possible flaws and hazards. These relays employ cutting-edge technology and advanced algorithms to continuously monitor the electrical system and provide rapid, accurate protection when needed. Figure 5.12 shows the REX640 protection relay with its HMI display. [24]



**Figure 5.12 REX640 Protection Relay [37]**

The REX640 is a multi-functional relay that may provide overcurrent, overvoltage, and undervoltage protection, as well as protection against earth faults and short circuits. It also supports a broad number of communication protocols, including IEC 61850 and Modbus, making it simple to incorporate into existing systems.

REX640 provides extensive basic functionality. However, the device can be further customized to satisfy specific installation requirements by including any number of the available optional application packages into a single REX640 relay. The functionality of the specified application packages can be expanded by incorporating the relevant add-on package (See Figure 5.13). The function that this thesis work will be focusing on is GSLPTOC and has been developed by [25]. This function will be discussed in Chapter 7 and implementations and testing of the function will be discussed in Chapter 8. [26] contains more information regarding the product that will not be covered in this thesis work.

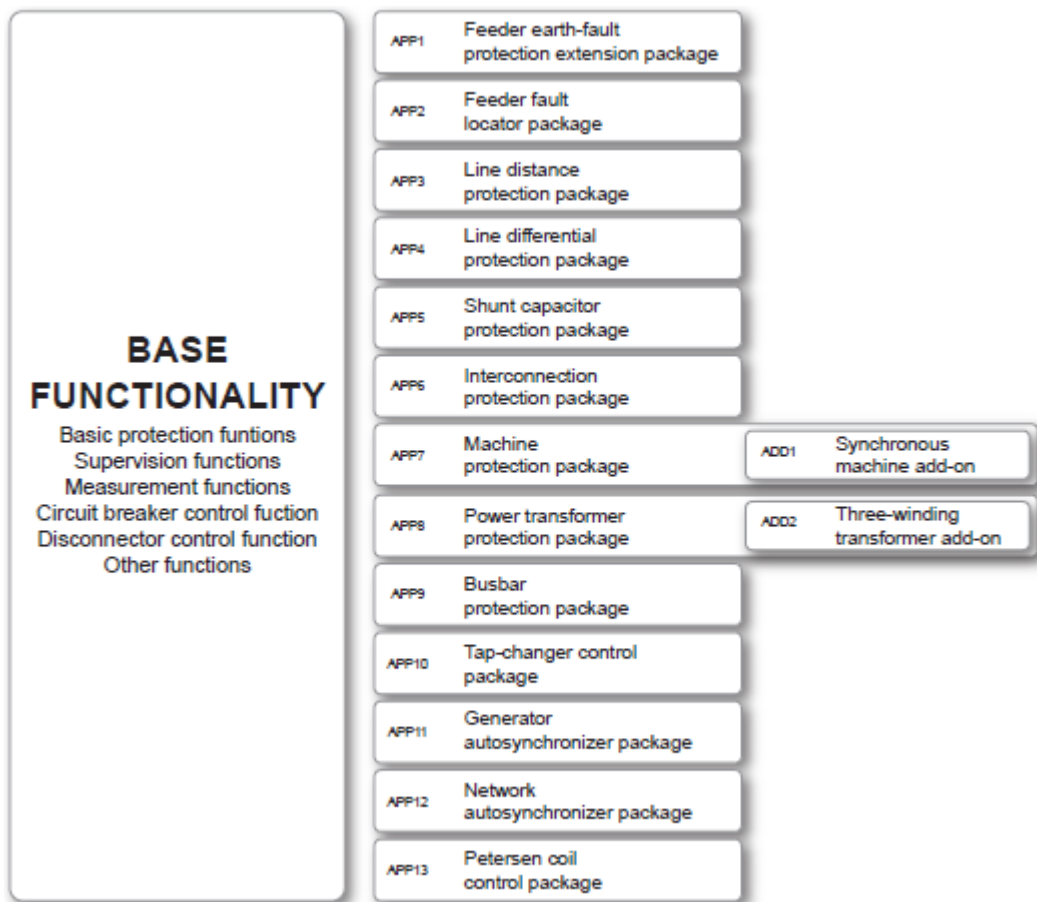


Figure 5.13 REX640 Base Functions [26]

REX640 provides several options for developing a human-machine interface. These options include the LHMI (Local HMI), SHMI (Switchgear HMI), and WHMI (Web HMI). These will be shortly introduced and more information regarding these human-machine interfaces for REX640 can be found in [26].

The LHMI uses a tough 7-inch color screen with capacitive touch sensing technology (Figure 5.14). The user interface has been developed to provide the user with the best situational awareness. Visualization of key process data, events, alerts, and switching item statuses simplifies and clarifies local interaction with the relay. Through pop-up operator dialogues, the LHMI serves as a control point for the specified primary devices.

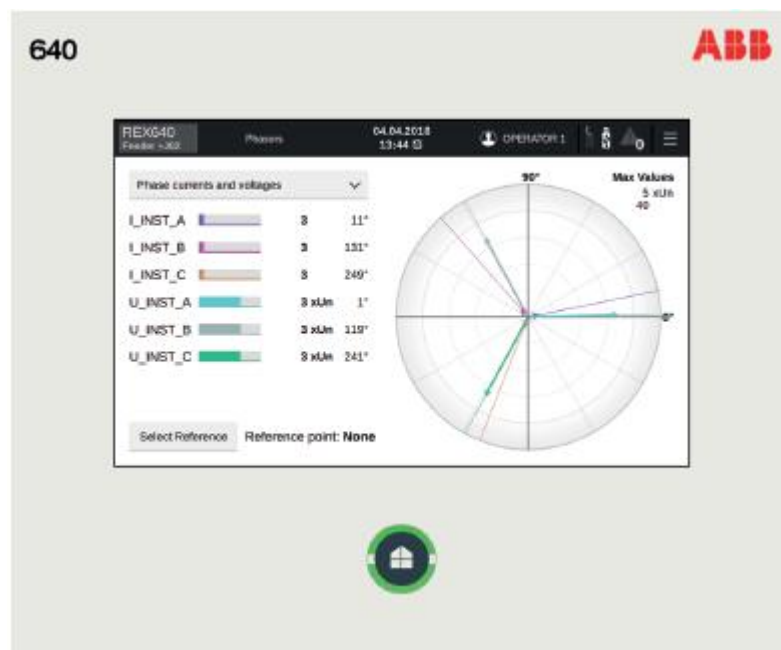


Figure 5.14 LHMI example [26]

The SHMI, like the LHMI, also has a tough 7-inch high definition color screen with capacitive touch sensing technology. The navigation page gives an overview of the whole switchgear array, which can show up to four switchgear panels simultaneously as shown in Figure 5.15. Additionally, one SHMI can handle up to 20 relays and an installation can have multiple non-overlapping SHMI panels.

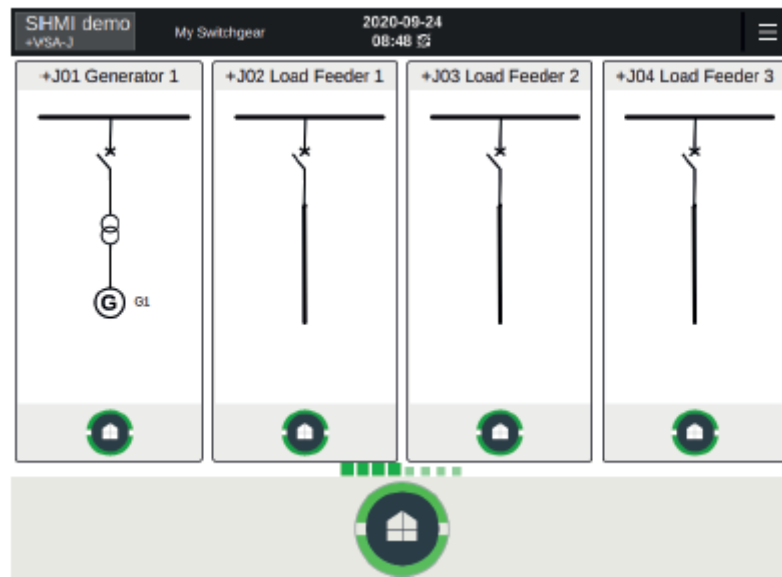


Figure 5.15 SHMI example [26]

Each individual switchgear panel can be shown as a static figure, a photo of the actual panel, or a dynamic single-line diagram. SHMI automatically saves backups of the settings of the linked relays. If a relay has to be replaced with a spare relay that has at least the same capabilities as the original, the SHMI panel may be used to restore the relay setup and settings.

The WHMI allows relays to fully function without being connected to a physical HMI. The relays feature a Web server that allows WHMI access. An overview of the WHMI is shown in Figure 5.16. The web server is deactivated by default and must be enabled by changing a parameter setting in PCM600.

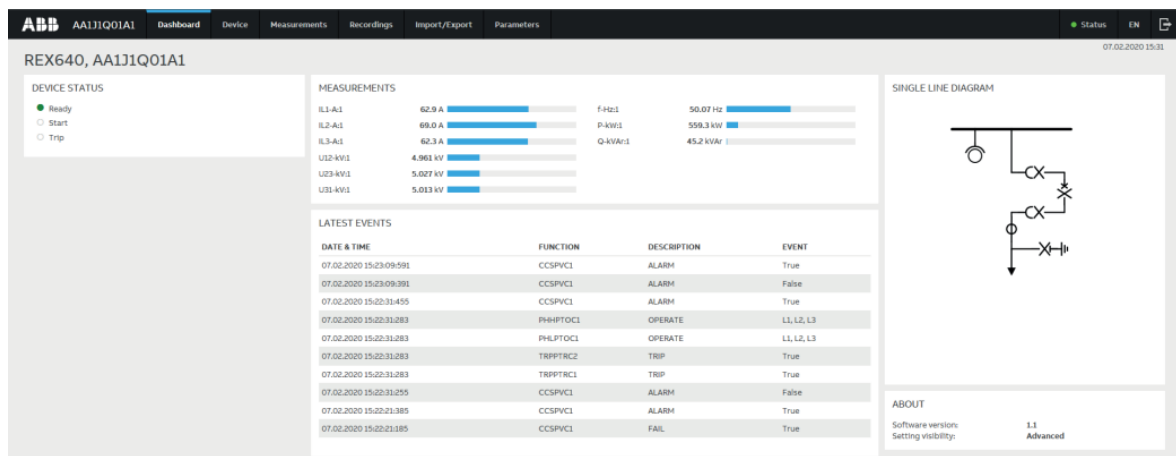
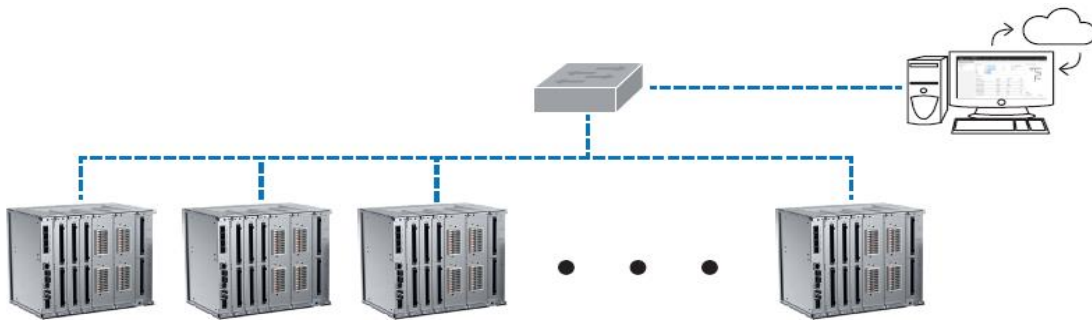


Figure 5.16 WHMI Overview [37]

Additionally, even if the relay is attached to a physical HMI, the WHMI may be utilized. Figure 5.17 provides an example layout of the WHMI being used to control several relays.



**Figure 5.17 WHMI example [26]**

## 5.7 Configuring an ABB REX640 Protection Relay

For configuring the ABB REX640 protection relay following things are required:

1. PCM600 software and a computer, which is used to configure and monitor the protection relay as well as communicate with the protection relay.
2. Communication cable, which is used to connect the protection relay to the computer. The communication protocol the protective relay uses will determine the type of cable to be utilized.
3. An IED (Intelligent Electronic Device) configuration file: The PCM600 software is used to load this file, which contains the settings for the protection relay, into the relay.
4. A REX640 User Manual is helpful but not necessary in case the user is already familiar with configurations of the REX640 with PCM600. This Manual offers comprehensive instructions on how to set up the protective relay using the PCM600 software.

In addition to these key points in how to configure the REX640, a good understanding of the relay and the power system that it is protecting is required.

### 5.7.1 PCM600 Software

In the electrical power sector, a software application called PCM600 is utilized for engineering and commissioning. Users can design, model, and test electrical systems, such as power plants, transmission networks, and distribution systems, using this potent tool. Because PCM600 complies with IEC 61850, IED engineering is made simpler and data sharing with other IEC 61850 compliant instruments is made possible.

To communicate with an IED, a connectivity package is downloaded. Downloading the connectivity package for a specific IED includes all data for describing said IED, such as, the setting range, a list of existing parameters, and the access rights. The connectivity packages can be found in the PCM600 Update Manager tool. [27]

PCM600 can be used for all ABB Relion protection and control relays. The benefits of using the PCM software include:

- Easier way to configure relays.
- A comprehensive overview of parameter settings.
- IEC 61850 certification assures that ABB's products may interchange data and be integrated into any IEC 61850 system.

