Dynamic Protection System Performance Using Rogowski Coils

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ABSTRACT

The traditional protection system consists of a conventional current transformer (CT) and a protective relay. The CT has unique physical characteristics, which means that each application requires CTs to be designed specifically. The introduction of the non-conventional instrument transformer means that current transformers can be universal in design. The non-conventional instrument transformer discussed throughout this paper is the Rogowski coil.

The modern protective relay is a digital device, which means that the signal generated by the instrument transformer needs to be converted to a digital signal. The analogue-to-digital (A/D) converter in the relay has a finite dynamic range based on the number of bits. The A/D converter system defines the upper limit at which clipping will occur, which in the case of an overcurrent relay, is typically between 30 and 40 times above the nominal current.

The dynamic range of the Rogowski coil is much larger than the traditional CT. However, the protective relay is still limited by the A/D process. Interestingly, the protective relay still requires the user to define a CT ratio for a Rogowski coil configuration. In this paper, we explore the opportunity this allows, specifically how, by changing the CT ratio, the performance of the relay can be optimized to match the application.

The power system is evolving with a growing need for renewable energy. This also includes the growing trend for microgrids. Within these microgrids, inverter-based resources (IBRs) are becoming the predominant source for fault current. This means that the fault level can be significantly reduced. One particular use case is an islanded network converting from diesel generation to a battery energy storage system (BESS) and solar system. The network needs to be able to operate on either IBR only, diesel generation only, or a combination of both.

Using this case, this paper demonstrates the present capability of the protection system to dynamically adapt to the varying fault level in the protected network using multiple setting groups.

INTRODUCTION

The key parameters used, when designing a protection system, are the power system current levels. These parameters influence the design considerations for the current transformer (CT) physical construction, the protective relay construction, and the protection settings. The conventional power system has historically had little difference between maximum and minimum fault levels. The rapid evolution of the power system with the large uptake of inverter-based resources (IBRs) is having a significant impact on these parameters.

The Rogowski coil, although earlier technology, has recently been standardized. The standardization of this technology allows integration into third-party devices without the need for the Rogowski coil manufacturer to provide the integrator. The standardization of the Rogowski coil technology is beneficial for developing engineered solutions for existing and evolving issues within protection systems.

Wide dynamic range, low signal levels, and the need to perform signal integration present new challenges, but at the same time, they open new opportunities to rethink and optimize the relay signal processing architecture. Flexibility through setting configuration is one of the new opportunities, which is discussed in this paper.

The combination of the Rogowski coil and the protective relay provides the possibility to address issues associated with the rapidly evolving power system. In particular, it supports the increased construction of medium-voltage (MV) microgrids.

PERFORMANCE COMPONENTRY

To understand how the performance of a secondary system can be dynamic, first the system componentry needs to be defined.

Conventional Protection System

The conventional system block diagram is shown in Figure 1. The instrument transformer performance is well known, and the key construction parameters are the CT ratio and the secondary nominal current rating.

The fixed CT ratio has the most impact on the overall performance of the secondary system. The CT ratio is impacted by two power system current levels:

1. Maximum continuous current—electrical thermal rating of the CT
2. Maximum fault current—saturation of the iron core construction

Once the CT ratio has been selected, changing it is difficult.

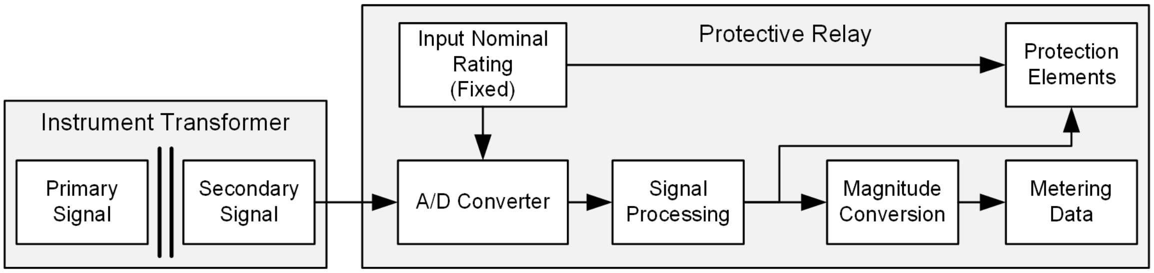


Figure 1 Conventional Secondary System Block Diagram

The conventional CT inputs for a protective relay have a nominal rating. This rating is used to influence processes within the protective relay. Figure 1 shows that this parameter is provided to both the A/D and protection settings blocks. The A/D converter uses this parameter to define the range and the discrete step size for the digital representation of the secondary current.

