Multi voltage systems for flexible test cell

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Bachelor's Thesis
Electrical Engineering
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EXAMENSARBETE

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Inriktningsalternativ/Fördjupning:	Elkraftsteknik
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Titel: *Flerspänningssystem för flexibel testcell*

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Abstrakt

Detta examensarbete har gjorts åt Wärtsilä Finland Oy. Arbetet utfördes under hösten 2015 och våren 2016. Min arbetsplats var Wärtsilä motorlaboratorium vid Metviken i Vasa. Min uppdragsgivare och arbetshandledare från Wärtsilä var Nicklas Johansson och min handledare från Novia var Ronnie Sundsten.

Syftet med detta examensarbete är att planera om en befintlig testcell till en flexibel testcell som kan testa flera olika typer av motorer och generatorer. Den flexibla testcellen ska göra det möjligt att relativt enkelt och snabbt byta ut den motor som testas till en annan motor. Detta är ett helt nytt koncept och det blir den första flexibla testcellen för hela globala Wärtsilä. Den flexibla testcellen kommer att göra det enklare och snabbare för Wärtsilä att testa en stor mängd olika motorer.

Det som gör det möjligt att testköra en så stor mängd olika motorer är en flerspänningstransformator, som ger ett brett spänningsområde att jobba med. Examensarbetet handlar också, till stor del, om att se över olika komponenter och hitta deras leverantörer, samt att få den bästa mätnoggrannheten för mättransformatorerna. Examensarbetet är till största delen teoretiskt. Resultatet blev två lösningsförslag på hur den flexibla testcellen kan konstrueras.

Språk: engelska Nyckelord: flexibel testcell, flerspänningstransformator

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Abstract

This bachelor’s thesis was done for Wärtsilä Finland Oy during the autumn of 2015 and the spring of 2016. My employer was Wärtsilä engine laboratory in Vasa.

The purpose of this thesis is to plan the first engine test cell into a flexible engine test cell. The construction of the flexible cell enables testing of a great range of different engines. It should be possible to change the engine and genset that is being tested, to another engine, in only a couple of days or weeks, depending on the engine and genset. This is a brand new idea for Wärtsilä and this will be the first flexible test cell. This flexible test cell will improve the Wärtsilä laboratory, considering it makes it possible to test a large group of different engines.

The thesis is also about choosing which electrical components that will be used and which supplier will deliver these components. To make it possible for the flexible test cell to test and run different engines, advanced components with high specifications are needed. The component which will make it possible to test and run so many different engines is the multi voltage transformer. This specific transformer will give a wide voltage range to work with. The measurement accuracy of the measurement transformers was another important part of this thesis. In this thesis, there are two construction alternatives.

Language: english Key words: flexible test cell, multi voltage transformer

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I would like to thank everyone at Wärtsilä engine laboratory that have been involved in this thesis. A special thanks to my supervisors Nicklas Johansson at Wärtsilä and Ronnie Sundsten at Novia University of Applied Sciences.

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1 Introduction

This thesis is made for Wärtsilä Finland Oy, Research and Development / Testing and Validation, Vasa, during autumn 2015 and spring 2016. The thesis is a project to reconstruct the current engine test cell into a flexible engine test cell. There are currently four different engine test cells at the engine laboratory in Vasa. The first test cell is planned to become the flexible test cell. The flexible test cell will make it possible to frequently change the engine that is being tested and have another engine there up and running for tests in a couple of days depending on the engine and genset. In the other three test cells there are engines that are being tested for longer periods of time.

The main parts of the thesis are to find different components for this project as well as finding the suppliers of these components. The multi voltage transformer is the biggest and most important component in this project. With the primary side of the transformer at 10,5 kV and the secondary 3,3 – 6,6 – 13,8 – 15,8 kV. It will allow us to test a great range of different engines, since the generators are producing different voltages depending on the engine setup.

Other important components are the switchgear, cables, protection relays and measurement transformers. The measurement accuracy of the measurement transformers is another important part of this thesis.