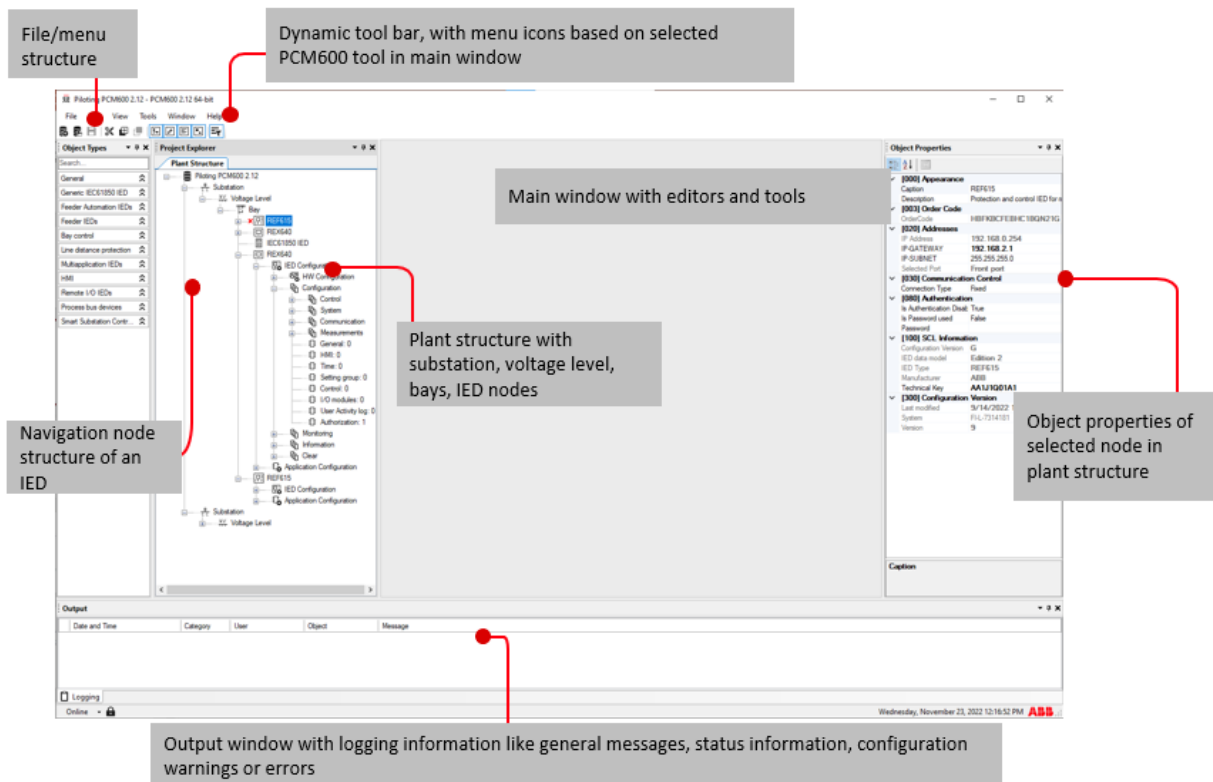


Figure 5.18 PCM600 Graphic Interface [36]

The **Graphical Interface** of the PCM600 software is shown in Figure 5.18.

The power system can be replicated in PCM600 as a digital model. The digital model includes the configuration of components such as generators, switchgear, transformers, and protection devices. As shown in Figure 5.18, the plant structure of the power plant can be seen in a tree structure that includes:

- Substation.
- Voltage Level.
- Bays.
- IEDs.

The **Update Manager** has, as previously described, the connectivity packages for product series, Language add-ons, and IED documentation. The Update Manager also includes recommended updates that offer help in keeping the software up to date, the ability to export software packages for exporting to other media as well as the offline mode to support installation from other media.

PCM600 is a single configurator tool for all the ABB protection and control IEDs which offers versatile functionality for the entire lifecycle of ABB protection and control IED applications. It provides a significant degree of flexibility in the development of advanced applications.

It benefits the customer by ensuring that IED applications are configured and validated efficiently via:

- A graphical application setup that allows for cutting-edge configuration and monitoring of the whole IED program.
- Graphical support for protection parameter adjustments that is informative.

In addition to these benefits, PCM600 also has various diagnostics and monitoring tools that enable quick corrective actions in the event of IED incidents. These include the reading and analysis of disturbance recordings as well as IED and security incident signal monitoring and reading.

PCM600 offers a particularly comprehensive parameter setting management available on the market. In addition to these benefits PCM600 supports various cyber security features such as a secure communication between IED and PCM600 and Central Account Management.

### 5.7.2 Configuring the ABB REX640 Protection Relay With PCM600

The ABB REX640 can easily be configured by using the PCM600 software. The software can enable or disable the desired protection modules depending on the customer's specifications.

The steps necessary to configure the REX640 protection relay may vary depending on the version of the relay and software. However, these steps should generally be followed when configuring the REX640 with PCM600:

1. Install PCM600 on your computer and connect it to the REX640 protection relay.
2. Download the connectivity package for REX640 from the update manager software.
3. Create a project in PCM600 and as the target device, select REX640.
4. Download the REX640 configuration file to PCM600 from the relay using the "Read from IED" function found in PCM600.
5. Configure the I/O mapping and application parameters in PCM600.
6. Upload the updated configuration file from PCM600 to the REX640 using the "Write to IED" function in PCM600.
7. Monitor the process variables and verify the I/O status to ensure that the REX640 is operating properly. This can be accomplished by using the "Online Monitoring" function found in the Application Configuration of the project.
8. Save the PCM600 configuration file for future reference and usage.

Additionally, it is important to use the correct connectivity packages when configuring the REX640 as well as using the correct PCM600 version. Some connectivity packages that are more recently added to the update manager might not be accessible due to the PCM600 version being outdated. It is always helpful to refer to the REX640 manual if troubleshooting is needed. Additionally, if troubleshooting is needed, PCM600 offers support and helpful information. [27]

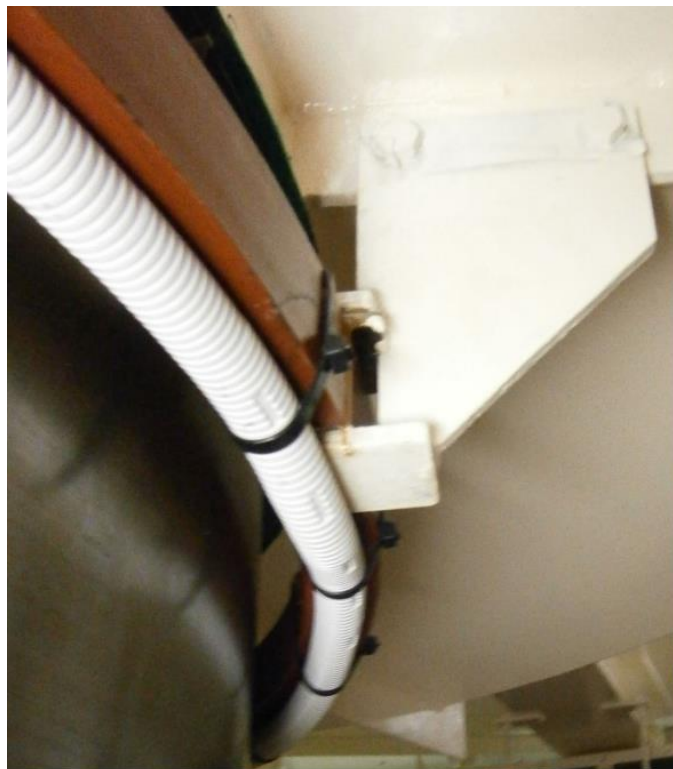
## 6 Technical Data

Here, technical data for the components used will be described. Technical data will mainly include the Rogowski coil, the Knick amplifier, and the FREJA relay test system. This is due to those components being vital in testing the shaft's current protection function.

### 6.1 Rogowski Coil

As discussed earlier, a Rogowski coil is an air-cored coil placed around a conductor. The voltage induced in the coil is a result of the alternating magnetic field produced by the current. This voltage is proportional to the rate of change of current.

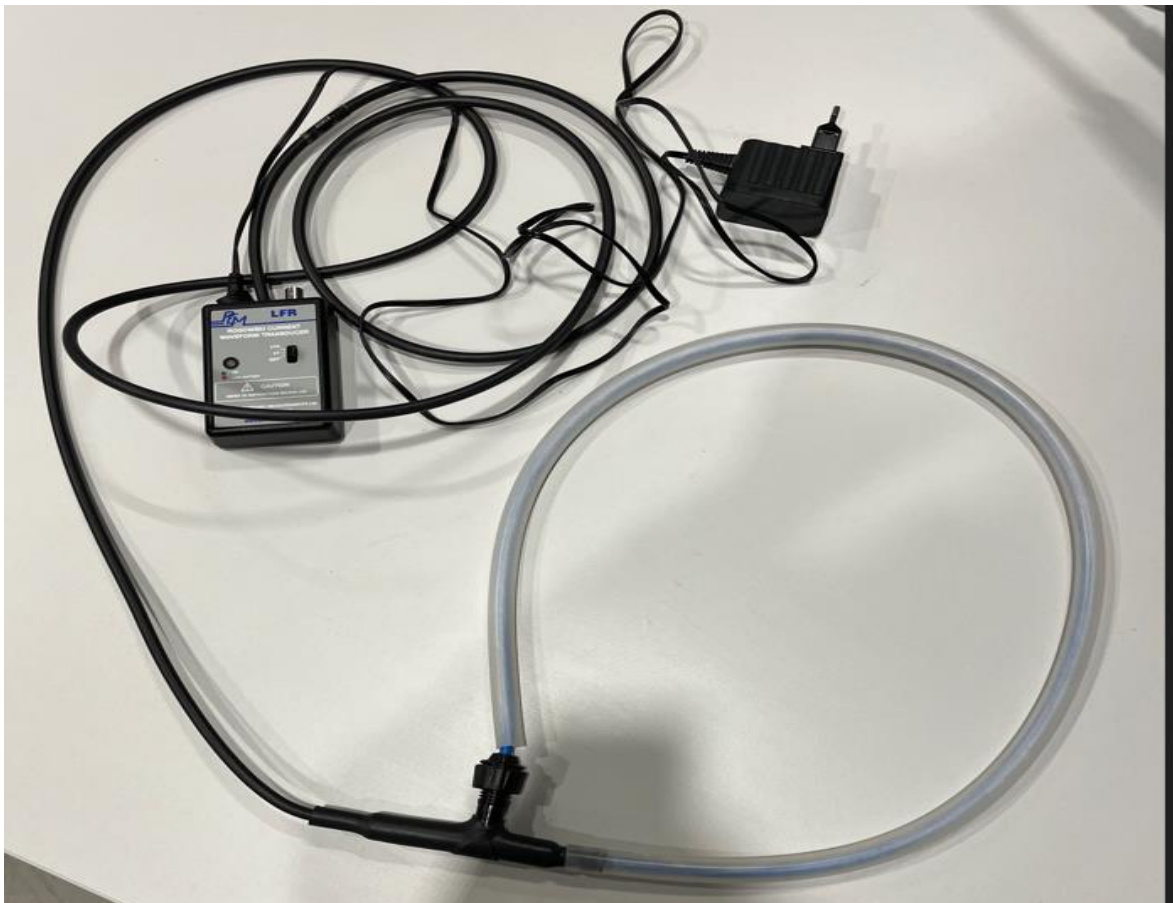
The use of a Rogowski coil is an alternative technique for determining shaft current. A Rogowski coil has the benefit of being more adaptable and simpler to mount than a shaft CT. The Rogowski coil is installed around the shaft, and if installed as shown in Figure 6.1, it can be mounted below a shaft CT for duplicate protection. Similar to the shaft CT, it is impossible to mount the Rogowski coil using a metal mounting bracket that encloses the coil because doing so would result in a shorted turn around the Rogowski coil. [22]



**Figure 6.1** The mounting of a Rogowski coil below a shaft CT [22]

The Rogowski coil that will be used for this thesis work is the LFR current probe, by Power Electronic Measurements Ltd, and is shown in Figure 6.2. LFR, also known as a Low Frequency Rogowski coil, is suitable for applications requiring power quality and leakage currents. It is optimized to provide the lowest noise floor and the least amount of phase measurement error from 45 Hz to 20 kHz. The noise floor is the level of background noise or interference in a system or environment. It stands for the minimum amount of noise that may be measured or detected in a given signal or system. Several factors, such as electrical interference, thermal noise or any other unwanted man-made signals, can have an impact on the noise floor.

The integrator box that is connected to the Rogowski coil has an indication if the coil is on or off and a range switch for sensitivity. For the power supply, a 9 V battery with typically a 50-hour battery life can be used, or simply a 12 V – 24 V power supply. The integrator box is linked to the Rogowski coil through a double-shielded coaxial wire, with a BNC connection on the output side. Table 6.1 offers more technical data provided by [28].