The nominal rating of the CT input parameter is also used by the protective relay to define the setting range of protection settings. These ranges define the possibilities a protection engineer can use to detect abnormal conditions on the power system. The minimum and maximum system fault current levels are predominantly used when determining these settings.

Non-Conventional Protection System

The Rogowski coil instrument transformer produces a secondary signal, which is representative of the primary current. The secondary signal is a voltage signal proportional to a derivative of the primary current. Due to the exceptionally wide dynamic range of the Rogowski coil-based low-power instrument transformer (LPIT) rated current (a key parameter in the case of the conventional CT), it loses its importance allowing it to become a protective relay setting parameter, which can be adjusted in the field.

The protective relay has had to change its process to use the signal generated by the Rogowski coil; Figure 2 shows the new block diagram. The process still incorporates an A/D converter, which has a set of new parameters necessary to define the Rogowski coil sensitivity and the range of the coil output signal. This setting is in relation to the primary current, because the secondary voltage signal is proportional to the primary current.

The Rogowski coil output is a derivative of the current which means the protective relay needs to integrate the signal to obtain an accurate current measurement. The integration process can be done via analogue components prior to the A/D process or by implementing in the software postprocess; the relay used in testing implements the analogue integrator.

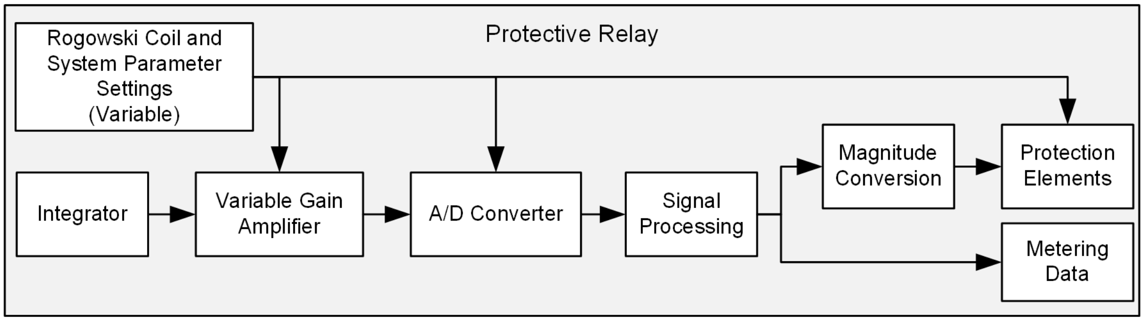


Figure 2 Non-Conventional Secondary System Block Diagram

The current signal is a digitized version of the primary current. The protection algorithms require a secondary current signal to perform the same function. The protective relay uses settings that define a CT ratio to convert the primary current signal to a secondary equivalent to be used in the protection algorithms.

The protection settings maintain a consistent approach regardless of the instrument used to measure the primary system current. The range of settings follows the same structure. The secondary nominal rating is used to determine these values. The protective relay has a configurable secondary nominal rating setting.

ROGOWSKI COIL DYNAMIC PERFORMANCE

The use of MV LPITs (also known as MV sensors) has become increasing popular in recent years for electrical networks. Based on low-power principles, such as the Rogowski coil and resistive or capacitive voltage dividers, these devices have been available on the market since the early 1990s.

Connected to the evolution of the MV grid, during the past few years there has been a rapid growth in the use of LPITs in both in greenfield applications as well as in retrofit solutions. In contrast, conventional instrument transformers, with magnetic cores, have been used for more than 120 years and are widely accepted in most electrical installations today. Both technologies are suitable for measurement and protection purposes and offer unique benefits that must be weighed based on the application and individual project need. [1].

Low-Power CT (LPCT, Rogowski Coil)

LPCTs are based on the Rogowski coil principle and are made of a flexible toroidal air-core coil winding. Unlike traditional CTs, there is no ferromagnetic core, which results in a linear and non-saturable response for a wide range of primary currents.