2 Wärtsilä Oy

Wärtsilä was founded in 1834. In 1834, Wärtsilä was established as a sawmill in the county of Karelia. In 1851, Wärtsilä´s sawmill was reconstructed into an iron mill and in 1938 Wärtsilä began its diesel engine era. The first diesel engine was completed in Turku 1942. /24/

Today Wärtsilä is a global Finnish company which is world leading in power solutions and marine- and energy markets. In the year 2015, Wärtsilä's revenue was 5 billion Euros and they had about 18.900 employees. Wärtsilä operates in about 70 countries and has over 200 units all around the world. There are totally four Testing & Validation units (T&V), at Wärtsilä. Two of them are located in Finland; Vaskiluoto and in the centre of Vasa. The other two T&V units are located in Trieste, Italy and in Bermeo, Spain. Wärtsilä is split into three main parts, **Marine Solutions**, **Energy Solutions** and **Services**. T&V is under Marine Solutions.

Marine Solutions is the world leading provider of ship machinery, propulsion and manoeuvring solutions. Wärtsilä is a supplier of engines, generating sets, propulsion equipment, reduction gears, control systems and sealing solutions for all types of vessels and offshore applications. Wärtsilä holds a strong position in all main marine segments as a supplier of high rated ship machinery and systems.

Energy Solutions is a leading supplier of power plants in the decentralised power generation market. Wärtsilä offers power plants for baseload, peaking and industrial self-generation purposes, both for the oil and gas industry. The strengths of Wärtsilä power plants are their high efficiency, low emission levels and flexible design. Wärtsilä holds a strong position in all main segments.

Services supports Wärtsilä's customers throughout the lifecycle of their installations. Wärtsilä provides service, maintenance and reconditioning solutions both for ship machinery and power plants. /1/

3 Purpose and challenges

The purpose of this thesis is to improve Wärtsilä’s engine laboratory. It will, with the flexible test cell, be able to test a greater range of engines and gensets than before. The flexible test cell will make it easy and fast to change engines that need to be tested, since the components are chosen to fit many different engines and gensets. This will be a great improvement of Wärtsilä’s laboratory. The laboratory will become unique, because it will be the first laboratory that will have a flexible engine test cell of this kind.

The biggest challenge in this thesis was to find components with the right specifications according to the flexible test cell’s needs. The specifications were specially designed for this project and therefore it was very hard to find a supplier that was able to deliver the components and at a reasonable price.

Another challenge was to find a place for the multi voltage transformer. It was difficult to know if it would be possible to place and install the multi voltage transformer in an existing building, or if it would require a new building/cage. If the latter is the chosen alternative, it would also require a pit for an oil bath, in case there would be any oil leakage from the transformer which would increase the cost of this project.

Another challenge was the measurement accuracy. The laboratory requires the best measurement accuracy possible since the laboratory’s purpose is to improve the engines. The requirement of the measurement components made it very difficult for the supplier to deliver them to us. A requirement that made it difficult for the suppliers to deliver was the frequency range of 20-60 Hz. Hence, when the frequency is getting low, the AC wave is becoming too much like DC. This will make the core reach magnetic saturation which will cause the magnetizing current to increase and overheat the transformer. This might have been the main problem as well as the wide voltage range and current range. /5/

4 Theoretical points and background

Wärtsilä's engine laboratory in Vasa will reconstruct their first engine test cell. The test cell has just finished its last tests and it has been cleaned and emptied. It is this cell that is planned to be reconstructed into the flexible test cell. The whole cell will need a complete renovation, both mechanically and electrically. New cooling systems and water pipe systems will be needed. Old unusable cables must also be removed. This is a very big project and a lot of people will be involved. It will be a huge investment and improvement of the engine laboratory in Vasa.

Theoretically, the flexible test cell will replace multiple engine test cells in a way that it will make it possible to test a great range of different engines, although it will only be possible to test one engine at a time. The flexible test cell is very good if there is an engine that has to be tested promptly. It will be relatively easy to change the engine in the flexible test cell and test the engine that is in need for tests.