**Figure 6.2 LFR Current Probe with integrator box and power supply [25]**

**Table 6.1 LFR Characteristics**

|  | <b>X10</b>                                  | <b>X1</b>    |
|--|---|--------------|
| <b>Type</b>                              | <b>LFR 03/3</b>                             |              |
| <b>Sensitivity (mV/A)</b>                | <b>100.0</b>                                | <b>10.0</b>  |
| <b>Peak current (A)</b>                  | <b>60.0</b>                                 | <b>600.0</b> |
| <b>Phase error at 50Hz max.(deg.)</b>    | <b>&lt; 0.85</b>                            |              |
| <b>Noise typ. (mV RMS)</b>               | <b>3.0</b>                                  | <b>1.0</b>   |
| <b>LF (-3dB) bandwidth typ. (Hz)</b>     | <b>0.45</b>                                 |              |
| <b>Peak di/dt (kA/<math>\mu</math>s)</b> | <b>0.015</b>                                | <b>0.25</b>  |
| <b>Typical Linearity</b>                 | <b><math>\pm 0.05\%</math> (full scale)</b> |              |

The measurement signal that goes through the integrator box is transferred to the Knick amplifier using a single-shielded coaxial cable and BNC-to-screw-adapter.

The LFR has a large bandwidth and is optimized to provide flat sensitivity (V/A) and low phase error across a wide frequency range. At low frequencies of 1 kHz, the phase inaccuracy of the sensor is mostly due to high stability passive components. As a result, any phase mistake is predictable. At frequencies greater than 10 kHz, the phase error is determined by the dynamics of the Rogowski coil, the connecting cable, and the electronic integrator, all of which are carefully managed to ensure a predictable frequency response.

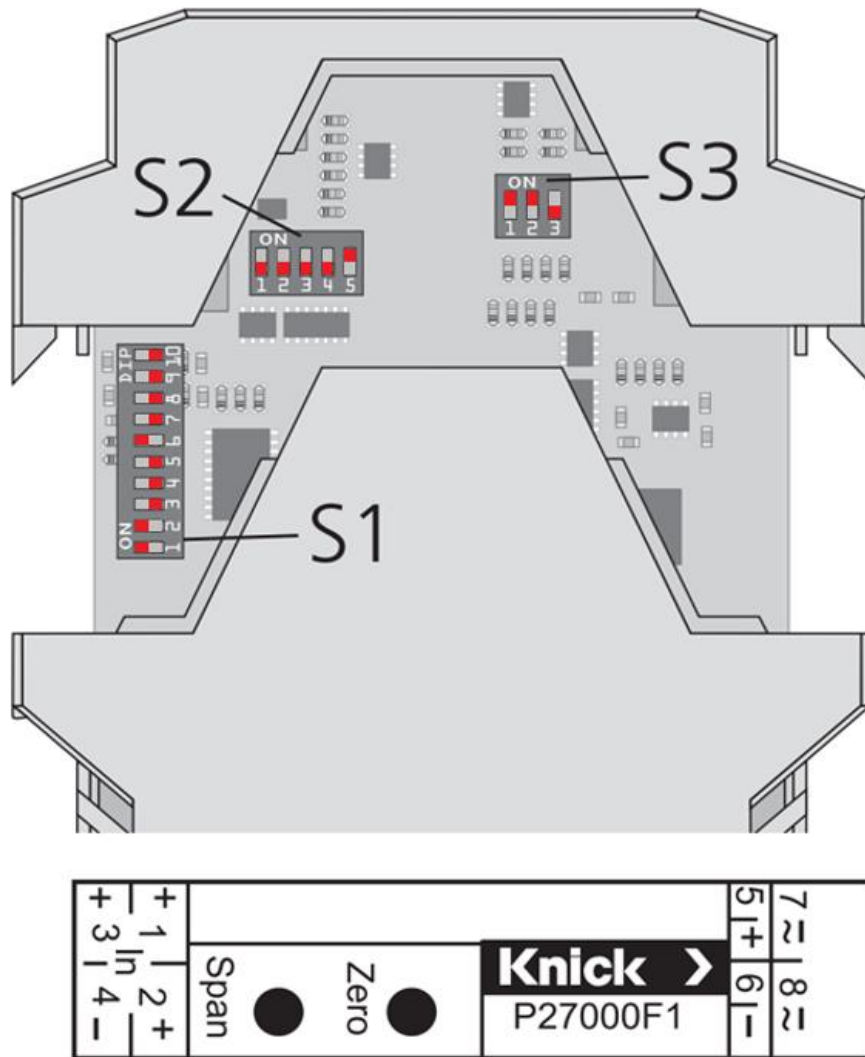
## 6.2 Knick Amplifier

The amplifier used for the measurement arrangement is supplied by Knick International. The objective of using this amplifier is to get the desired voltage signal fed to the REX640.

Technical details regarding the component will be shortly discussed and more information concerning the Knick amplifier can be found in [29].

The VariTrans P27000 amplifier galvanically isolates and converts the measurement signal from the Rogowski coil into a standardized signal. It applies to any input signals from  $\pm 20$

mV to  $\pm 200$  V and from  $\pm 0.1$  mA to  $\pm 100$  mA. For the testing that will be done in this thesis work, a configuration of the amplifier is necessary. This is accomplished by opening its case and adjusting the DIP switches. The necessary switch positions for test purposes are shown in Figure 6.3.



**Figure 6.3** P27000 DIP-switch setting and connection terminals [27]

The positions of the DIP-switches give the Knick the following amplifications:

Since 1 and 2 were switched on S1 it means the Input value is between  $0... \pm 300$  mV. Figure 6.4 shows some of the different input ranges that can be chosen, as well as the input range that was chosen for the amplifier used in this thesis work, marked in the red boxes.

| Eingang         | S1 |    |   |   | S2 |   |   |    | Klemmen |   |
|-----------------|----|----|---|---|----|---|---|----|---------|---|
|                 | 1  | 2  | 3 | 4 | 1  | 2 | 3 | 4  | +       | - |
| Eingangsbereich |    |    |   |   |    |   |   |    |         |   |
| 0 ... ± 60 mV   |    |    |   |   |    |   |   | ON | 2       | 4 |
| 0 ... ± 100 mV  | ON |    |   |   |    |   |   | ON | 2       | 4 |
| 0 ... ± 150 mV  |    | ON |   |   |    |   |   | ON | 2       | 4 |
| 0 ... ± 300 mV  | ON | ON |   |   |    |   |   | ON | 2       | 4 |

Figure 6.4 Input Value Knick Amplifier [29]

The output signal selected was 0... ± 5 V. Given that the amplifier's input signal is 0... ± 300 mV, a signal of 300 mV on the input would be converted to 5 V at the output. Figure 6.5 shows the chosen output signal and the other options available as output signals.

| Ausgang                             |                 |         | S1 |    |    | S3 |    |
|-------------------------------------|-----------------|---------|----|----|----|----|----|
| Ausgangsbereich                     | Ausgangs-Spanne | Endwert | 5  | 6  | 7  | 1  | 2  |
| 0 ... ± 10 V                        | 10 V            | 10 V    |    |    |    | ON | ON |
| 2 ... 10 V                          | 8 V             | 10 V    | ON |    |    | ON | ON |
| 0 ... ± 5 V                         | 5 V             | 5 V     |    | ON |    | ON | ON |
| 1 ... 5 V                           | 4 V             | 5 V     | ON | ON |    | ON | ON |
| 0 ... ± 20 mA                       | 20 mA           | 20 mA   |    |    | ON |    |    |
| 4 ... 20 mA                         | 16 mA           | 20 mA   | ON |    | ON |    |    |
| Offset<br>(in % der Ausgangsspanne) |                 |         | S1 |    |    | S2 |    |
|                                     |                 |         | 8  | 9  | 10 | 5  |    |
| 0 %                                 |                 |         |    |    |    | ON |    |

Figure 6.5 Output Signal from Amplifier [29]

### 6.3 FREJA Relay Test System

The FREJA 300 relay test system (Figure 6.6) will be used for simulating the shaft current during the tests. It can be used with or without a PC, but since the computer used in the tests only has one Ethernet port, the FREJA 300 will be used without the PC.

The outputs that FREJA 300 has can generate 4x150 V (82 VA) and 3x15 A (87 VA) or 1x45 A (250 VA) with the possibility of changing each output separately. The primary purpose of FREJA 300 is the secondary testing of protective relays. Almost all protective relay types can be tested, which is why the FREJA 300 was chosen for the tests.

Configuring the FREJA without a PC is called Local Mode. Settings are easily made and adjusted by turning and clicking using the dial. The settings are automatically saved when turning off the FREJA, but they can be assigned names and saved separately for easier access if preferred. The display monitor shows the value that is being generated. Details regarding the use of FREJA 300 with a PC can be accessed in [30].

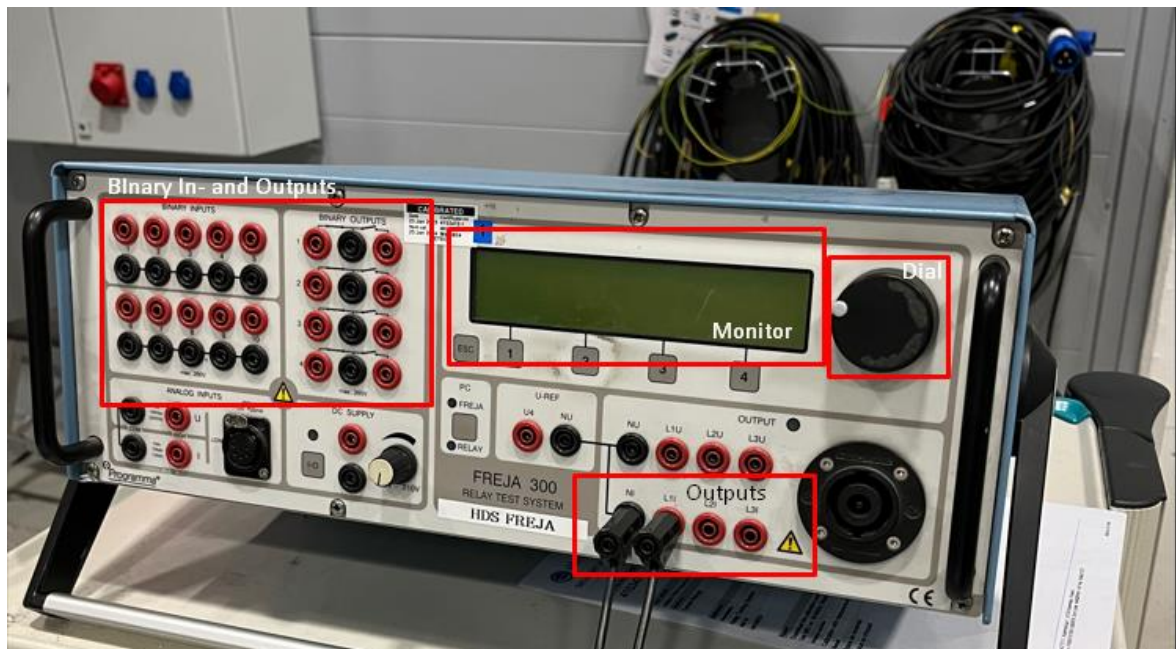


Figure 6.6 FREJA 300 Relay Test System

## 7 Function specification for Shaft Current Protection

The function for the shaft current protection with REX640 is developed by [25]. This document includes parameters, inputs, and outputs, reported data, and communication mappings for IEC 61850. The function, which is called GSLPTOC (Generator Shaft Current Leakage Protection), compares the measured shaft current to the set alarm and operate levels. The function block is shown in Figure 7.1.

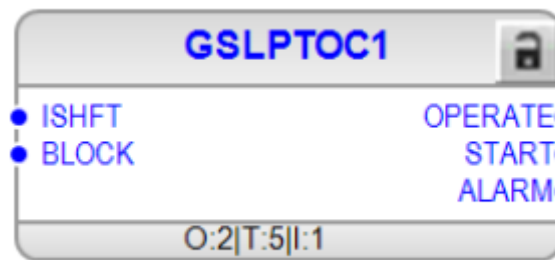


Figure 7.1 Symbol for the shaft current protection function [25]

A module diagram (Figure 7.2) has been made for describing the operation of the function.

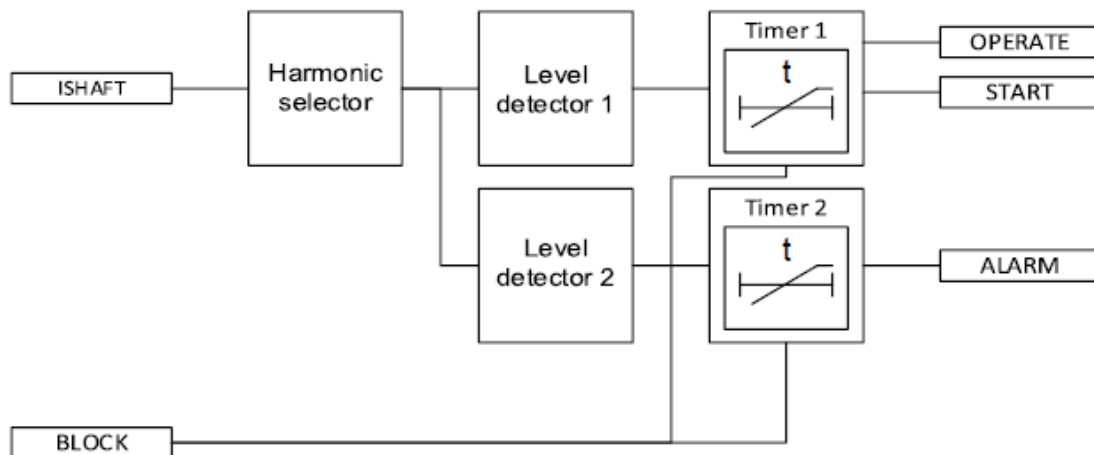


Figure 7.2 Module diagram for the shaft current protection function [25]

Where the ISHAFT input takes the analogue signal from the measurements (Rogowski coil), which provides a voltage signal that amplifies for the relay input. Within the function, the current gets converted from the voltage signal. Another viable solution for measuring shaft currents can be to only use the current transformer directly with the relay current input.