When a current flows through the primary conductor, it induces a magnetic flux in the Rogowski coil; a voltage is then induced across the coil turns and is proportional to the derivative of the primary current. The output of a LPCT is dependent on the cross section, the number of turns of the Rogowski coil, and any change in the primary current. The output signal is usually a low-voltage signal measured in millivolts and is represented by (1) [2]:

$$u(t) = -K\frac{di(t)}{dt} \tag{1}$$

where:

u(t) = Secondary output voltage

i(t) = Primary current

K = Constant based on core dimensions, number of turns, and mutual inductance

The output signal is then provided to compatible intelligent electronic devices (IEDs), such as protective relays, that process this information to read the primary current. Another significant advantage of the flexible air-core winding is that the weight of a typical sensor is much lower than an equivalent conventional CT with a ferromagnetic core. [1].

Comparison Between Sensors and Traditional Instrument Transformers

The key component-level distinction between sensors and traditional instrument transformers is the elimination of the large ferromagnetic circuit, commonly referred to as a “core,” in the traditional instrument transformer. This core is used to create a strong magnetic coupling between the MV and low-voltage (LV) (primary and secondary) windings of the instrument transformer, which in turn transfers power between the MV and LV windings and allows for the accurate delivery of voltage and current, at much reduced levels, to the receiving devices.

Elimination of this ferromagnetic circuit in the instrument transformer, leads to interesting advantages for the sensing device. In addition to the elimination of the core from the instrument transformer, a change in the method of conversion of the voltage and current signal is also introduced. In typical MV sensors, the primary winding in a traditional instrument transformer is replaced by a resistive or capacitive voltage divider circuit.

Typical current conversion in MV sensors is made using air-core inductors, generally referred to as Rogowski coils. The core in a conventional instrument transformer is the key component for transferring power from the primary to the secondary side of the device; elimination of this component causes sensors to be very low energy devices, not capable of transferring power from the primary to the secondary side of the device. Most MV sensors today, especially those in a line-post form factor, are low energy analogue devices.

The sensors deliver an analogue signal on the secondary side of the device. This analogue signal is an accurately scaled version of the MV or primary signal, but it cannot convey power to the receiving device. In the future, as better methods of delivering power to electronics become available, it is expected that more MV sensors will be able to support on board analogue-to-digital conversion allowing new product variants and use cases, further supporting the increasingly digitally enabled grid. [3].

Advantages of the Rogowski Coil Technology

As mentioned previously, Rogowski coil technology brings numerous advantages compared to the conventional CTs. These advantages are discussed in the following.

Reduced Footprint

Due to the smaller size of internal components and the elimination of a relatively large ferromagnetic core, sensors tend to have a smaller footprint and weigh significantly less than their conventional instrument transformer counterpart. This allows for a decrease in the footprint and dimensions of the whole system, not only the components. The bay shown on the left side of Figure 3 illustrates a typical panel, assembled using conventional instrument transformers; on the right side is the solution, assembled using non-conventional instrument transformers.

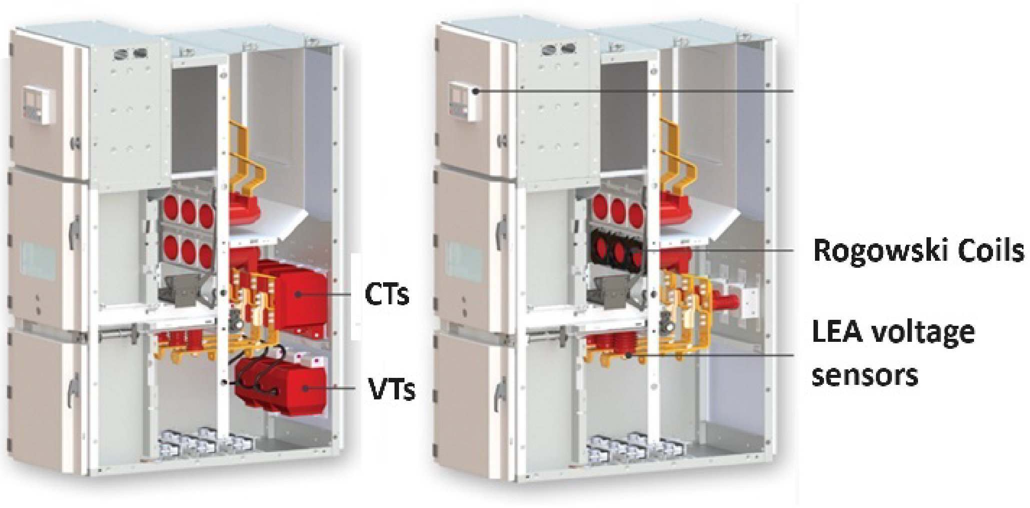


Figure 3 Comparison of Different Switchboard Instrument Constructions

Simplification of the Connection Between Instrument Transformers and IEDs

The complexity of electrical wiring in switchgear may represent a major part of the integration costs. Wiring complexity can become intricate in traditional instrument transformers.