In Table 1 are some calculations on the current that will occur according to the power of the multi voltage transformer and the voltage level the generator is producing. It is according to these calculations most of the components have been chosen, such as current transformers, voltage transformers, switchgear and cables. The greatest current will occur with a power of 9 MVA and a voltage level of 3,3 kV.

Power (kVA)	Voltage (kV)	Nominal Current (A)
16000	15.8	585
16000	13.8	670
16000	10.5	880
16000	6.6	1400
9000	3.3	1575

Table 1: Nominal current according to power and voltage

It is very unlikely that a scenario like 9 MVA and 3,3 kV would occur, but the flexible test cell is still scaled according to this scenario. At this point the nominal current range is quite wide, ranging from 585 A to 1575 A.

With the power limited to 9 MVA at 3,3 kV, it is possible to test main engines such as W6L32, W9L32DF and W12V34DF. If the transformer were not limited to 9 MVA, the current in the conductors would be too much and the conductors might melt. Other than the main engines, it is also possible to test some auxiliary engines.

4.1 Engine & genset statistics

This chapter discusses the statistics of the engines and generator sets that have been tested at Wärtsilä. The statistics in this chapter are based on the three first quarters of the year 2015. The amount of engines that have been tested at Wärtsilä during Q1-Q3 2015 has been about 200. In this number, there are no W20 engines included. Figure 1 shows which voltage level was the most common during Q1-Q3 2015. As shown in the figure were 6,6 kV, 13,8 kV and 11 kV, the most common produced voltage levels.

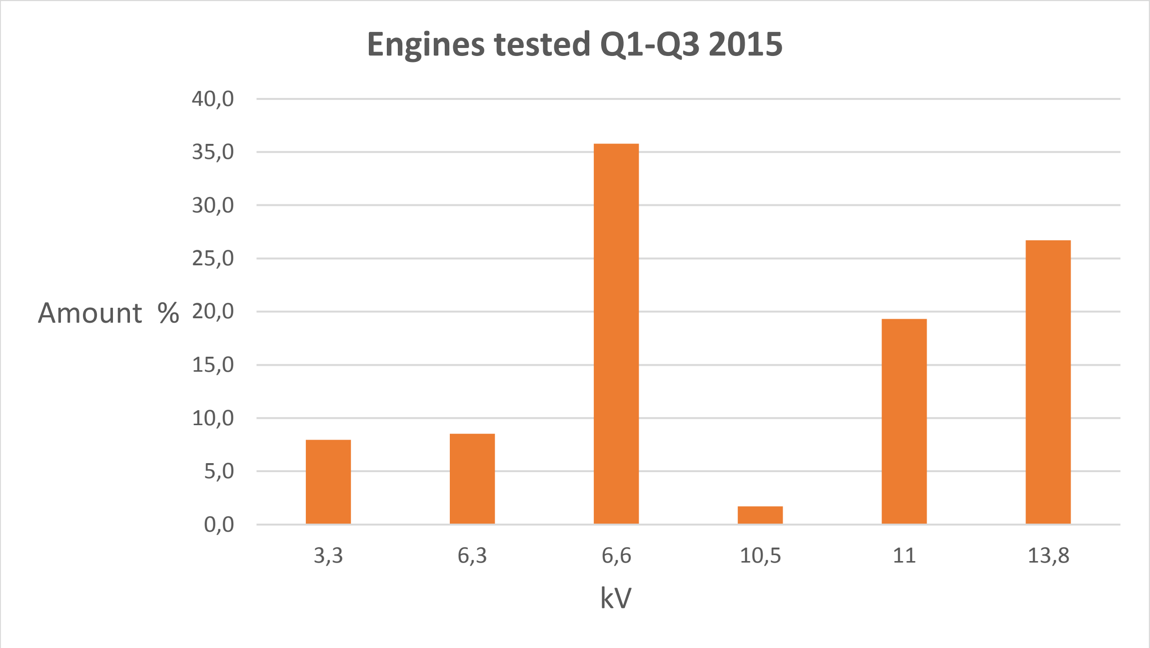

Figure 1: The amount of engines tested during Q1-Q3 2015

The flexible test cell is planned to support 6L32 to 20V31 engines. This is quite a wide range of engines and generator sets.