The harmonic selector is determined based on the dominant frequency component which is done through the commissioning tests. The dominant frequency component is identified by measuring current with the Rogowski coil while the generator is at full load. A fault condition is simulated with a resistor and an ammeter by grounding the non-mover side. The measurements are done with a disturbance recorder when manually triggered during previously described fault conditions. Measurements that are recorded during this are analyzed and the dominant frequency can thus be identified.

Level detectors 1 & 2 compare shaft currents that are measured that are set in primary amps. Level 1 compares against Operate start value and Level 2 against Alarm start value. If the set value is exceeded, an enable signal is sent to either Timer depending on which Level that was exceeded.

Timer 1 activates the START output when it receives the enable signal. When the value set by Operate delay time is reached by the operate timer, OPERATE output is activated. However, the reset timer is activated if the fault resolves before the module provides an OPERATE signal. Reset delay time specifies the value needed to be reached by the reset timer, which if reached, resets the operate timer. When the BLOCK signal is activated, Timer 1 is reset and the OPERATE and START outputs are deactivated.

Timer 2 activates the alarm timer when it receives the enable signal. The ALARM output is turned on when the alarm timer reaches the value specified by the Alarm delay time. However, the reset timer is activated if the fault resolves before the module provides an ALARM signal. When the BLOCK signal is enabled, ALARM output is disabled, and Timer 2 is reset. Both Timer 1 and Timer 2 have timing characteristics that follow Definite time (DT).

For measuring the shaft currents with the function, a CT or a Rogowski coil are to be installed around the generator shaft. Recommended measurement arrangements include amplifying the voltage signal which are shown in Figure 7.3 and Figure 7.4.

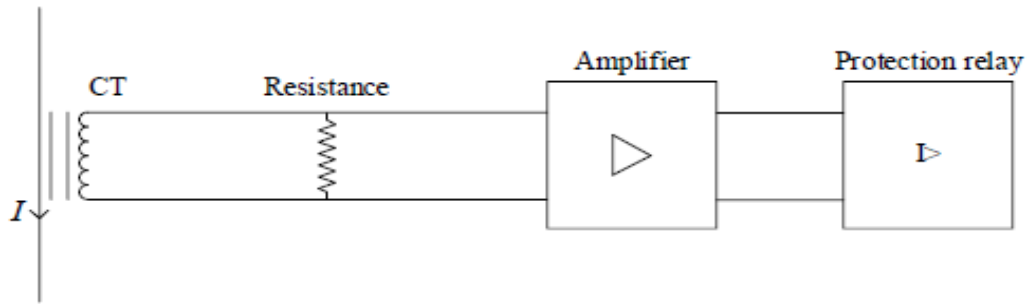


Figure 7.3 Measuring Arrangement for Current Transformer [25]

Alternatively shaft currents can be directly measured from the current transformer with the Protection relay. However, acceptable operation accuracy requires proper signal levels.

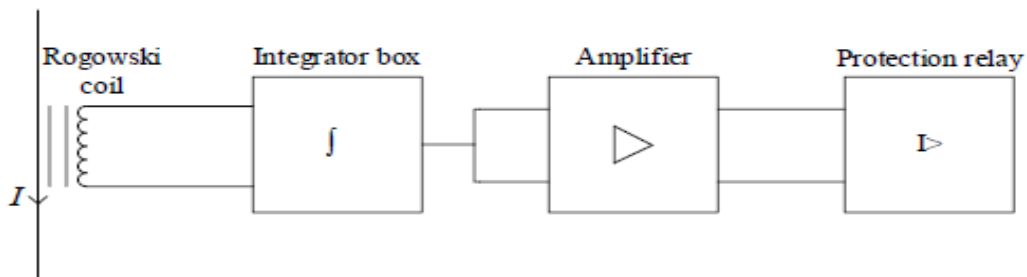


Figure 7.4 Measurement Arrangement for Rogowski Coil [25]

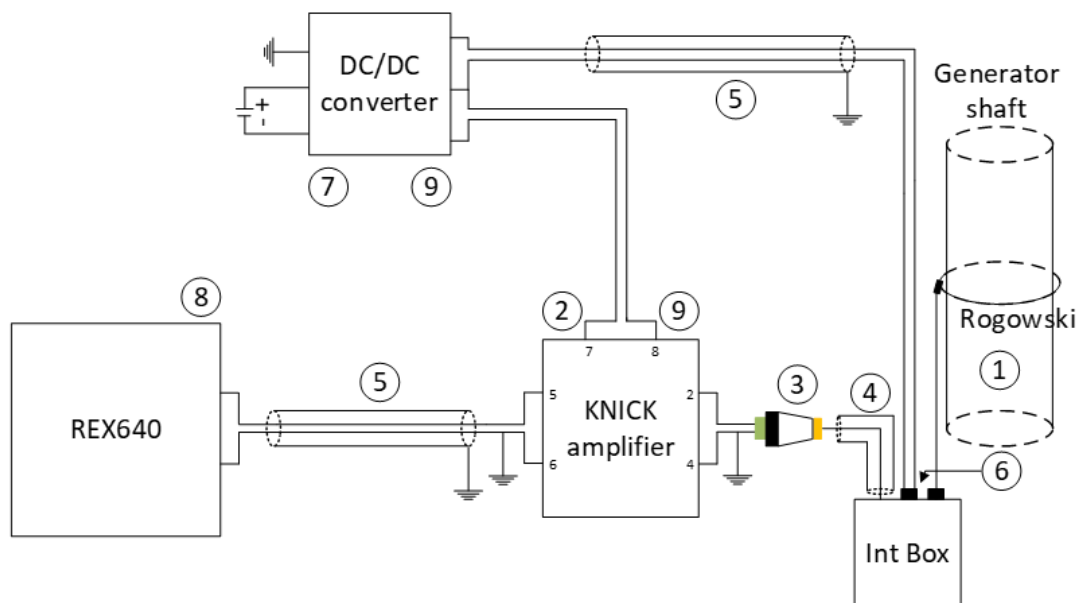
Setting alarm values depend on the contact surface of the bearings. It can be determined that current densities over  $0.1 \text{ A/mm}^2$  begin damaging bearings. The suggested value for Operate start value is 0,5 A and 0,25 A for Alarm start value. This is recommended since currents over 1 A are considered harmful. Both are specified in primary amperes.

When setting primary and secondary values for analog measurements, they must be configured in order for the measured signal to be converted correctly. The primary and secondary values depend on the type of setup used for measurements. [25] describes that a Rogowski coil with a  $1 \text{ A} / 0,1 \text{ V}$  conversion ratio and an amplifier that multiplies the signal 40 times, for example, would have a 1 A main setting and a 4 V secondary setting. Furthermore, the lowest secondary value feasible should be chosen to attain the maximum accuracy. This may be accomplished by lowering both primary and secondary values in the same proportion while keeping the original ratio. More details about the function data, outputs, monitored data, and group settings can be found in [25].

## 8 Testing the New GSLPTOC Function

For testing of the function that was developed and discussed earlier, a REX640 relay and Rogowski coil were brought to the ABB FAT (Factory Acceptance Test) located in the KT-building in Vaasa.

The tests will be done by using a Rogowski coil connected to the REX640. The measured shaft current from the Rogowski coil will be fed to the protection relay where the function as described earlier, compares the current signal to the operate levels and set alarm. A FREJA relay testing system will be used to simulate a current flowing through the Rogowski coil, which represents the generator shaft shown in the measurement arrangements. The measurement arrangements follow Figure 7.4. When taking a closer look into the measurement arrangement, a more accurate picture including the connections between the devices can be accomplished as Figure 8.1 shows.



**Figure 8.1 Connection diagram of the measurement arrangement [31]**

Table 8.1 describes the components used in the measurement arrangement. The numbers in the table correspond to the components seen in Figure 8.1.

**Table 8.1 Components used in a Generator application using Rogowski coil**

| <b>#</b> | <b>Description</b>                           | <b>Proposed</b>     |
|----------|--|---------------------|
| <b>1</b> | Rogowski coil                                | PEM UK Ltd.         |
| <b>2</b> | Amplifier                                    | KNICK International |
| <b>3</b> | BNC-to-screw terminal adapter                | Farnell             |
| <b>4</b> | Single-shielded coaxial cable                | Any                 |
| <b>5</b> | Shielded twisted-pair cable 1mm <sup>2</sup> | Any                 |
| <b>6</b> | DC Power Plug 2.1 mm 5.5 mm                  | Farnell             |
| <b>7</b> | DC-DC converter DR-240D-24                   | Farnell             |
| <b>8</b> | REX640                                       | ABB Oy              |
| <b>9</b> | DIN rail for mounting # 2 and 7              | Any                 |

Additionally, it is possible to retrofit a current transformer to match a similar setup to the one using the Rogowski coil as shown in Figure 8.2. However, it is necessary to take the resistors' multiplicative factor into account when using the retrofitted current transformer measurement arrangement as the secondary value is to be multiplied by the ohm amount of the resistor. Table 8.2 describe the components used for the retrofit current transformer measurement arrangement. Additionally, the numbers presented in the table correspond to each placement of the component in Figure 8.2. [31]

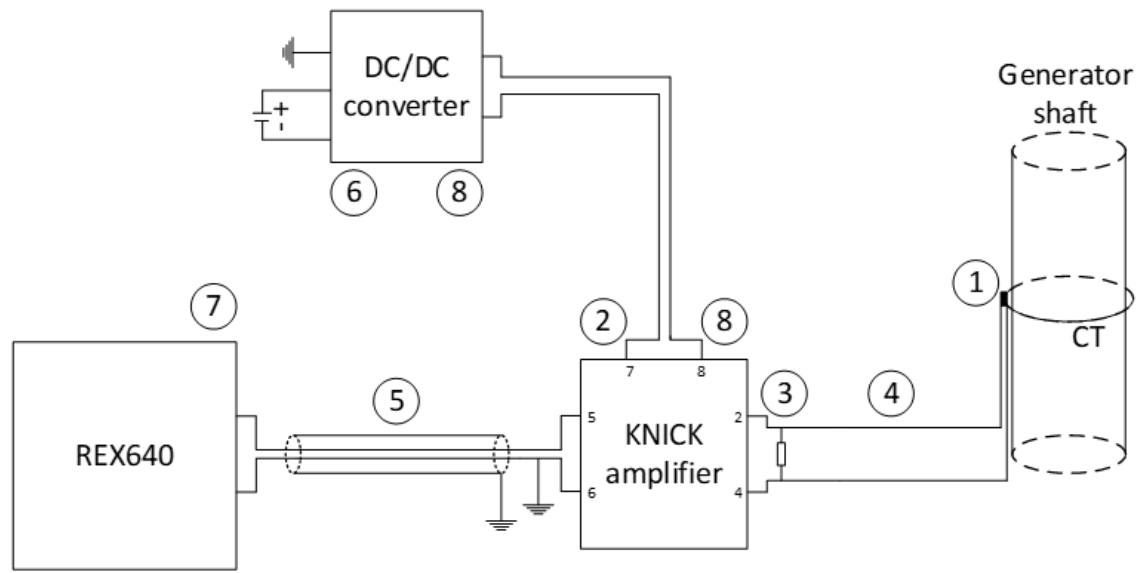


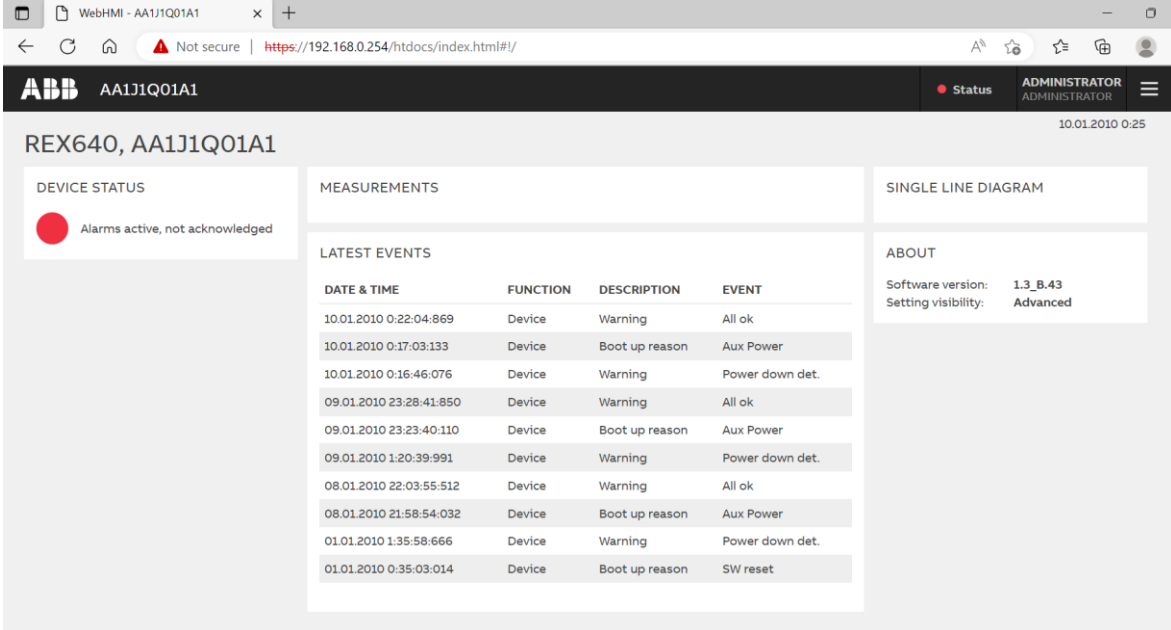
Figure 8.2 Measurement Arrangement Current Transformer [31]

Table 8.2 Retrofit Current Transformer measurement arrangement [31]

| # | Description                      | Proposed            |
|---|----------------------------------|---------------------|
| 1 | Current transformer              | Existing (retrofit) |
| 2 | Amplifier                        | KNICK International |
| 3 | Resistor                         | Mouser              |
| 4 | Single-shielded coaxial cable    | Any                 |
| 5 | Shielded twisted-pair cable 1mm2 | Any                 |
| 6 | DC-DC converter DR-240D-24       | Farnell             |
| 7 | REX640                           | ABB Oy              |
| 8 | DIN rail for mounting # 2 and 6  | Any                 |

To be able to read the measurements from the test results, it is necessary to use the correct application configuration in PCM600, which is discussed in Chapter 8.1.

