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CONTRIBUTION TO THE REDUCTION OF THE SHIP'S SWITCHBOARD BY APPLYING SENSOR TECHNOLOGY

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Abstract. The paper discusses the contribution to energy efficiency by reducing the dimensions of the main switchboard (medium voltage or High Voltage - used on ship). Reducing the dimensions of the switchboards can be achieved by reducing the dimensions of the bus bars, while fully satisfying the conditions with regard to thermal and mechanical stresses. The same can be achieved by modifying some other components, such as the application of new technology for measuring current and voltage, using current and voltage sensors that fall into the category of completely new technological solutions. By replacing conventional measuring transformers (IT), compact and efficient sensor technology significantly contributes to reducing the dimensions and mass of switchboards, which ultimately contributes to energy efficiency. Previous applications, the possibility of improving existing solutions, especially in applications in marine power systems, and new technological solutions that contribute to the efficiency of the marine power system using the Rogowski coil sensor and voltage divider voltage sensors are also considered.

Keywords: medium voltage switchgear; voltage sensors; ship's electrical system; energy efficiency rogowski coil sensor

Introduction

Improving energy efficiency of the electrical system on a ship is a continuously ongoing global trend. The improvement of energy efficiency is achieved by reducing various factors that have a direct or indirect influence. Since the ship's electrical system is complex the optimization of the system should be carried out by analyzing each component of the system. The ship's switchboard or the individual switchgear is a component whose optimization is the focus of the "CEKOM-BSSB 17.5" project.

The optimization goals include decreasing losses, reducing dimensions and weight and all other factors that ultimately contribute to energy efficiency while still fulfilling the required technical characteristics.

The analysis of the various electrodynamic phenomena (Yusop et al. 2011; Szulborski et al. 2020; Labridis et al. 1996; Yusop et al. 2011; Popa et al. 2016; Muhammood et al. 2012) in the busbar compartment of the switchgear in the aim to reduce the busbar dimensions is one solution to ultimately reduce the ship's switchboard. Newly developed technologies such as the novel current and voltage sensors, offer to replace outdated components in order to further optimize the designs. The working principle of such sensors is not a novelty but their use in medium voltage switchgear is made possible by the development of microprocessor-based protection relays (Suttner et al. 2015) that can utilize the low power signal output of the sensors. Further improvements could be achieved with the implementation of the developed communication protocol IEC 61850-9 – 2 (Starck et al. 2013)[1] in the goal to digitalize the distribution of electrical energy i.e. realization of Smart distribution networks. In this paper the focus is the reduction of the ship's switchboard by implementing the novel sensor technology in the proposed "CEKOM" design while also presenting the implementation advantages.

Theory of operation

Rogowski coil current sensor

As explained in detail in (Sohn et al. 2003) the Rogowski coil consists of an air cored toroidal winding encircling the conductor whose current is to be measured. The structure of the Rogowski coil is shown in Figure 1.

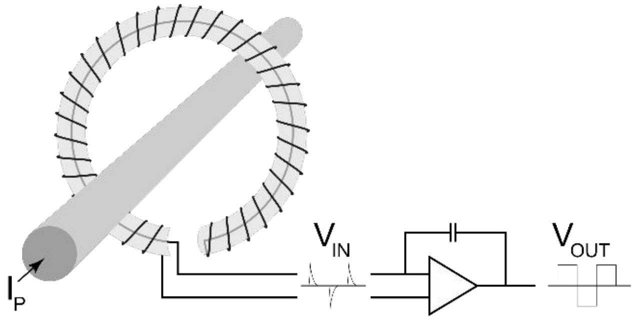

Figure 1. Rogowski coil structure[2)]

Rogowski coils work on the principle of Faraday's Law of induction. The current passing through the conductor creates an alternating magnetic field that consequently induces a voltage on the terminals of the coil. The output voltage is proportional to the rate of changing current that is measured. The voltage waveform that accurately reproduces the current waveform is achieved with the implementation of an electronic integrator.