Although the W20 engines are not shown in the chart, they are the majority of the engines tested at Wärtsilä. Because of that, there might be a need to test W20 engines, or other auxiliary engines with low voltage generators. To do so, it requires a transformer. The low voltage generators have a standard to produce 400, 690 or 810 V. Therefore, will a transformer be needed to transform the voltage to 10,5 kV. The transformer would have three secondary voltage levels of 400 – 690 – 810 V and a primary voltage level of 10,5 kV. This is still only an option under investigation and it has not yet been decided upon.

5 Components

This chapter discusses the different components that are planned to be used in this project. It will also discuss how the components are chosen. There are six key components in this project. These key components are making the flexible test cell work as mentioned earlier. The six key components are: multi voltage transformer, switchgear, voltage measurement transformer, current measurement transformer, cables and protection relays.

The multi voltage transformer makes sure that there are many different voltage levels, which allows the flexible test cell to use different gensets and the possibility to test a great range of different engines and generators. It also makes it possible to produce energy to the Finnish grid, since it is transforming the voltage to 10,5 kV. Although, it will only be possible to produce energy to the grid if the frequency is 50 Hz. If tests with other frequencies than 50 Hz are being done, it will not be possible to produce the energy to the grid. Therefore, will the tests run the energy through the resistors. The current transformers and the voltage transformers are measuring the current and the voltage that are going through the conductors. They are connected to a power monitor unit (PMU) or to protection relays. There will be four protection relays for this project. A generator protection, two differential protection relays and an arc light protection relay. These relays will be connected with the measurement transformers.

5.1 Construction alternatives

This chapter discusses how the flexible test cell can be constructed. There are two alternatives. The components are specially chosen according to the two construction alternatives. Both construction alternatives are quite alike, but have their own advantages and disadvantages.

5.1.1 Alternative 1

The first alternative will imply a five cubicle system in the switchgear. The first cubicle is for the generator and the next three cubicles are for the secondary voltages from the multi voltage transformer 3,3 – 6,6 – 13,8 kV. The last cubicle is for the primary voltage from the multi voltage transformer 10,5 kV. The place for the multi voltage transformer depends on which cooling system it will be using, since the cooling system is affecting the size of the transformer. In this alternative, however, the transformer will be placed at the yard, since it will be too big to fit into an existing building. A transformer cage will have to be constructed, as well as an oil bath, for possible oil leakage from the transformer. The multi voltage transformer and the switchgear are connected with aluminium conductors, as well as from the generator to the switchgear. The amount of cable calculated to be used for this would be around 1500 m. This alternative will require two conductors per phase for the 3,3 – 6,6 and 10,5 kV cubicle, while the 13,8 kV cubicle will manage with a single conductor per phase. The measurement transformers that will measure the current and voltage will be placed in the switchgear. Totally, there will be 42 measurement transformers, of which 18 are protective measurement transformers with the class 5P10. The 5P10 class means that at 10 times nominal current, the measurement transformer will have an error accuracy of 5 %. For example, a transformer with 800 A as nominal primary current is able to measure a current peak of 8000 A. The measurement transformer will then show a value within 7600 – 8400 A, which is an error accuracy of 5 %.

$$800\text{ A} * 10 = 8000\ A \qquad 0{,}95 * 8000A = 7600\ A \qquad 1{,}05 * 8000A = 8400\ A$$

This class is used only for the protective measurement transformers. Normal measurement transformers with the accuracy class 0,1 %, would not be able to detect a great voltage or current peak, which might result in damaging the components.

The advantages of this alternative are that it is quite easy to construct and it is possible to execute the project without greater issues. The components are not so restricted, which will make it easier to find a supplier who can deliver the components. The measurement transformers will give better measurements, since they are placed in five different cubicles. The cubicles are split into four different voltages. This will make it easier to scale the measurement transformers for each cubicle.