The WHMI, which was discussed earlier, can also be used to monitor the Relay remotely. For access to the WHMI, it is necessary to enable the WHMI parameter from “off” to “on” in the PCM600 parameter settings. After changing the WHMI parameter, you can access the WHMI by typing `Https://` and the IP-address of the relay and then entering the username and password. The WHMI overview is shown in Figure 8.3.



WebHMI - AA1J1Q01A1

Not secure | <https://192.168.0.254/htdocs/index.html#!/>

ABB AA1J1Q01A1

Status ADMINISTRATOR ADMINISTRATOR

10.01.2010 0:25

REX640, AA1J1Q01A1

DEVICE STATUS

Alarms active, not acknowledged

MEASUREMENTS

SINGLE LINE DIAGRAM

LATEST EVENTS

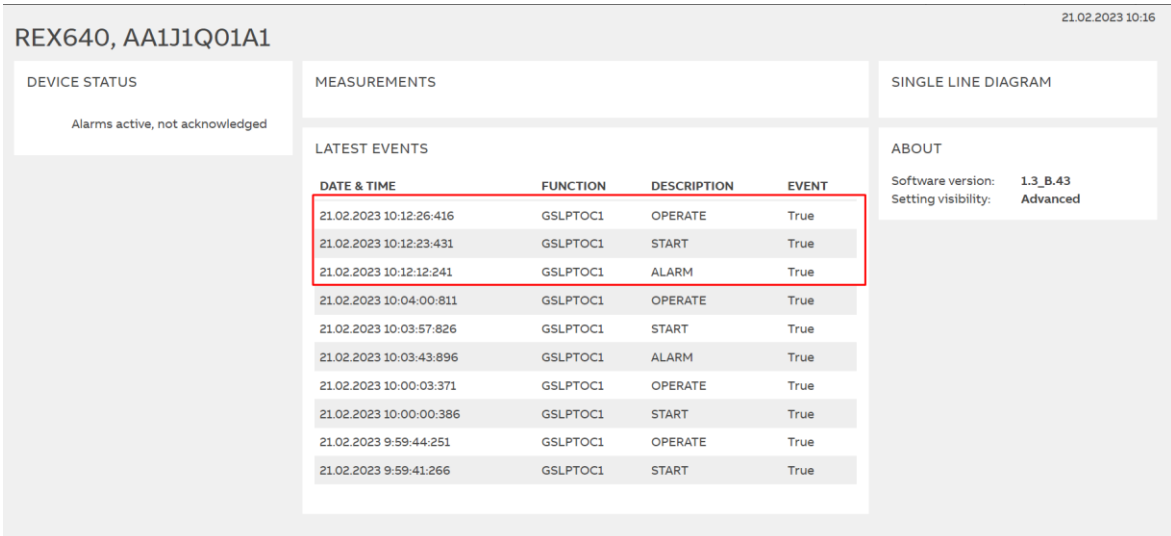
| DATE & TIME             | FUNCTION | DESCRIPTION    | EVENT           |
|-------------------------|----------|----------------|-----------------|
| 10.01.2010 0:22:04:869  | Device   | Warning        | All ok          |
| 10.01.2010 0:17:03:133  | Device   | Boot up reason | Aux Power       |
| 10.01.2010 0:16:46:076  | Device   | Warning        | Power down det. |
| 09.01.2010 23:28:41:850 | Device   | Warning        | All ok          |
| 09.01.2010 23:23:40:110 | Device   | Boot up reason | Aux Power       |
| 09.01.2010 1:20:39:991  | Device   | Warning        | Power down det. |
| 08.01.2010 22:03:55:512 | Device   | Warning        | All ok          |
| 08.01.2010 21:58:54:032 | Device   | Boot up reason | Aux Power       |
| 01.01.2010 1:35:58:666  | Device   | Warning        | Power down det. |
| 01.01.2010 0:35:03:014  | Device   | Boot up reason | SW reset        |

ABOUT

Software version: 1.3\_B.43  
Setting visibility: Advanced

**Figure 8.3 WHMI Overview from REX640**

The WHMI offers the ability to monitor data as well as disturbance records and check the latest events. Figure 8.4 shows an example where three signals have been tripped, showing a Boolean “True” event for the trip.



REX640, AA1J1Q01A1

21.02.2023 10:16

DEVICE STATUS

Alarms active, not acknowledged

MEASUREMENTS

SINGLE LINE DIAGRAM

LATEST EVENTS

| DATE & TIME             | FUNCTION | DESCRIPTION | EVENT |
|-------------------------|----------|-------------|-------|
| 21.02.2023 10:12:26:416 | GSLPTOC1 | OPERATE     | True  |
| 21.02.2023 10:12:23:431 | GSLPTOC1 | START       | True  |
| 21.02.2023 10:12:12:241 | GSLPTOC1 | ALARM       | True  |
| 21.02.2023 10:04:00:811 | GSLPTOC1 | OPERATE     | True  |
| 21.02.2023 10:03:57:826 | GSLPTOC1 | START       | True  |
| 21.02.2023 10:03:43:896 | GSLPTOC1 | ALARM       | True  |
| 21.02.2023 10:00:03:371 | GSLPTOC1 | OPERATE     | True  |
| 21.02.2023 10:00:00:386 | GSLPTOC1 | START       | True  |
| 21.02.2023 9:59:44:251  | GSLPTOC1 | OPERATE     | True  |
| 21.02.2023 9:59:41:266  | GSLPTOC1 | START       | True  |

ABOUT

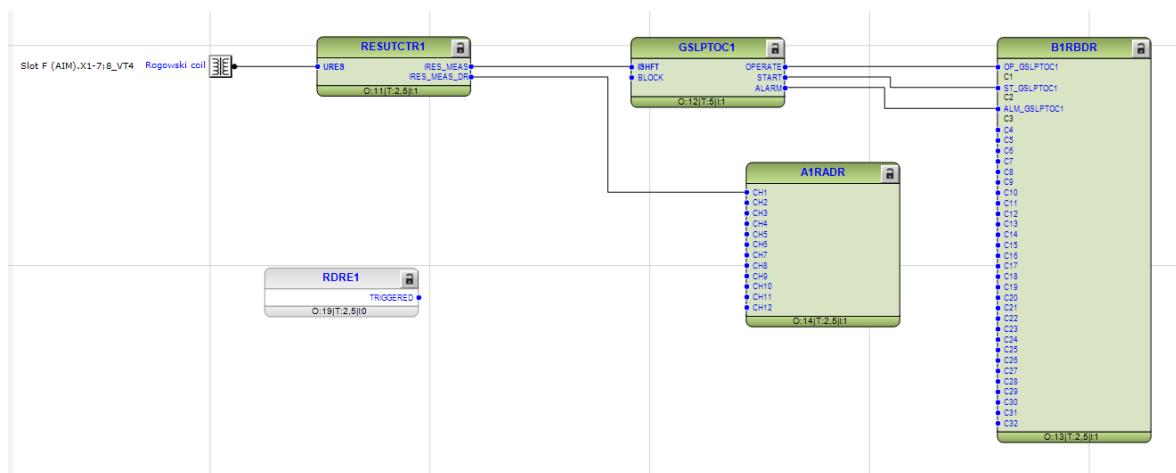
Software version: 1.3\_B.43  
Setting visibility: Advanced

**Figure 8.4 WHMI Trip Events**

## 8.1 Measurement Function

As previously mentioned, the measurement signal goes through the Rogowski coil Integrator box and is converted to voltage. This voltage is then transferred to the VT4 (Voltage Transformer) port on the REX640, which is located on Slot F (AIM). In the Application Configuration this signal is transferred to RESULTCTR1 function that converts the voltage to current. RESULTCTR1 means Residual Voltage to Current Preprocessing and must be configured by setting the parameters depending on the conversion ratio of the Rogowski coil. Setting the conversion ratio has been discussed earlier and will thus not be further elaborated. The GSLPTOC then receives the signal and constantly compares it to the alarm set values. The current and harmonic values that the GSLPTOC function block has can also be monitored from the WHMI.

The A1RADR and B1RBDR are disturbance recorders for Analogue respectively Binary channels. Figure 8.5 shows the application configuration with A1RADR and B1RBDR on the right hand side. These function blocks create the disturbance records that can later be analyzed from the disturbance handler. The disturbance records generated in the disturbance handler can for example be opened and analyzed with the ABB Wavewin32 software.



**Figure 8.5 Application Configuration for GSLPTOC**

## 8.2 Harmonic Selector

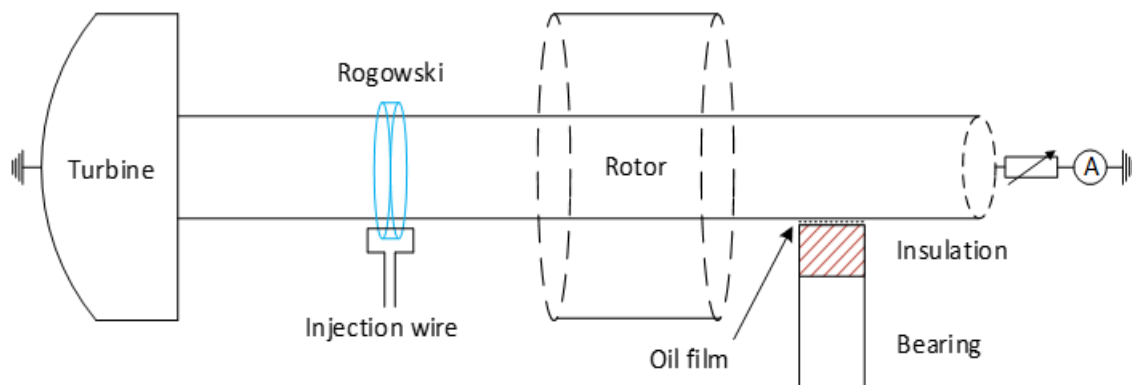
A harmonic wave is a sinusoidal wave and has a frequency that is an integer multiple of the fundamental frequency, which is the frequency at which a system is designed to operate, or the frequency of the initial periodic signal.

For selecting the Harmonic, the GSLPTOC parameter setting has to be changed. The harmonic determines the frequency that the system uses. This can be done by commissioning testing, which was discussed in Chapter 7. In the parameter settings for GSLPTOC, it is possible to switch the operating harmonic by choosing either Fundamental (First Harmonic) which is 50 Hz, Third Harmonic which is 150 Hz, or Fifth Harmonic which is 250 Hz. The Harmonic selector is shown in Figure 8.6.

| GSLPTOC1: 1            |     |               |    |      |       |
|------------------------|-----|---------------|----|------|-------|
| I>.GS(1)               |     |               |    |      |       |
| Operation              |     | on            |    |      |       |
| Reset delay time       |     | 1000          | ms | 0    | 10000 |
| settingGroup 1         |     |               |    |      |       |
| ✓ Sel operate harmonic |     | Fundamental   |    |      |       |
| Alarm start value      |     | Fundamental   |    | 0,10 | 10,00 |
| Operate start value    |     | Third hamonic |    | 0,10 | 10,00 |
| Alarm delay time       |     | 3000          | ms | 40   | 30000 |
| Operate delay time     | 100 | 100           | ms | 40   | 30000 |

**Figure 8.6 Harmonic Selector GSLPTOC**

When selecting the harmonic, it is important to investigate which dominant frequency component is present as discussed in Chapter 7. The fault condition is simulated by grounding the non-mover side with a resistor and an ammeter while grounding the mover side with water (hydro generators) or a grounding brush (turbogenerators). Figure 8.7 shows the application for determining the dominant frequency component.



**Figure 8.7 Application for Fault Simulation**

### 8.3 Tests with Fundamental Harmonic

The fundamental harmonic is tested by setting the FREJA relay tester to 50 Hz. This can be verified by measuring the frequency output with a Fluke Multimeter, as shown in Figure

8.8. The Rogowski coil integrator box is set to 10X to show the correct values that are fed from the FREJA. The reason for setting the integrator box to 10X is due to the parameter settings in the RESUTCTR block, where primary and secondary values were determined.



**Figure 8.8 Verifying the Fundamental Frequency**

When feeding the current through the Rogowski coil, values can be measured from the WHMI online. The I\_SHAFT parameter name which is shown in Figure 8.9, demonstrates the current that the Rogowski coil measures. I\_SHAFT\_H1 shows the value for the fundamental harmonic which is currently chosen in the parameter settings.