In contrast, Rogowski coils employ a single RJ45 secondary cable, which connects directly to an IED. There is no need for any burden calculation or additional secondary wiring requirement. As the secondary cable may vary, LPIT accuracy is tested together with the specific secondary cable.

Measured correction factors are then assigned and can be input into a compatible IED. For proper functionality, LPIT load impedance must be well defined. In the latest family of IEC 61869 standards, load impedance is defined to be 2 MΩ / 50 pF. This is an important step ensuring the compatibility between various vendors. The simple connection between sensor and IED is shown in Figure 4.

Figure 4 Ease of Connection Between Sensor and IED Example

Reduced Chances of Failure

Because of the method of construction, sensors inherently ha fewer points of potential failure compared to traditional instrument transformers, especially MV instrument transformers.

Linearity and Wide Dynamic Range

In their paper, "Impact of MV Sensors on Different Protection Performance" Lasheeka Prokop and Vaclav Prokop state that

> Due to the absence of a ferromagnetic core the Rogowski coil sensors have an inherently linear response over a very wide range of primary currents, far exceeding the typical range. Thus, current sensing for both measurement and protection purposes can be realized with a single secondary winding.
>
> In addition, one standard sensor can be used for a broad range of rated currents and is also capable of precisely transferring signals containing a wide range of frequencies. A typical current sensor can reach the metering class 0.5 (optionally 0.2 s) for continuous current measurement in the extended accuracy range from 5% of the rated primary current (e.g., 4 A) up to the rated continuous thermal current (4,000 A).
>
> For dynamic current measurement (for protection purposes), current sensors can fulfill the requirements of the protection class up to an impressive value reaching the rated short-time thermal current (e.g., 85 kA) [4].

Figure 5 shows an example of the typical accuracy curve.

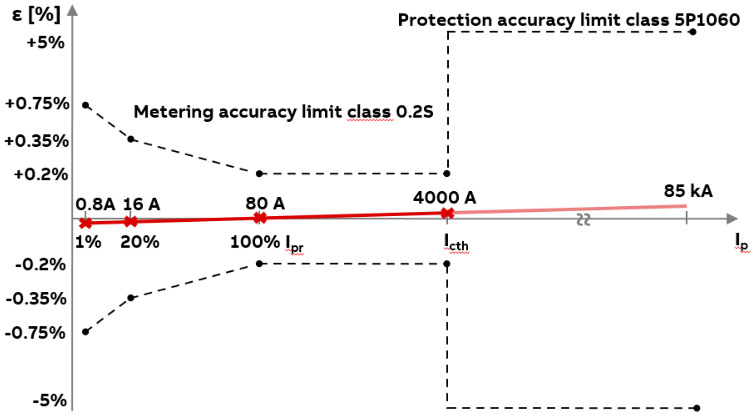


Figure 5 Typical Accuracy Curve for a Rogowski Coil Instrument Transformer

Energy Savings

Most power losses that occur in CTs and voltage transformers (VTs) can be categorized into core and winding losses. Core losses include hysteresis losses, which result from the constant magnetization and demagnetization within the core of the instrument transformer, and eddy current losses, which result from the induced circulating currents inside the ferromagnetic core material. Winding losses include resistive losses in the winding conductors (usually copper) as current flows through them. These are typically dissipated as heat inside switchgear.

In contrast to conventional instrument transformers, LPITs employ Rogowski coil and capacitive / resistive voltage divider (CVD/RVD) technology, which has minimal power transfer from the primary side to the secondary side, as the secondary output on an LPIT is low voltage (in the case of LPVTs) or very low voltage (mV, in the case of LPCTs). This results in negligible power losses and low energy power consumption compared to traditional instrument transformers [1].

Summation of the Rogowski Coil

According to the IEC 61869 series standards, LPITs are divided into two categories: low-power passive instrument transformers and electronic instrument transformers. Passive instrument transformers do not require external power, making them highly robust and easy to use in MV applications. The summation of multiple Rogowski coils is based on the serial connection principle, which complies with the passive LPIT requirement.