A disadvantage with this alternative is that the multi voltage transformer will be placed on the yard. This will lead to additional costs, such as construction of the transformer cage, digging for the oil bath, oil bath, longer cable route and more cables. Another disadvantage with this alternative is that it will need 42 measurement transformers and 5 cubicles, which will require quite a lot of space.

Positive: **Easier to execute, better measurements**

Negative: **Expensive, requires more space and components**

5.1.2 Alternative 2

The second alternative will include a switchgear with four cubicles. Three of them will be in use and the fourth will be an extra spare cubicle. The first cubicle is for the generator and the second cubicle is for all the secondary voltage levels from the multi voltage transformer. In this alternative, there will be two additional secondary voltages, which makes all the secondary voltages to 3,3 – 6,6 – 11 – 13,8 – 15,8 kV. The third cubicle is for the primary voltage from the multi voltage transformer 10,5 kV. The spare cubicle might become useful in a later phase to run the test through the power converter, which will allow more advanced tests. This is still only an idea and is under further investigation.

In this alternative, the multi voltage transformer will be placed under the switchgear in an existing building. This will reduce the amount of cable that will be needed, since the transformer will be right under the switchgear and there will only be three cubicles in use. All of these cubicles will, however, need two conductors per phase. The conductors that will be used are the same aluminium conductors as in alternative 1. The calculated amount of cables required for this alternative is about 500 m, which would be about 1/3 of the first construction alternative. There will be a total of 30 measurement transformers, of which 18 are protective measurement transformers with the class 5P10. The rest of the measurement transformers have an accuracy of 0,1 %.

This will be the ideal way to construct the flexible test cell. One advantage with this alternative is that it will require fewer components, which will save space in the switchgear. Another advantage is that the multi voltage transformer have a wider voltage range and is placed under the switchgear, which will make the cable route very short. The disadvantage with this alternative is the measurement transformers. It is still uncertain if it is possible to measure the wide current range in the cubicles. It depends on whether the suppliers are able to produce accurate measurement transformers for this task or not. If they are able to supply is this the best alternative to construct the flexible test cell.

Positive: **Fewer components, requires less space, multi voltage transformer have a wider voltage range and is placed under the switchgear.**

Negative: **Might give inaccurate measurements.**

5.2 Multi voltage transformer

Max power:	16 MVA
Nominal voltage, primary:	10,5 kV
Nominal voltage, secondary:	3,3 – 6,6 – 11 – 13,8 –15,8 kV
Voltage taps:	±2x2,5 %
IP class:	IP00
Vector group:	Proposed
Frequency:	20-60 Hz

In this project, there is a great need for a multi voltage transformer, or several voltage transformers. Several voltage transformers would, though, not be suitable for this project, since it would require so much space and it would not be an economic benefit. Therefore, it is a good choice to go with a multi voltage transformer. There will be three secondary voltage levels 3,3 – 6,6 – 13,8 kV. The primary voltage level is 10,5 kV. With the primary voltage level 10,5 kV it will be possible to produce energy to the grid.

The place for the transformer is still not decided, since it is depending on the size of the transformer. The size of the transformer depends on which cooling system will be used. With better cooling systems, it is possible to make a smaller and more compact transformer. Another important thing to keep in mind when searching for new transformers is the ecodesign requirement from 2015. It is a requirement for better efficiency and therefore it is more environment friendly. The transformer that is chosen for our project will have a total power of 16 MVA, which will normally have a minimum efficiency of 99,615 %. With the ecodesign requirement, the same transformer must have a minimum efficiency of 99,663 %. The ecodesign requirement will make the transformer more expensive than a regular transformer.