Monitoring / I/O Status / Current Protection / **GSLPTOC1** / Monitored Data 21.02.2023 9:13

Monitoring - Monitored Data

| PARAMETER NAME | RELAY VALUE | UNIT | MIN. | MAX. | STEP |   |
|----------------|-------------|------|------|------|------|---|
| I_SHAFT        | 0.20        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H1     | 0.20        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H3     | 0.00        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H5     | 0.00        | A    | 0    | 10   | 0.01 | ? |
| START_DUR      | 0.00        | %    | 0    | 100  | 0.01 | ? |

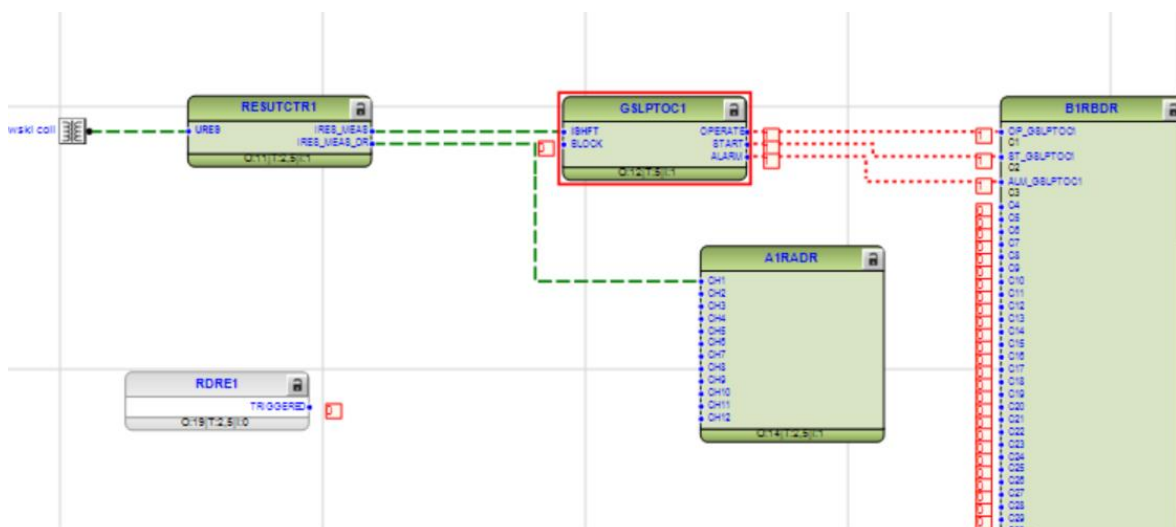
**Figure 8.9 WHMI Monitored Data**

The value for ALARM is set to 0,25 A with an Alarm delay time of 3000 ms, meaning that if the value is 0,25 A or over for 3 seconds, an alarm signal is generated. The Alarm signal was tested by feeding 0,25 A through the Rogowski coil and a disturbance record was received.

The values for START and OPERATE are set to 0,5 A with an Operate delay time of 3000 ms. This means when 0,5 A is fed through the Rogowski coil, START will be activated. If START is active for 3000 ms, Operate signal will be activated. In reality, the Operate time delay is shorter than 3000 ms since it is important that it trips fast to prevent damages. A disturbance record was also received from the Operate trip.

When determining the trip values, Pick-up and Drop-off tests were done. This was done by inserting a multimeter in Slot B (BIO), connector X2, terminals 3 and 4 that beeps when pins are activated. When the trip occurs for the Start signal, the current in mA and the voltage in mV were observed. These tests determined that the current value that trips the Start signal was approximately 500 mA and the voltage value was 1960 mV when tripped. The drop out values for the Start signal were tested and the concluded values where the Start trip stops were 480 mA and 1960 mV. These tests further prove that the relay receives the right values from the Rogowski coil and trips according to the set values.

When pressing the “Work online” button in PCM600, live monitoring can be done. The live monitoring shows the connections as green and the tripped signals as red. Figure 8.10 shows the application configuration when ALARM, START, and OPERATE have been tripped. This is due to the set values being exceeded by the generated current from the FREJA.



**Figure 8.10 Alarm, Start and Operate signals tripped**

When configuring the disturbance recorder, the operation, record length, and Pre-trg length must be set. The operation parameter decides whether a disturbance record is to be made or not, with the ability to choose either “on” or “off” from a drop-down menu. The Record length decides how long it records, Figure 8.11 shows 50 cycles as the chosen value with 1 cycle being 20 ms. The Pre-trg length determines how much is recorded before the actual trigger. The set value of 50 % on the Pre-trg length means it will start recording 25 cycles before the trip occurs.

| Group / Parameter Name    | IED Value | PC Value | Unit   | Min | Max |
|---------------------------|-----------|----------|--------|-----|-----|
| ✓ Disturbance recorder: 0 |           |          |        |     |     |
| ✓ Disturbance recorder    |           |          |        |     |     |
| ✓ General                 |           |          |        |     |     |
| ✓ Operation               |           | on       |        |     |     |
| ✓ Record length           |           | 50       | cycles | 10  | 500 |
| ✓ Pre-trg length          |           | 50       | %      | 0   | 100 |

**Figure 8.11 Disturbance Recorder Parameter Settings**

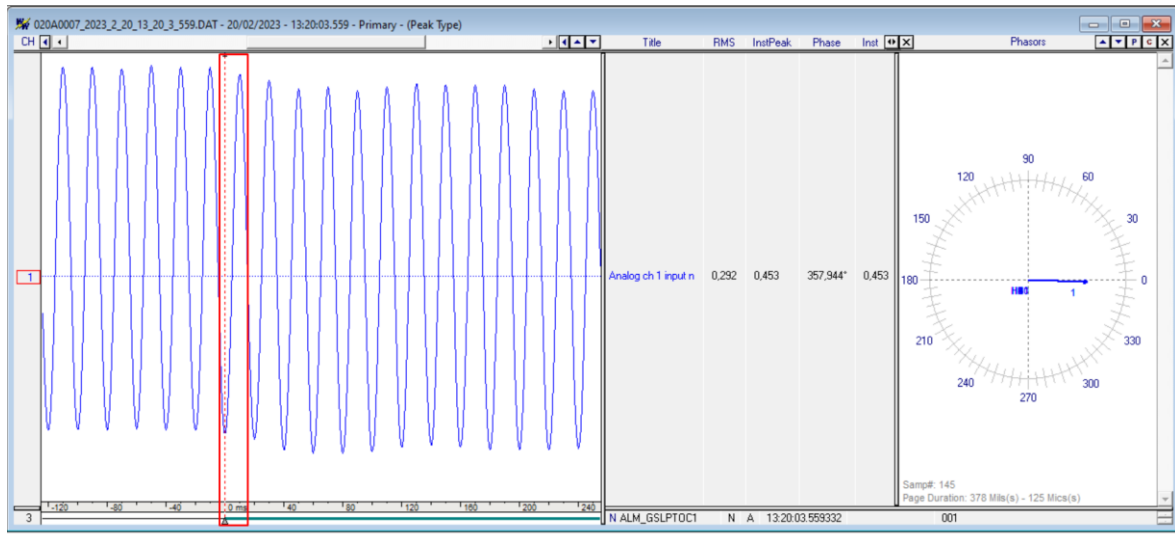
The Recording can be saved by opening the “REX640 – Disturbance Handling” and reading recordings from the IED. The recorded disturbances appear with timestamps along with the name of the unit as shown in Figure 8.12.

|   | Trig Date Time         | Stn Name | Obj Name      | IED Name   | Rec No | Trig Channel | PreTrig Time |
|---|------------------------|----------|---------------|------------|--------|--------------|--------------|
| ▶ | 1.1.0001 0.00.00.000   | GSLPTOC  | 192.168.0.254 | AA1J1Q01A1 | 1      | No-value     | 0            |
| ▶ | 20.2.2023 13.20.03.559 | REX640   | 192.168.2.10  | AA1J1Q01A1 | 2      | No-value     | 500          |
| ▶ | 20.2.2023 13.20.27.114 | REX640   | 192.168.2.10  | AA1J1Q01A1 | 3      | No-value     | 500          |
| ▶ | 20.2.2023 13.20.30.099 | REX640   | 192.168.2.10  | AA1J1Q01A1 | 4      | No-value     | 500          |

**Figure 8.12 Disturbance records in PCM600**

The recording can then be accessed by opening the recording with the Wavewin32 software as shown in Figure 8.13 where a recording of the Alarm signal trip was made. As Figure 8.13 shows, a time was recorded prior to the trip value, this is explained by referring back to the pre-trg length, that is set to start recording 25 cycles prior to the trip. Additionally, the cursor can be moved throughout the figure where the RMS (Root Mean

Square) shows the value it possesses at a certain time. Wavewin32 also shows the title of the signal, function block and the phase of the recording.



**Figure 8.13 Disturbance recording from Alarm tripped in Wavewin32**

After testing the ALARM signal trip, the current was increased to 0,5 A to trip the START and OPERATE signals. The Operate delay time was changed to 100 ms to ensure that once the Start signal was activated at 0,5 A, the Operate signal would trip 100 ms after. The three teal colored lines at the bottom of Figure 8.14 demonstrate the three different signals that were tripped, with number 1 being the Operate signal which is shown to trigger 80 ms after number 2, which is the Start signal. Signal number 3 is the Alarm signal, which is activated under the whole duration due to the current being above the set value at all times during the record and pre-trg length.



**Figure 8.14 Disturbance record for OPERATE and START**

## 8.4 Tests with Third Harmonic

Testing the third harmonics requires changing the FREJA settings. Since the third harmonic works at 150 Hz, this will be set as the frequency output of the FREJA. This can be done manually by choosing the frequency setting and increasing it to 150 Hz.

As the frequency output has changed, the parameter settings for the GSLPTOC also need to be changed. As previously mentioned, the parameter settings offer the ability to choose between the fundamental, third, and fifth harmonic. When monitoring the current with the third harmonic setting, I\_SHAFT\_H3 receives the same current as the I\_SHAFT. This is due to the I\_SHAFT\_H3 being the third harmonic current value. The values are visible through the WHMI and shown in Figure 8.15.

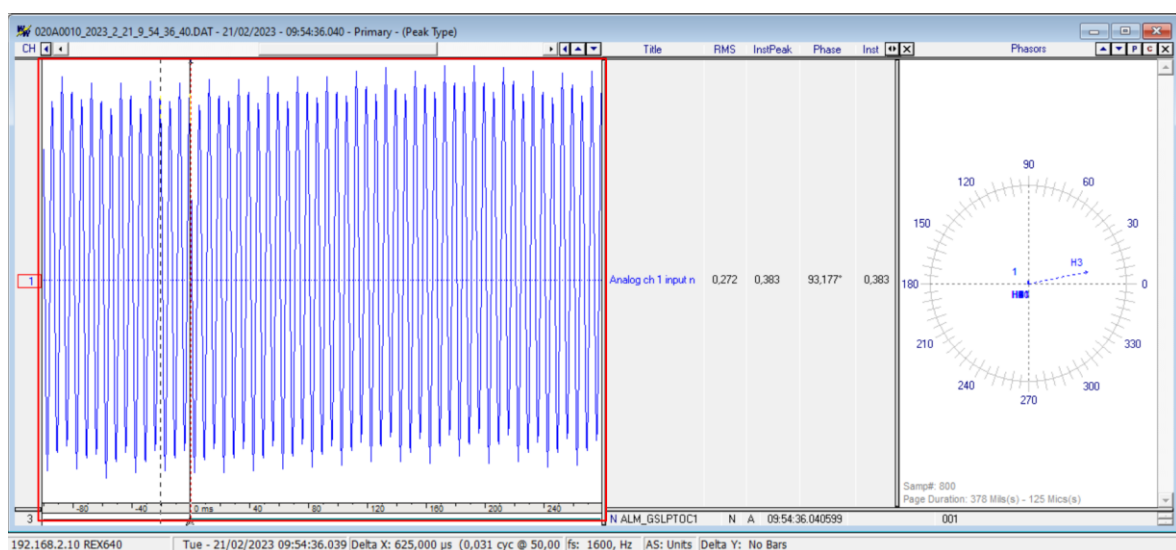
Monitoring / I/O Status / Current Protection / **GSLPTOC1 / Monitored Data** 21.02.2023 9:53

Monitoring - Monitored Data

| PARAMETER NAME | RELAY VALUE | UNIT | MIN. | MAX. | STEP |   |
|----------------|-------------|------|------|------|------|---|
| I_SHAFT        | 0.20        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H1     | 0.01        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H3     | 0.20        | A    | 0    | 10   | 0.01 | ? |
| I_SHAFT_H5     | 0.00        | A    | 0    | 10   | 0.01 | ? |
| START_DUR      | 0.00        | %    | 0    | 100  | 0.01 | ? |

**Figure 8.15 WHMI Third Harmonic Data Monitoring**

After the current was set to the trip value for the Alarm signal (0,25 A), the disturbance record shown in Figure 8.16 shows an increase in the frequency of the current, which is due to the frequency being 150 Hz instead of the fundamental 50 Hz.



**Figure 8.16 Wavewin32 Disturbance Record for Alarm trip in the Third Harmonic**

The same Pick-up and Drop-off tests were also conducted for the third harmonic, where the threshold of the Start signal trip was tested. Tests conclude that the Start signal activates at approximately 508 mA and 2040 mV and that the Start signal trip drops at 478 mA and 1910 mV.