The internal connection of the signals is such that S2 terminal (Pin 2) of the first coil is connected to the S1 terminal (Pin 1) of the second coil and so on. If the summated signal is regarded as a single measurement, then the output of the summation device needs to be analyzed for the impact on accuracy. The schematic view of this type of connection is shown in Figure 6.

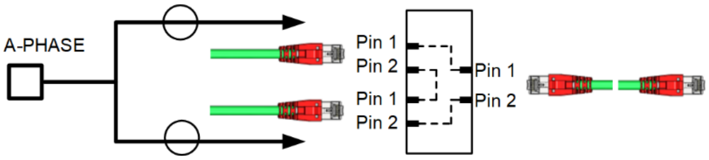


Figure 6 Schematic View of the Summation of Rogowski Coil Signals

When connected in series, correction factors of all summed LPITs should be averaged. The phase offset of such an arrangement can be also mitigated by this approach to provide high overall accuracy. The tested arrangement resulted in combined sensors meeting the requirements defined for a single sensor in IEC 61869.

The ability to summate Rogowski coil signals provides the same functionality to solve the same issues that resulted in the need to summate conventional CTs. When the summation is designed correctly, it demonstrates a high level of accuracy.

PROTECTIVE RELAY DYNAMIC PERFORMANCE

The protective relay performance has two main criteria:

1. Ability to accurately digitize the analogue signal
2. Allowable setting range of protection elements

In Figure 1, the block supplying information to the A/D block and protection settings block is the input nominal rating. Historically, for the conventional system, the protective relay would have different rated current inputs (i.e., phase current and neutral current inputs). This would change the clipping value and also the pickup values for settings using that particular digitized current signal.

The conventional CT would have a designed accuracy limiting factor (ALF), which is a multiple of the nominal rating. Measured current less than the ALF would result in the secondary current being within the accuracy of the CT; a typical ALF would be 20. The protective relay would design its A/D range to accurately digitize the full range of the CT; this would typically be 30 times the nominal rating.

The protection-setting range is based on the nominal rating of the protective relays CT input. The fixed CT ratio of the conventional CT means that these settings are effectively fixed for primary currents. Changing a CT ratio setting in the relay does not change the secondary current measured by the relay and used in the protective relay's algorithms. The sensitivity of a protective relay is defined by the minimum pickup of a protection element.

The dynamic function of the relay is its ability to change its configuration without the need to change a setting file or hardware. The implementation of setting groups in a numerical protective relay allows this functionality. These setting groups have traditionally been used to change the protection-setting thresholds depending on the network configuration.

Performance of the Digitized Signal

The saturation point for the A/D converter defines the performance characteristic of digitizing the signal. The non-conventional protective relay uses configurable settings to dynamically change this performance criterion. The settings associated with defining the A/D saturation point (maximum fault current level) are located within each setting group.

The digitization process still requires some minimum level of accuracy and immunity to noise. These limitations are based on the construction of the Rogowski coil rated primary current (I_{PR}) and secondary voltage (U_{SR}). The upper limit has been defined by the feeder rated current setting, which would be the equivalent of the primary rating of the conventional CT. Due to the minimum level requirement to reduce measurement noise, the minimum value for the feeder rated current parameter is limited.

The impact on the digitized signal performance of a protective relay, due to a configurable setting, was observed through testing. The test consisted of looping a test lead through a Rogowski coil to develop a large enough primary current to cause clipping. Once clipping was observed, the parameter used to define the clipping value was increased and then the same test was executed again.

The single plot in Figure 7 shows both test results. The blue line illustrates when the A/D saturation limit has been exceeded and clipping occurred. To allow a better visualization of the effect that changing a configurable setting has on the performance of the protective relay, the second test result has been superimposed onto the first test result.