According to TUKES, this requirement is only to be applied if the transformer will be continuously active. This requirement will not be applied for this project, since the transformer will be shut down during the change of an engine or genset. This will allow the project to get a transformer without the ecodesign requirement, which will in turn make it cheaper. /8/14/15/

5.2.1 Cooling systems

This chapter discusses the different cooling systems for the multi voltage transformer. The cooling system will have a huge impact on the size and price of the transformer. The size will also determine where the transformer will be placed, which will have an important role in this project. Three different cooling systems have been found suitable for this project. In this chapter, there will be a brief explanation about the three cooling systems, as well as some advantages and disadvantages. /13/

		Letter	Description
Internal	First Letter (Cooling medium)	O	Liquid with flash point less than or equal to 300°C
		K	Liquid with flash point greater than 300°C
		L	Liquid with no measurable flash point
	Second Letter (Cooling mechanism)	N	Natural convection through cooling equipment and windings
		F	Forced circulation through cooling equipment, natural convection in windings
		D	Forced circulation through cooling equipment, directed flow in man windings
External	Third letter (Cooling medium)	A	Air
		W	Water
	Fourth letter (Cooling medium)	N	Natural convection
		F	Forced circulation

Figure 2: Description of each letter of the cooling system

Alternative 1

The first cooling system is an ONAF – Oil Natural Air Forced. It is an oil transformer with fans at the radiator. The fans are cooling the radiators where oil is flowing through. This type of cooling system will make it possible for the transformer to run at the maximum power without overheating. With this cooling system, it will not be possible to place it under the switchgear, since it will be too big. It will instead have to be placed at the yard, which will add some extra costs as mentioned earlier. An offer, on a transformer with the ONAF cooling system, has been received from ABB. The transformer's price was very expensive.

The conclusion of this is that the ONAF cooling system may be too expensive for this project. The transformer is very expensive to begin with and it will add additional costs because of the size of the transformer. /12/

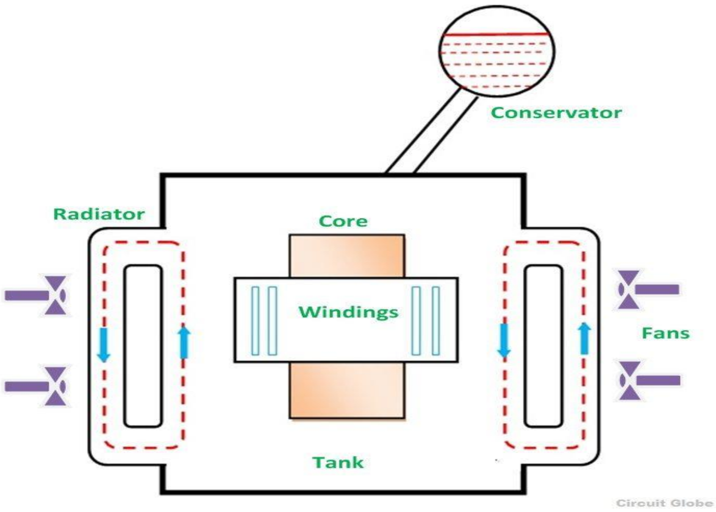

Figure 3: ONAF transformer

Alternative 2

The second transformer cooling system is an OFWF – Oil Forced Water Forced, which is an oil transformer. The pump is circulating the oil to the radiator. In the radiator is a water inlet, which is cooling the circulating oil. This is a very effective cooling system and it is considered to give the transformer the most effective cooling. This cooling system will make it possible for the supplier to make the transformer very small and compact. This will allow the transformer to be placed under the switchgear, which is a great benefit.

An offer has been received from BTB plaza, a Finnish transformer marketplace with a range of different suppliers. The price of the transformer is about 50 % of the ONAF transformer. The conclusion is that it will be a good alternative to use an OFWF cooled transformer, since it gives the most effective cooling and it was quite cheap. A drawback, with this cooling system, is that a cooling circuit will have to be constructed, where the water is circulating from the transformer to cool down after the heat exchange. This will add some extra costs for the cooling system. /6/