Figure 8.17 shows the Start and Operate trips in the third harmonic as a result of exceeding the set value of 0,5 A over 3 seconds.

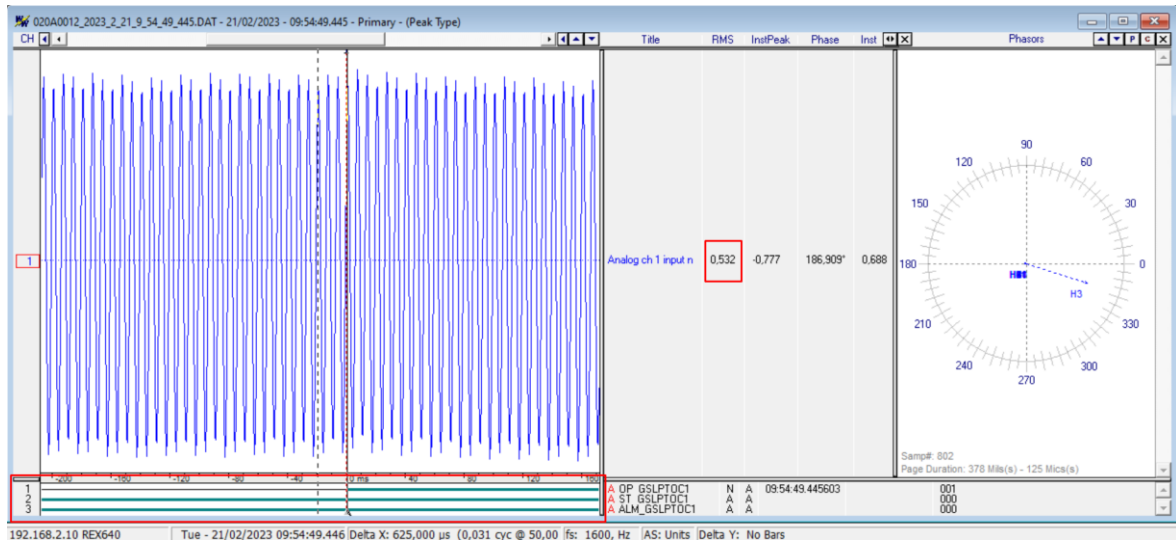


Figure 8.17 Wavewin32 Disturbance record for Start and Operate in the Third Harmonic

## 8.5 Tests with Fifth Harmonic

To test the fifth harmonic, the frequency on the FREJA must be raised to 250 Hz. This was done by manually entering 250 Hz as the frequency output on the FREJA. Figure 8.18 shows FREJA set to 250 Hz.



Figure 8.18 FREJA set to Fifth Fundamental (250Hz)

Testing the fifth harmonic started with monitoring the data that the GSLPTOC function was receiving in the WHMI. The WHMI shows a current on the parameter I\_SHAFT\_H5, indicating that the fifth harmonic is being used. Figure 8.19 shows the monitored data when 0,2 A was fed through the Rogowski coil using the fifth harmonic.

Monitoring / I/O Status / Current Protection / **GSLPTOC1 / Monitored Data** 21.02.2023 10:03

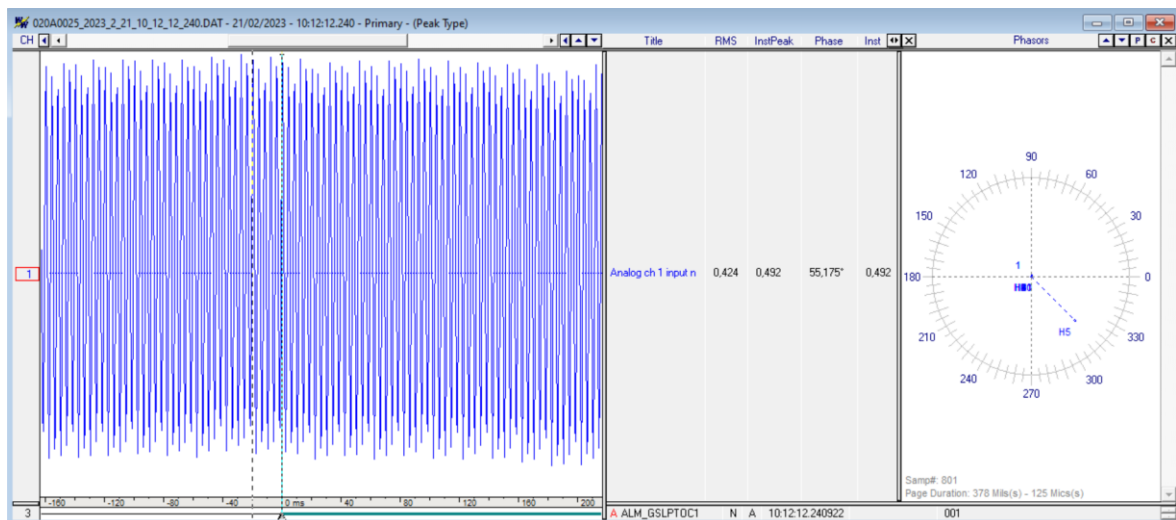
Monitoring - Monitored Data

| PARAMETER NAME | RELAY VALUE | UNIT | MIN. | MAX. | STEP |     |
|----------------|-------------|------|------|------|------|-----|
| I_SHAFT        | 0.20        | A    | 0    | 10   | 0.01 | (?) |
| I_SHAFT_H1     | 0.02        | A    | 0    | 10   | 0.01 | (?) |
| I_SHAFT_H3     | 0.00        | A    | 0    | 10   | 0.01 | (?) |
| I_SHAFT_H5     | 0.20        | A    | 0    | 10   | 0.01 | (?) |
| START_DUR      | 0.00        | %    | 0    | 100  | 0.01 | (?) |

**Figure 8.19 WHMI GLSPTOC Monitored Data for Fifth Harmonic**

The Pick-up and Drop-off tests for the fifth harmonic conclude that the trip occurs at 508 mA and 2000 mV and drops out at 478 mA and 1900 mV. Multiple tests where the current generation was increased over the set value of the Start signal and again lowered below the set value were performed to ensure that these values remain accurate.

The higher frequency may be determined by examining the disturbance data after the alarm was tripped. The Wavewin32 record shown in Figure 8.20 demonstrates the alarm value tripped with the fifth harmonic active.



**Figure 8.20 Wavewin32 Alarm tripped with Fifth Harmonic**

The same was done for the Start and Operate signals, which have a trip value of 0,5 A. Figure 8.21 shows the disturbance record that was taken when the Start and Operate signals were tripped. Compared to the third harmonic, the frequency is noticeably higher.

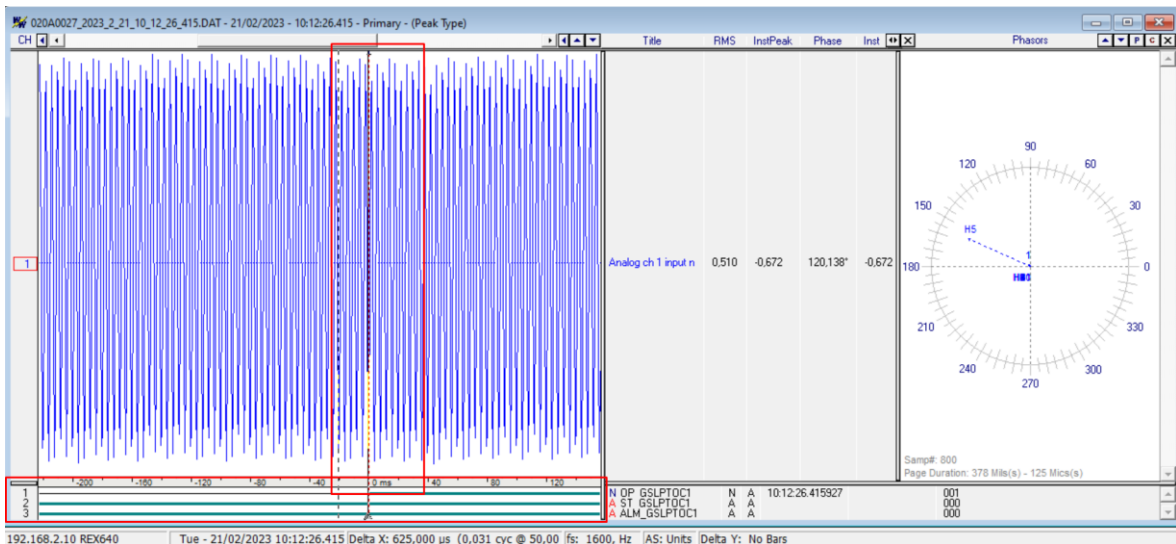


Figure 8.21 Wavewin32 disturbance record of Start and Operate with Fifth Harmonic

### 8.6 Trip Time Tests

When using the FREJA relay test system the trip times can be measured by activating a binary output from the REX640 to the binary inputs of the FREJA so that once the Operate and Start outputs turn high (as shown in Figure 8.22), the signal transferred back stops the FREJA from generating more current.

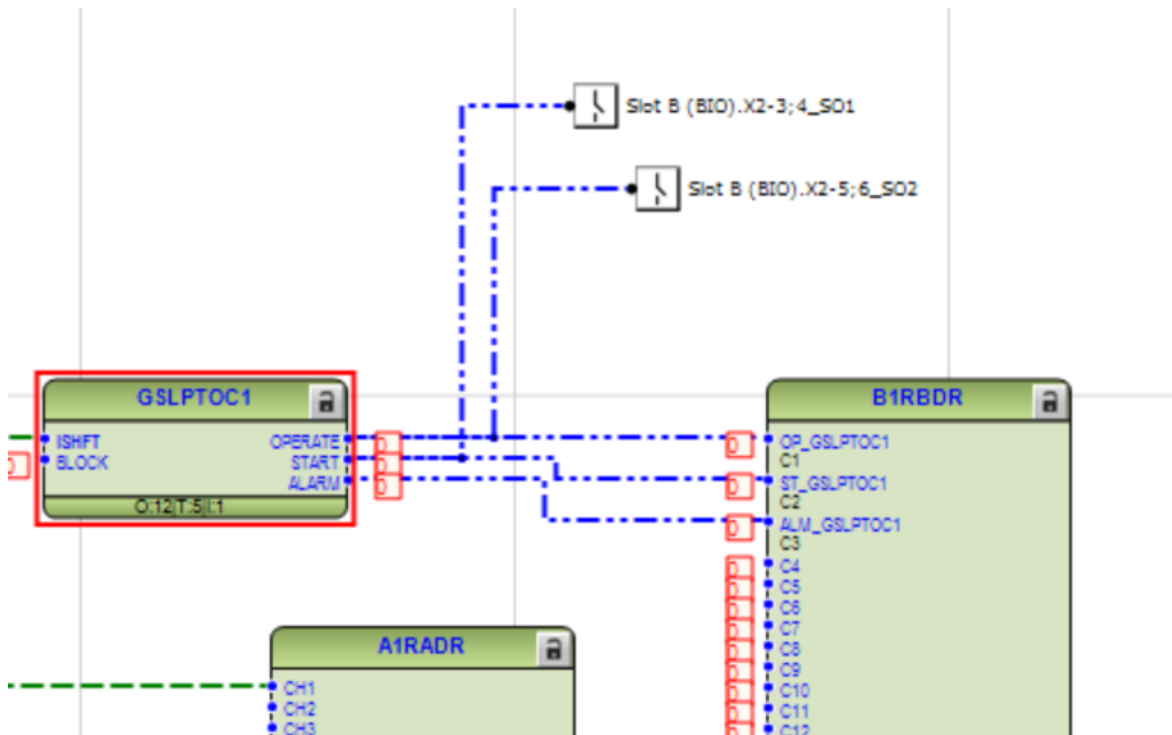
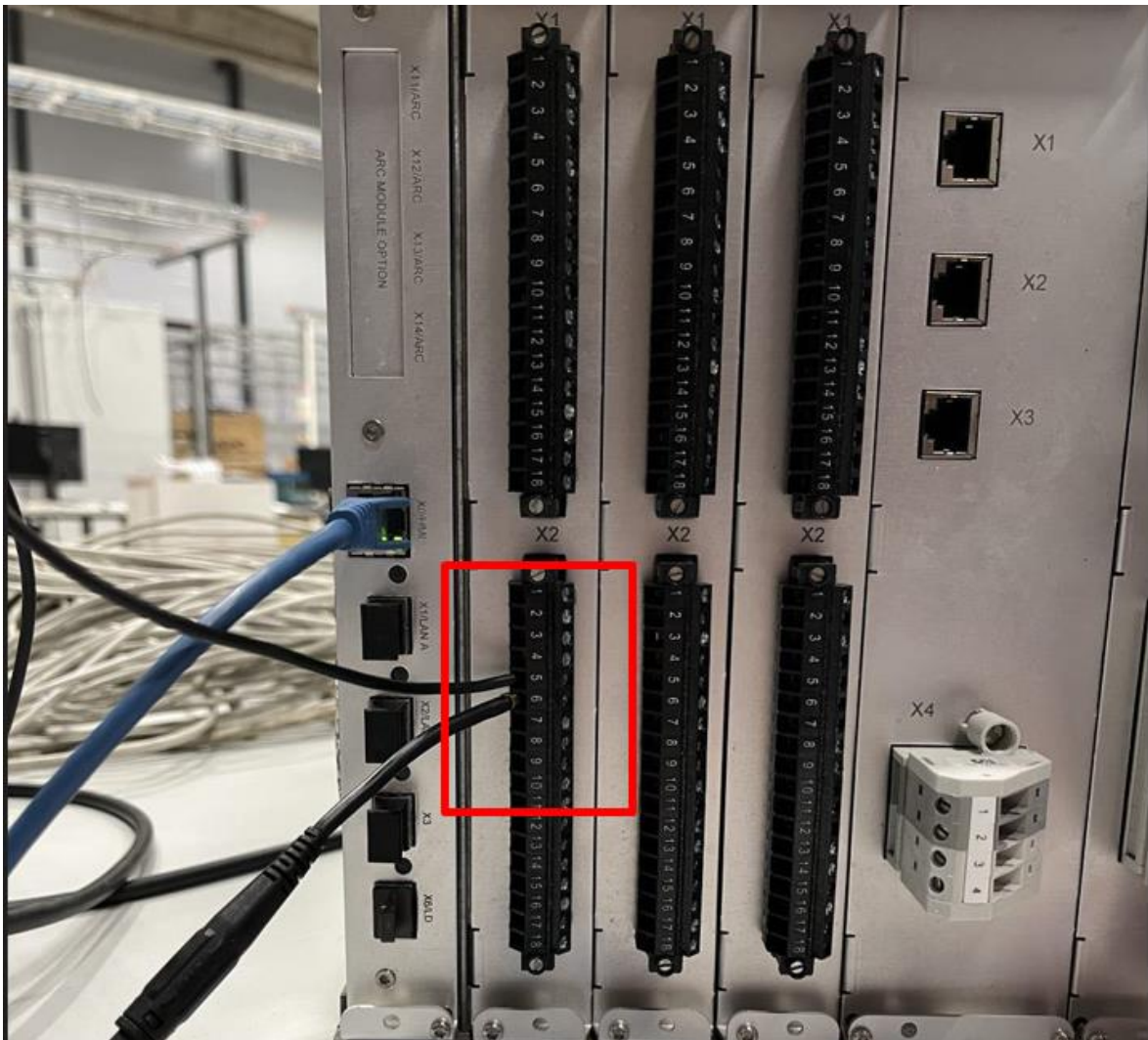