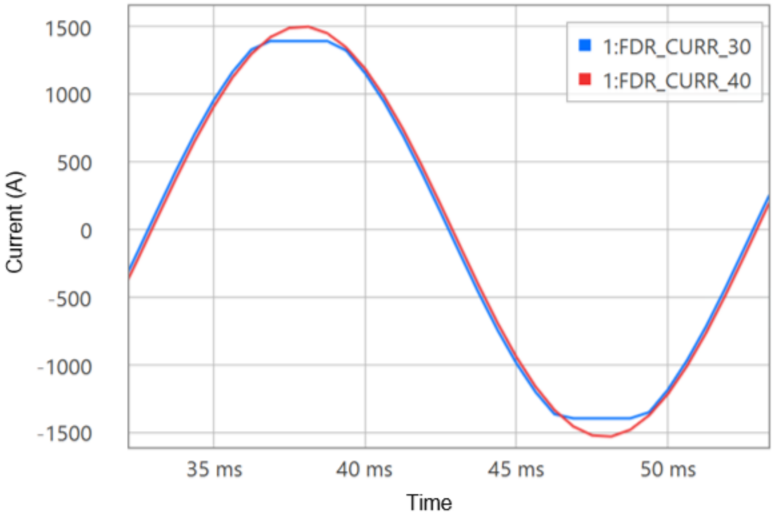


Figure 7 Signal Clipping Testing Results

Protection Element Sensitivity

The setting range of the protection element is also dictated by the same parameters that influenced the performance of digitalization process. The setting range is fixed based on a secondary current rating. Protection-setting design is based on a primary system study; the primary settings are then converted to a secondary level to be used in the protective relay. The same is true for the non-conventional system. The difference is that now the signal received by the relay is a voltage signal replicating a primary current. It is through settings that the user defines what the secondary current magnitude will be.

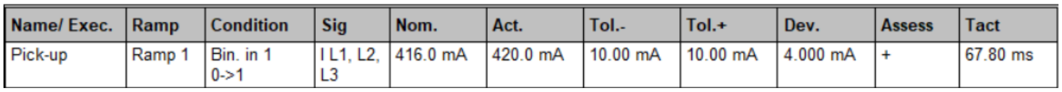
As previously mentioned, the need for the protection settings for a conventional network is based around larger fault currents. With the significant decrease in fault levels of a system supplied by only IBRs, the setting range may not be capable of setting a sensitive enough protection. Therefore, changing the minimum primary current range by another configurable setting could allow the designer to deal with the evolving network.

To prove that this is possible with the non-conventional system, two tests were conducted with the following parameters.

- Test 1
  - Twelve loops of test lead were wound around the Rogowski coil
  - CT ratio setting was 100, effective CT ratio was 100/12 = 8.33

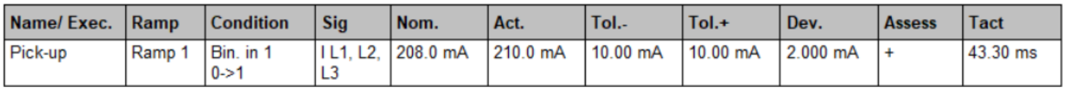
  - Overcurrent element was configured to 0.05 A secondary pickup
  - Injected current pickup pass result 0.05 • 8.33 = 416 mA primary
- Test 2
  - Twelve loops of test lead was wound around the Rogowski coil
  - CT ratio setting was 50, effective CT ratio was 50/12 = 4.17
  - Overcurrent element was configured to 0.05 A secondary pickup
  - Injected current pickup pass result 0.05 • 4.17 = 208 mA primary

Using the ramp test, the current was increased until the protective relay provided feedback that the element pickup had been exceeded. As shown in both Figure 8 and Figure 9, the primary current pickup changed with the parameter. This demonstrates that the protection-setting primary range can be changed without any physical change to the protective relay or instrument transformer.



Name/ Exec.	Ramp	Condition	Sig	Nom.	Act.	Tol.-	Tol.+	Dev.	Assess	Tact
Pick-up	Ramp 1	Bin. in 1 0->1	I L1, L2, L3	416.0 mA	420.0 mA	10.00 mA	10.00 mA	4.000 mA	+	67.80 ms

Figure 8 Test 1 Pickup Results



Name/ Exec.	Ramp	Condition	Sig	Nom.	Act.	Tol.-	Tol.+	Dev.	Assess	Tact
Pick-up	Ramp 1	Bin. in 1 0->1	I L1, L2, L3	208.0 mA	210.0 mA	10.00 mA	10.00 mA	2.000 mA	+	43.30 ms

Figure 9 Test 2 Pickup Results

MV MICROGRID APPLICATION

Background

An existing network consisted of several distributed individual LV switchboards. Connected to these LV switchboards are motor loads and diesel generators capable of supplying power to the motors. These switchboards also did not have a main grid connection.

Incorporating renewable energy to supply power to these disturbed loads required the installation of a MV network. A kiosk substation was installed at each LV switchboard location to allow connection of each load into the new MV network. These kiosk substations were supplied by the 22 kV main switchboard that had the new BESS and photovoltaic (PV) sources connected to it. Figure 10 shows a reduced version of the final network.