The output voltage is described with the following equations:

$$V_{out} = M\frac{di}{dt} \qquad (1)$$

For a sinusoidal current it becomes:

$$V_{out} = Mj\omega I_p \qquad (2)$$

Where V_{out} is the output voltage of the Rogowski coil, M is the mutual inductance of the Rogowski coil, $\frac{di}{dt}$ is the rate of change of the measured current, ω is the angular frequency and I_p is the measured current.

Voltage divider voltage sensor

As explained in detail in (Milovac et al. 2017; Garnacho et al. 2017) the voltage sensor is a passive device composed of resistive or capacitive components connected in a voltage divider. The output voltage at the low voltage branch is at an adjusted voltage ratio in regard to the high input voltage. The structure of a voltage divider is shown in Figure 2.

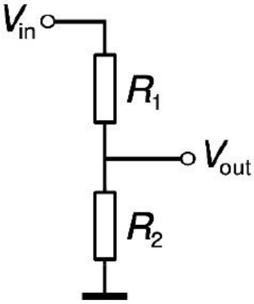

Figure 2. Voltage divider structure

The output voltage is given in the following equation:

$$V_{out} = V_{in}\frac{R_2}{R_1+R_2} \qquad (3)$$

Where V_{out} is the output voltage of the voltage divider, Vin is the input voltage of the voltage divider, R_1 is the high voltage branch and R_2 is the low voltage branch.

Sensor advantages

The aforementioned voltage and current sensors offer several advantages compared to conventional instrument transformers:

- Non-saturable as no iron core is used
- High degree of accuracy
- Personnel safety (low secondary voltages)
- Small size and weight
- Extensive dynamic range
- Environmental friendliness since less raw material is used

The one valid argument for sensor implementation in switchgear is the limited selection of IEDs with sensor compatible inputs but could be overcome as the sensors gain more usage in the future.

The graded comparison (level 1 – 3) of characteristics is given in Table 1.

Table 1. Graded comparison of sensors and ITs characteristics (Proca et al. 2005)

	Voltage IT	**Resistive divider Voltage sensor**	**Current IT**	**Rogowski coil current sensor**
Transient duty response	Satisfactory for slow protection functions (2/3)	Excellent (3/3)	Satisfactory with special and costly construction (2/3)	Excellent (3/3)
EM compatibility	No problem (3/3)	Screening preferred (2/3)	No problem (3/3)	Screening required (2/3)
Secondary charge variability	It is permitted a range of charge values (2/3)	Leads to a change of the ratio (1/3)	It is permitted a range of charge values (2/3)	The sensor is calibrated for each charge (1/3)
Insulation quality in time depending on initial PD level and on ageing	Depending on factors either constructive or technological (2/3)	No problems (3/3)	Depending on factors either constructive or technological (2/3)	No problems (3/3)
Insulation capability to withstand voltage over-stress	Depending on the insulation between two winding layers (2/3)	Insulation insensitive to the overstresses appeared (3/3)	Depending on the over-sizing degree and on ageing (2/3)	HV insulation belongs to the bushing (3/3)
Errors in steady duty	Excellent (3/3)	Excellent (3/3)		

Earth discharge of the HV line	Yes (3/3)	Yes (3/3)		
Ferro-resonance with the system or self-one	Possible (1/3)	Insensitive (3/3)		
Short-circuit in secondary winding	Requires fuses to avoid IT damage (1/3)	long secondary short circuit if R2<<R1 (3/3)		
Multiuse in measurement and protection			Not possible. Distinct cores required (1/3)	Single sensor with lower accuracy (2/3)
Behavior at short-circuit currents			Short-circuit is a major risk factor for IT and secondary circuit (1/3)	Short circuit current is sensed as a normal current (3/3)
Phase error			~ between 5 and 50min (2/3)	90° possible correction by integrator (2/3)
Open secondary winding			Dangerous case for staff and equipment (1/3)	Secondary winding can be open (3/3)
Measurement accuracy stability under the action of some aleatory factors			None (3/3)	Affected by temperature, mounting tolerances, 90° bends of the current bar (1/3)

Implementation in switchgear

The replacement of conventional ITs of considerable size with compact novel voltage and current sensors makes the reduction of overall dimensions of the switchgear possible. The reduced dimensions of the proposed "CEKOM BSSB 17.5" design compared to an existing AIS, for example as in "Končar-električni uređaji", are shown in Figure 3 and Figure 4.