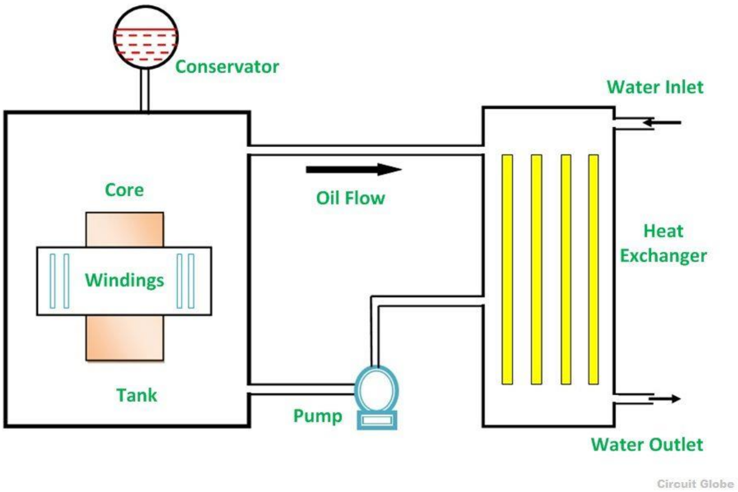

Figure 4: OFWF transformer

Alternative 3

The third cooling system alternative is an OFAF – Oil Forced Air Forced transformer, which is an oil transformer. The pump is circulating the oil to the radiator. The radiator is being cooled down with fans. With this cooling system, it is possible for suppliers to make it small enough to fit under the switchgear, which is a great benefit. An offer has been received from BTB plaza on a transformer with this cooling system. The price of this transformer is about 10 % more expensive than the OFWF transformer. The conclusion is that this is also a good alternative for this project. It will give the transformer effective cooling at a reasonable price and it will also be small enough to fit under the switchgear. /6/

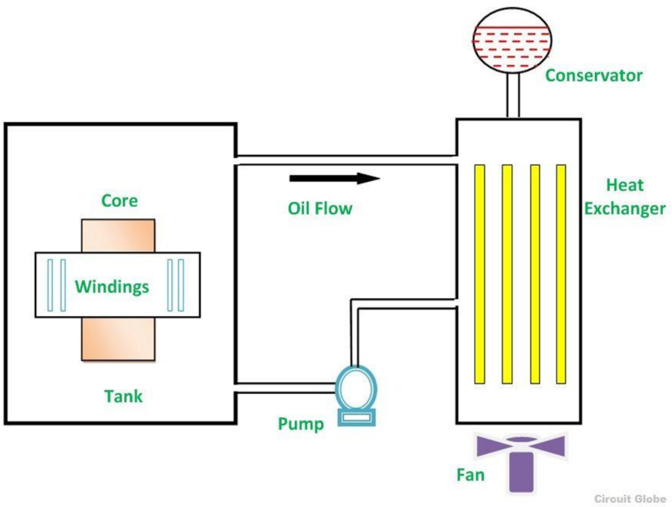

Figure 5: OFAF transformer

5.2.2 Utilization of the transformer

Another important factor of the multi voltage transformer was how the secondary voltages were obtained. This chapter discusses how the manufacturers have obtained the secondary voltages and how the multi voltage transformer is utilized.

ABB

A drawback with the ABB's ONAF transformer is that the transformer is not fully utilized for all the voltages. The transformer is only using the whole windings at 13,8 kV. At 3,3 kV are only a small part of the windings used. In other words, this is not considered cost efficient. It is shown in Figure 6 how the windings are planned to be used.