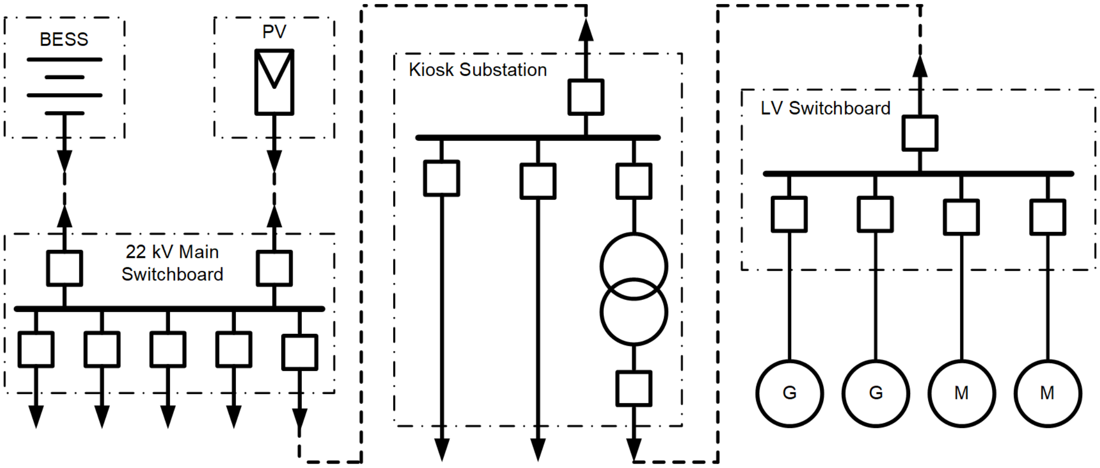


Figure 10 Reduced Network Single Line Diagram

Plant Specification

The primary plant procurement influenced the overall project timeline because of the long lead times. This forced the designer to make secondary system specifications early in the project. The instrument transformers needed to be specified so they could be installed when the switchgear was being manufactured. To determine the specifications for the instrument transformer, the designer would require knowledge of the system parameters and the protection requirements.

The system parameters are not as simple as studying the system design of today but trying to predict the future system. In the past, parameters such as fault levels and types of loads were predictable, but future networks are not so predictable. Designing the primary and secondary systems to be adaptable to whatever the network looks like in the future requires technology that has a larger dynamic range.

In this case, the network conditions can change in a moment from a combination of IBR and conventional sources to one or the other; fault level range, depending on the source configuration, varied from 0.25 to 2 kA. At the time of procuring the main switchboard and kiosk substations, the complete visibility of the network parameters were not known. The full dynamic range of the instrument transformer and protective relays discussed in previous sections meant that the project could proceed without risk of incorrectly specifying these pieces of equipment.

Protection Scheme Design

Before IBR integration, the protection philosophy for radial MV networks was based around overcurrent protection. The protection would then use grading margins between upstream and downstream protective relays to create discrimination. The initial concept for this system employed this protection philosophy, one that has worked well in conventional systems.

The integration of IBR sources, in particular micro grids, does not provide the same conditions to allow this protection philosophy to work. For a time-graded overcurrent protection philosophy to be used, there must be a clear separation of maximum load current and minimum fault current expected. The IBR sources do not provide a large enough minimum fault current to coordinate with the maximum load conditions. This issue was identified early in the concept phase. The limited literature around protection philosophy of MV microgrids meant that using the philosophy of unitized protection would be the best option based on literature discussing the integration of IBR into transmission networks.

Developing a unitized protection philosophy for the site had two options:

1. Centralized protection and control system (using IEC 61850)
2. Conventional line differential protection

Due to the step change in source and additional network, the decision was made to use the convention line differential option.

Unitized protection philosophy is achieved by utilizing line differential protection for all 22 kV lines and bus differential protection for the 22 kV main switchboard. The decision was made to include the kiosk bus in the line differential zone of the 22 kV line from the main switchboard for simplicity and to reduce the need for additional bus-zone CTs.

To include the kiosk substation in the line differential protection requires the outgoing circuits of the kiosk bus to be connected to the line differential relay. Having three circuits meant that the protective relay either had to accept three sets of Rogowski coils or the Rogoski coils for each phase had to be electrically summated. The summation of Rogowski coil was investigated, but at the time of the project, only a two-into-one fit-for-purpose device was available, similar to what is shown in Figure 6. Cascading two of these devices to combine three sensors into one was tested and proven to provide a compliant signal to be used by the protective relay.