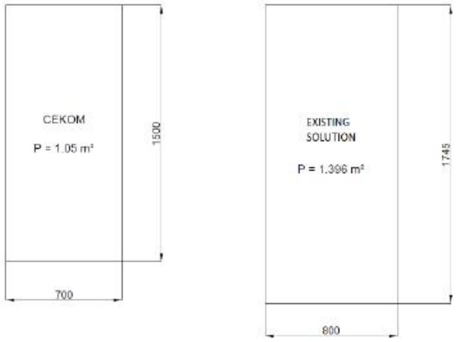

Figure 3. Footprint comparison of AIS designs

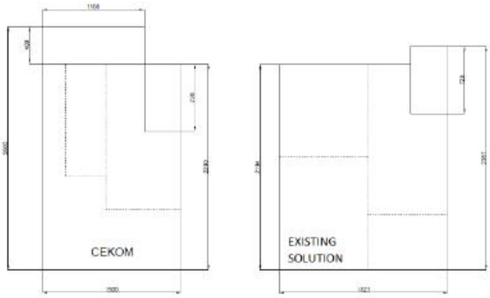

Figure 4. Side comparison of AIS designs

The considerable size reduction consequently makes the implementation of novel sensors relatively obligatory. The sensors make a considerable reduction in space consumption as seen in Figure 5 compared to the switchgear with conventional instrument transformers.

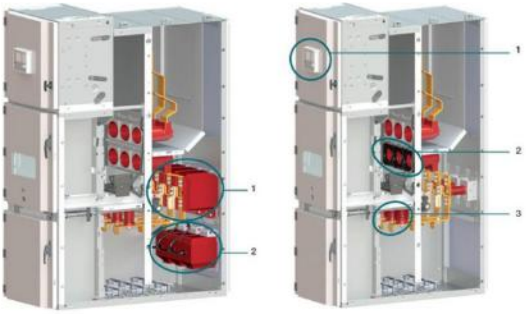

Figure 5. Comparison of AIS designs with instrument transformers and sensors[3)]

As such the optimal sensor location in the proposed "CEKOM" design is shown in Figure 6.

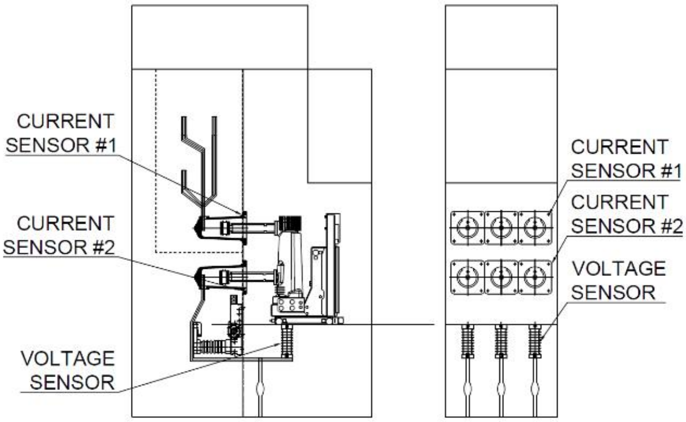

Figure 6. Sensor implementation in "CEKOM" switchgear

The proposed sensor implementation is based on the available data from a manufacturer that offers an IED with compatible sensor inputs and the advantage that "Končar-Električni uređaji" has previous experience of implementation of their equipment in their designs opting for minimal changes in their affirmed production process.

Knowing the rated voltage and current of the optimized design being 1600A and 17,5kV the applicable choice of sensors is taken from available data from the manufacturer.