Figure 8.22 Binary Outputs in the Application Configuration

As seen from Figure 8.22, the Binary outputs of the REX640 have been assigned to slot B, X2 rack, and pins 3-6. As the "Operate delay time" parameter setting has been set to trip the Operate signal after a three second delay, we are mainly interested in this testing's Operate signal trip time. Figure 8.23 shows the binary output connections made on the REX640 hardware.



**Figure 8.23 REX640 Binary Output connections**

When tripped, the binary input in the FREJA stops the generation of current through the Rogowski coil, as would happen in a real system when a high shaft current is detected. This was accomplished by setting the output current of the FREJA to 0,6 A, which is over the set values of Operate and Start. This will immediately activate the Start signal which counts to three seconds before tripping the Operate signal. This is verified by numerous tests using

all the different harmonics and documenting the trip times, as shown in Table 8.3. The trip time can be seen on the FREJA as in Figure 8.25, where the red box is marked.



Figure 8.24 FREJA Trip Time

Table 8.3 Trip Times

| FREJA Relay system tester trip times |                      |                      |                      |
|--------------------------------------|----------------------|----------------------|----------------------|
| Tests                                | 1 <sup>st</sup> Test | 2 <sup>nd</sup> Test | 3 <sup>rd</sup> Test |
| Fundamental                          | 3,02 s               | 3,01 s               | 3,02 s               |
| Third Harmonic                       | 3,01 s               | 3,01s                | 3,02 s               |
| Fifth Harmonic                       | 3,02 s               | 3,02 s               | 3,02 s               |

## 9 Conclusions

The generator protection markets are changing. As the manufacturing of the RARIC shaft current relay has stopped, a new way of shaft current protection was necessary.

The thesis work started out by acquiring knowledge about generator protection concentrating on shaft current protection which was covered and provided with a solid base in Chapter 5. The Rogowski coil was determined to be the best option in combination with the REX640 for shaft current protection purposes by the theoretical investigation for the thesis work. Additionally, the theoretical research revealed the possibility to retrofit an existing current transformer with the REX640 for said protection purposes.

Examples of measurement configurations were provided, along with an explanation of the function specification for the shaft current protection. For future work where the shaft current protection feature is required, example applications for hydro and turbogenerators were shown.

Tests were conducted where a simulated shaft current was passed through a LFR Rogowski coil to an amplifier which transferred the amplified signal to the REX640 protection relay. Testing of the fundamental frequency was successful, a current at 200 mA was passed through the Rogowski coil using the FREJA and the monitored data on the WHMI verifies the same value and frequency used. The value was then increased to match the Alarm set value at 0,25 A which activated the signal in the application configuration online monitoring mode on PCM600, verifying that the Alarm signal trips at the set value of 0,25 A. This was further verified by the Wavewin32 software that shows the trigger along with the RMS value in the disturbance record. When the output current is increased to 0,5 A to test the Start and Operate trips, Wavewin32 shows the delay time between the Start signal tripping and shortly after the operate delay time, the operate signal tripping, verifying the parameter settings that were implemented work accordingly. Furthermore, Pick-up and Drop-off tests were performed to ensure that the values where the Start signal trips, coincide with the set values in parameter settings.

The testing of the third and fifth Harmonics both yielded the same results as the fundamental frequency results, with the exception of having higher frequencies. These higher frequencies show more frequent sine waves in the Wavewin32 disturbance records.

Testing of the signal trip times was tested to verify the functionality of the implemented time delay set values which were set in PCM600. This was accomplished by adding binary outputs in the application configuration that generate signals to the FREJA relay test system when activated. When FREJA receives the trip signal generated, it stops the generation of current, simulating a fault situation. Trip time tests show that the Operate signal trips after approximately 3,01 seconds, confirming the functionality of the implemented delays, being set to 3 seconds.

The conclusion is that the tests and results went well, the protection function testing ensures that the system(s) are protected against high shaft currents that may damage the bearings in various generator applications.

## 10 Bibliography

- [1] ABB, "ABB Oy, Energy Industries," 2022. [Online]. Available: <https://new.abb.com/fi/abb-lyhyesti/suomessa/liiketoiminnat/power-generation>.
- [2] Heco Inc., "What are Electric Motor Shaft Circulating Currents?," 16 July 2016. [Online]. Available: <https://hecoinc.com/what-are-electric-motor-shaft-circulating-currents/>. [Använd January 2023].
- [3] planete energies, "planere energies: Energy Made Easy," January 2019. [Online]. Available: <https://www.planete-energies.com/en/medias/close/how-they-work-turbo-generators>.
- [4] M. Sarwar, "Gas turbine power plants: Parts and Functions," EE Power School, 3 June 2020. [Online]. Available: <https://www.eepowerschool.com/power-generation/gas-turbine-power-plants-parts-and-functions/>. [Använd 29 December 2022].
- [5] Water Science School, "Hydroelectric Power: How it Works," 6 June 2018. [Online]. Available: <https://www.usgs.gov/special-topics/water-science-school/science/hydroelectric-power-how-it-works#overview>.
- [6] P. L. Alger och H. Samson, "Shaft Currents in Electric Machines," *American Institute of Electrical Engineers*, 1923.
- [7] R. Ong, "An Investigation of Shaft Current in a Large Sleeve Bearing induction Machine," McMaster University, Ontario, 1999.
- [8] T. Rabuzin, "Shaft Current Protection," KTH Electrical Engineering, Stockholm, 2015.
- [9] ABB, "RARIC Shaft current protection," ABB, Västerås, 2004.
- [10] M. Costello, "Shaft Voltages and Rotating Machinery," *IEEE Transactions on Industry Applications Vol. 29, Issue: 2, March-April 1993*, pp. 419-426, 1993.
- [11] SKF, "Electrically insulated bearings from SKF," May 2006. [Online]. Available: [https://www.skf.com/binaries/pub12/Images/0901d1968008da41-6160-EN-Motor-Insocoat-hybrid\\_tcm\\_12-295325.pdf](https://www.skf.com/binaries/pub12/Images/0901d1968008da41-6160-EN-Motor-Insocoat-hybrid_tcm_12-295325.pdf).
- [12] Schaeffler Technologies, "Current-Insulating Bearings," 11 2020. [Online]. Available: [https://www.schaeffler.hu/remotemedien/media/\\_shared\\_media/08\\_media\\_library/01\\_publications/schaeffler\\_2/tpi/downloads\\_8/tpi\\_206\\_de\\_en.pdf](https://www.schaeffler.hu/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/tpi/downloads_8/tpi_206_de_en.pdf).
- [13] A. Muetze, "Design Aspects of Conductive Microfiber Rings for Shaft Grounding," IEEE, Coventry, 2007.

- [14] A. H. Willwerth och W. H. Oh, "New motor design with conductive micro fiber shaft grounding ring prevents bearing failure in PWE inverter driven motors," *Electrical Insulation Conference and Electrical Manufacturing Expo*, pp. 240-246, 2007.
- [15] ABB, "Bearing currents and how to beat them," 2022. [Online]. Available: <https://new.abb.com/motors-generators/media/bearing-currents-and-how-to-beat-them>.
- [16] P. I. Nippes, "Understanding Shaft Voltage and Grounding Currents of Turbine Generators," *Magnetic Products and Services Inc.*
- [17] L. Kojovic och R. Beresh, "Practical Aspects of Rogowski Coil," IEEE Power System Relaying Committee, 2010.
- [18] V. Skendzic och B. Hughes, "Using Rogowski Coils Inside Protective Relays," *66th Annual Conference for Protective Relay Engineers*, pp. 1-10, 2013.
- [19] M. Samimi, A. Mahari, M. Farahnakian och H. Mohseni, "The Rogowski Coil Principles and Applications: A Review," *IEEE Sensors Journal ( Volume: 15, Issue: 2, February 2015)*, pp. 651-658, 2015.
- [20] R. Ong, J. H. Dymond och R. D. Findlay, "A Comparison of Techniques for Measurement of Shaft Currents in Rotating Machines," *IEEE Transactions on Energy Conversion, Vol. 12, No. 4, December 1997*, pp. 363-367, 1997.
- [21] G. Crotti, D. Giordano och A. Morando, "ANALYSIS OF ROGOWSKI COIL BEHAVIOR UNDER NON IDEAL MEASUREMENT CONDITIONS," Lisbon, 2009.
- [22] T. Foxcroft, N. Fischer, D. Finney, S. Samineni och Y. Xia, "Advanced generator protection and monitoring using transducer measurements," IEEE, 2017.
- [23] W. F. Ray och C. R. Hewson, "High performance Rogowski current transducers," *Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy*, pp. 3083-3090, 2000.
- [24] ABB Oy, "REX640 Operation Manual," ABB Oy, 2020.
- [25] H. Hämäläinen, "AFL function specification for Generator shaft current leakage protection," ABB Oy, 2022.
- [26] ABB Oy, "REX640 Product Guide," ABB, 2020.
- [27] A. Oy, "Simplifying management of protection and control relays with PCM600 - Protection and control IED manager," ABB, [Online]. Available: <https://new.abb.com/medium-voltage/digital-substations/software-products/protection-and-control-ied-manager-pcm600>. [Använd 2 February 2023].

- [28] Power Electronic Measurements Ltd., "LFR Specification," March 2018. [Online]. Available: [http://www.pemuk.com/Userfiles/LFR/LFR\\_0318.pdf](http://www.pemuk.com/Userfiles/LFR/LFR_0318.pdf). [Använd 10 February 2023].
- [29] Knick Elektronische Messgeräte GmbH & Co. KG, "VariTrans P 27000," [Online]. Available: <https://www.knick-international.com/en/products/interface-technology/proline/universal-isolated-signal-conditioners/varitrans-p-27000/>. [Använd 15 February 2023].
- [30] Megger, "FREJA 300 Relay Test System," 2011. [Online]. Available: [http://www.stevoelectric.be/user/image/megger-freja-300\\_ds\\_en\\_v04.pdf](http://www.stevoelectric.be/user/image/megger-freja-300_ds_en_v04.pdf). [Använd 22 February 2023].
- [31] H. Hämläinen, *Application Note, Generator Shaft Current Leakage Protection*, Vasa: ABB Oy, 2022.
- [32] Sohre Turbomachinery Inc., "Damage Examples, Babbitt bearings," 5 January 2023. [Online]. Available: <https://www.sohreturbo.com/grounding-brushes/damage-examples/#1588376824470-1d4e2dc1-2018>.
- [33] Heco Inc., "Bearing Failures on VFD Controlled Electric Motors," 3 January 2017. [Online]. Available: <https://hecoinc.com/bearing-failures-on-vfd-controlled-electric-motors/>.
- [34] P. I. Nippes, "Early Warning of Developing Problems in Rotating Machinery as Provided by Monitoring Shaft Voltages and Grounding Currents," *IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 19, NO. 2*, pp. 340-345, 2004.
- [35] L. A. Kojovic, "Comparative Performance Characteristics of Current Transformers and Rogowski Coils used for Protective Relaying Purposes," *2007 IEEE Power Engineering Society General Meeting*, pp. 1-6, 2007.
- [36] A. Oy, "PCM600 Product presentation," ABB Oy, 2022.
- [37] ABB Oy, "Protection and control REX640," ABB Oy, [Online]. Available: <https://new.abb.com/medium-voltage/digital-substations/protection-relays/multiapplication/protection-and-control-rex640>. [Använd 4 February 2023].