Based on the available hardware, the protection philosophy was completed and the sensor requirement established. Due to the full dynamic range of the sensors and protective relay, the primary plant specification was released for tender prior to any protection or network studies being completed.

Non-Conventional Exception

The unitized protection of the 22 kV main switchboard was not able to use Rogowski coils. During the concept phase, a reference to busbar protection using Rogowski coils was found in an IEEE guide and is shown in Figure 11 [5].

This scheme required the electrical summation of seven circuits. The challenge with summating three circuits was discussed previously. Although the IEEE guide presented the concept shown in Figure 11 in 2007, a reference to the implementation of such a scheme was not found.

With no commercially available application-specific device to summate the Rogowski coils and the lack of industry experience with such a scheme, conventional instrument transformers and protection was required. The 22 kV switchboard implemented a high impedance bus scheme, which meant each bay required a mixture of conventional and non-conventional instrument transformers.

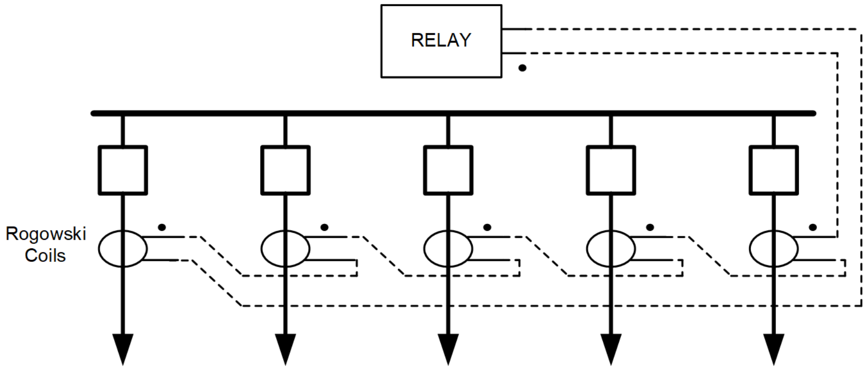


Figure 11 Busbar Protection With All Rogowski Coils Connected in Series

CONCLUSIONS

What will tomorrow's network look like? What can we as engineers design to allow for the protection system to adapt? The concepts discussed in regard to the advancements in the development of the Rogowski coil standardization and the implementation of this signal into the protective relay give engineers the capability to provide an answer to these questions.

The limited installations of such technology means that education was a key component of the project in the use case. The standardization of the technology has come after the implementation of the technology. The improvement driven by standardization is possibly overlooked due to unfavorable prior experience, leading to a hesitation towards this technology. However, education has worked, and future projects have already begun being scoped with this philosophy.

The protective relay's utilization of the signal from the Rogowski coil has given more control to the protection engineer. The key performance criterion is now determined by configurable settings. The use case described in this paper is only one example of using these features to solve a problem. Having the knowledge of how this works will lead to more innovative solutions for protection systems in the future.

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BIOGRAPHIES

Luke Napier is a protection application engineer at Schweitzer Engineering Laboratories, Inc. (SEL). He is a chartered professional engineer (CPEng) with more than 18 years of experience in the power industry. This experience includes 15 years with Ergon Energy in a variety of roles, including 5 years as a protection engineer. His current role at SEL exposes Luke to protection applications in the mining and industrial electrical networks.

Lukas Cesky holds a doctorate in Power Engineering from the Slovak University of Technology. He works as the global product manager responsible for MV sensors and is located at ABB's factory in Brno, Czech Republic. Lukas is a member of IEC and IEEE working groups, which focus on MV instrument transformers and sensors. Lukas is the author of many articles connected with this topic. Lukas' power industry experience includes design engineering of LV grids, R&D project engineering of MV instrument transformers and sensors, and product management of instrument transformers and sensors. He continues to lecture within the industry including at universities and international conferences.

Andrew Pilarski is a director and lead electrical engineer at Unity Power Engineers. Andrew has over 17 years of electrical design and consulting experience within the heavy industrial, utility, and mining sectors. Andrew has worked extensively in the primary metals and aluminium sector and since 2015 has been working as an electrical design engineer. Andrew's experience includes HV primary and secondary system design, protection studies, power system analysis, feasibility studies, and design management.

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