Considering the aim to reduce dimensions and weight of the switchgear the sensor configurations are:

– Separate current and voltage sensor[4)]
– Combined current and voltage sensor[5)]

The sensors require an IED model with the input configuration designed for sensors.[6)]

Reduction of energy consumption is a beneficial consequence of the replacement of ITs. The example in (Stefanka et al. 2013) presenting the energy consumption based on a typical switchboard consisting of 14 panels with a total of 42 current transformers with the 1A rated secondary (mostly used in Europe) with 5P20, 20VA protection core class connected to the IED and the metering core class 0.5Fs5, 5VA connected to an analogue ampere-meter.

Table 2. Energy consumption of sensors and instrument transformers (Stefanka et al. 2013)

	Quantity	Power consumption	Energy consumption in 30 years
CT 1000/1A	6	140 VA	36 698 kWh
CT 200/1A	24	448 VA	117 776 kWh
CT 100/1A	12	102 VA	26 724 kWh
Total	42	690 VA	181 198 kWh
Current sensors	42	0VA	0,000 07 kWh

The example presents the significant amount of energy consumption over a period of 30 years with the used current transformers while the energy consumed by the sensors could be regarded as non-existent. The vast difference is a considerable factor in energy efficiency improvement and contributes to the global effort to reduce energy consumption.

The weight difference of sensors in comparison with equivalent ITs taken from data in[7] is shown in Table 3 with the assumption that the combined sensor replaces both a current and voltage IT.

Table 3. Weight comparison of sensors and Its

	Weight [kg]	Difference [kg]
Current sensor	0,65	24,35 – 30,35
Current IT	25-31	
Voltage sensor	1,96	22,04
Voltage IT	24	
Combined sensor	20	29 – 35

Analyzing the switchboard used in the aforementioned example of replacing 42 current transformers with sensors, assuming the equivalent models as in Table 2, the overall weight reduction is 1022,7 – 1274,7 kg. The replacement of the voltage ITs with sensors, if the use of 3 voltage transformers per panel is assumed on the same 14 panels, reduces the overall mass by another 925,68 kg. Consequently, the weight reduction ultimately contributes to energy efficiency and fuel consumption.

On the same example, if the existing design dimension reduction is achieved by reducing the single panel width by 100mm the overall switchboard width is reduced by 1400mm and consequently reduces the main busbar length. The footprint reduction of a single panel (0,345m^2 yields the overall footprint reduction of the switchboard by 4,83m^2.

Overall improvements and discussion

The calculated improvements are based on the example switchboard, which consists of 14 panels with the following configurations:

– Configuration 1

Existing panel dimensions and designed with 3 current transformers and 3 voltage transformers per panel.

– Configuration 2

Proposed switchgear design with reduced dimensions and with 3 combined sensors per panel.

– Configuration 3

Proposed switchgear design with reduced dimensions and with 3 current sensors and 3 voltage sensors per panel.

The overall switchboard improvements using the aforementioned data are given as a percentage compared to the existing solution. The weight data represents only the weight of all instrument transformers or sensors (depending on the configuration) but ignores the weight of the switchgear structure. The results are shown in Table 4.

Table 4. Improvements to the switchboard

	Weight [kg]	Footprint (m2)	Length [mm]	Volume [m3]	Energy consumption
Existing solution	2058-2310	19.544	11200	48.73681	
Combined sensors	840	14.7	9800	38.22	
Separate sensors	109.62				
Combined sensor improvements	59.2 – 63.64%	24,8%	12,5%	21,6%	100%
Separate sensors improvements	94.67 – 95.25%				

Since the output signal of the sensors is very low and there is no significant power transfer from the primary to the secondary side, the power losses can be considered negligible. Consequently, the power consumption of the sensors and the internal temperature rise are very low. Since power losses occur in conventional instrument transformer and therefore energy is consumed which is converted to heat, where the energy consumed is much larger than the consumption of the sensors, the improvement in Table 4 is considered as an improvement of 100%. The accuracy of the measurement has been improved (Prokop et al. 2013) and can be further corrected with the correction factors provided by the manufacturer of the sensors. Since the value of transformation ratios (voltage or current) in ITs is chosen for specific applications and load currents the use of sensors simplifies the problem by covering a range of primary currents or voltages, since saturation does not occur. The comparison of current sensor and transformer secondary output as a function of combined error (ε) and primary current (I_P) is shown in Figure 7.

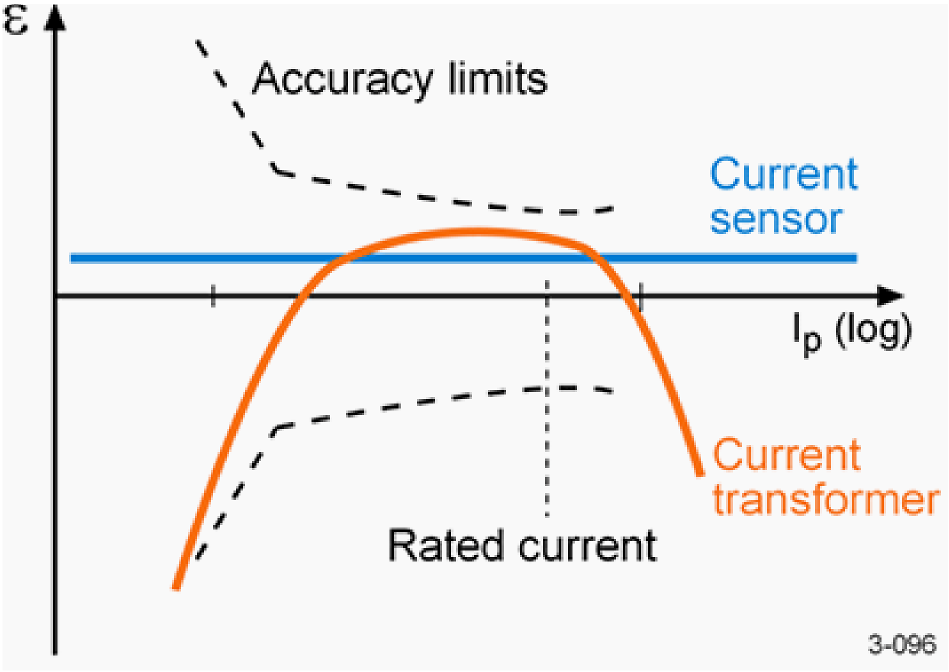

Figure 7. Current sensor and transformer output comparison[8)]

Another improvement is that the secondary output of a single sensor with double the rating can be used for both measurement and protection. Consequently, the design of the sensors is more environmentally friendly compared to IT's, as their manufacture requires less raw materials.

To further validate the choice of the sensor technology implementation in the proposed design a multi-criteria analysis was performed, using Visual PROMETHEE Academic Edition, based on the aforementioned configurations of the switchboard. The used parameters and criteria are based on data from Tables 1 and 4. In the analysis, the cost was neglected since no valid information is available. Since the sensor implementation in the switchgear yields significant improvements in several analyzed aspects the multi-criteria analysis unanimously favors the sensor configurations over the ITs, with the separate sensor configuration having an advantage. The results of the analysis are shown in Figures 8 and 9.

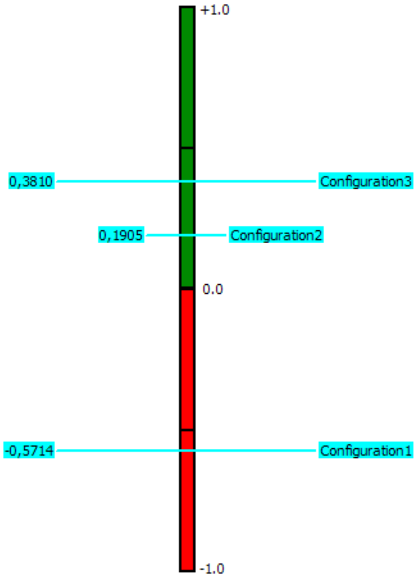

Figure 8. Multi-criteria analysis results in chart view

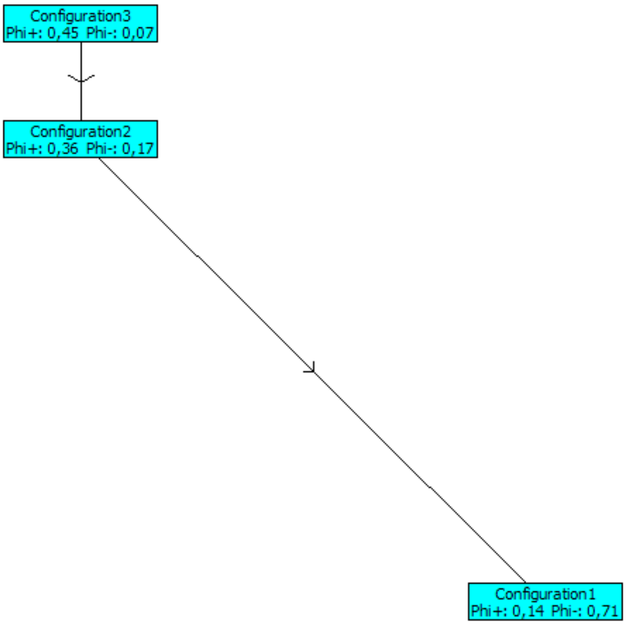

Figure 9. Multi-criteria analysis results in network view

The results of the analysis with the criteria weights are shown in Figure 10

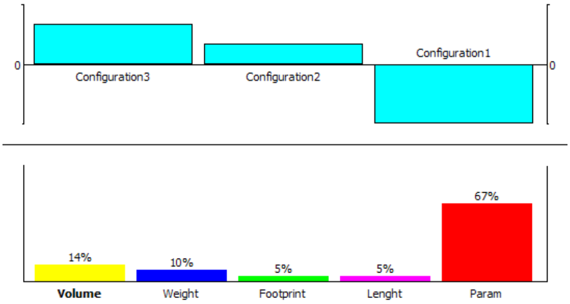

Figure 10. Multi-criteria analysis results with criteria weights

The aforementioned figures demonstrate that the third configuration is more favorable, with the grade value of the complete ranking being +0,3810; hence, it is proposed as the optimal configuration. Additionally, two scenarios were created and performed:

– Scenario 1

In the scenario 1, all criteria, both quantitative and qualitative, are modelled using the regular preference function (Usual).

– Scenario 2

In the scenario 2, the quantitative criteria (Table 4) are modelled using the regular preference function (Linear), while the qualitative criteria (Table 1) using the preference function (V-Shape), with the preference significance threshold p = 10.

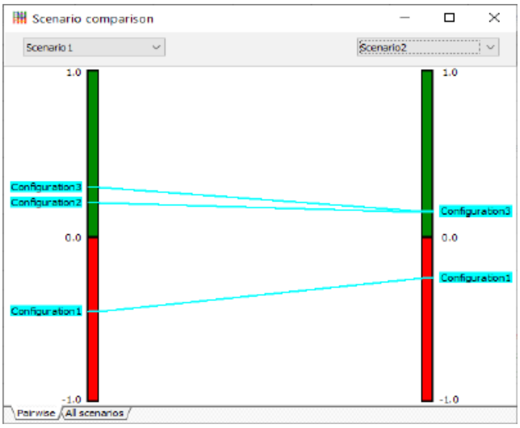

Figure 11. Results of the conducted scenarios

In both scenarios configuration 3 is the most acceptable

Conclusion

The implementation of sensor technology in medium voltage switchgear of a ship's switchboard offers several advantages and improvements. In the aim to increase energy efficiency or consequently reduce fuel consumption, either directly or indirectly, sensor technology contributes by lowering the overall energy consumption, weight and making the reduction of switchgear dimensions possible. Sensors also improve the characteristics of protection and measurement equipment compared to conventional ITs by eliminating saturation, increasing accuracy and protecting personnel as lower output voltages are used. In combination with the IEC 61850-9-2 standard the development of smart energy distribution grids could further improve safety, reliability, system functionality and energy efficiency.

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NOTES

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