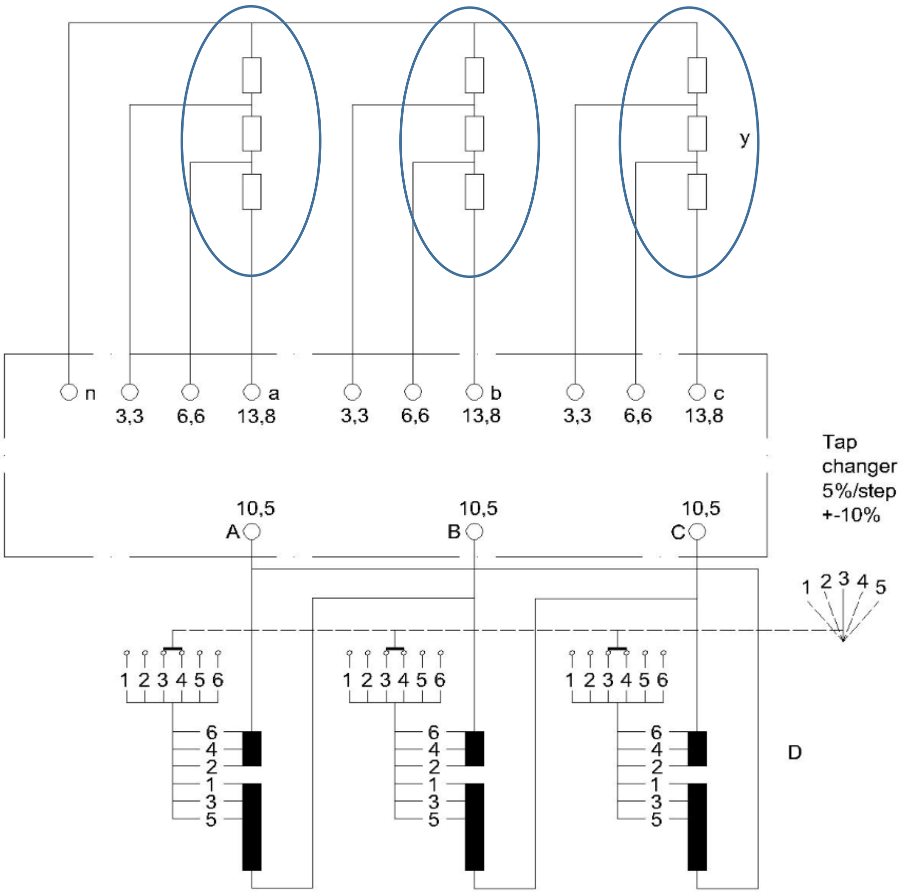

Figure 6: ABB´s Transformer connection diagram

BTB plaza

BTB plaza's transformers are smarter constructed. The transformer windings are fully utilized at all times regardless of which secondary voltage is being used. This is done by using different combinations of parallel and serial connections for delta- and star connections, as well as different tapping options. With these combinations it is possible to reach a great amount of different voltages. In Table 2 the different voltage levels are shown. This solution is very good, since it is more cost efficient. The transformer is using all of the windings no matter which voltage level is being used. The values that are blackened are the values that are important in this project.

	Delta-connection		Star-connection	
Tapping	Paralell	Serial	Paralell	Serial
131 %	4 330 V	8 660 V	7 500 V	**15 000 V**
121 %	3 983 V	7 966 V	6 899 V	**13 798 V**
100 %	**3 300 V**	**6 600 V**	5 716 V	**11 432 V**

Table 2: BTB plaza´s secondary voltage level solutions

5.2.3 Conclusion

In Table 3 are the advantages and disadvantages of the different transformers and cooling systems listed. According to this, both the OFWF and OFAF looks like good options for this project. Although, the OFWF seems to be a little bit cheaper, there will still be some additional costs that are not included. The ONAF transformer from ABB does not look so appealing according to the pros and cons, when compared with the BTB plaza transformers.

Manufacturer	ABB	BTB	BTB
Cooling systems	**ONAN**	**OFWF**	**OFAF**
Price index (Offer)	1	0.5	0.55
Suitable cooling system for this project	Yes	Yes	Yes
Possible to place under the Switchgear	No	Yes	Yes
Transformer fully utilized	No	Yes	Yes
Additional extra costs, constructions, etc.	Yes	Yes	No

Table 3: Advantages and disadvantages

5.3 Switchgear

Disconnectors:	Distance or manually controlled
Nominal current:	1600 A
Frequency:	20-60 Hz
Place for:	Protection relays
Place for:	Voltage transformers
Place for:	Current transformers

In the current switchgear, there are no extra space for more cubicles. Therefore, some cubicles have to be removed to make space for the flexible test cell cubicles. The amount of cubicles that needs to be removed is depending on which alternative is chosen. In this chapter there are two alternatives of the switchgear layout.

5.3.1 Alternative 1

The first alternative is a five cubicle system. The first cubicle is for the generator. The next three cubicles are for the secondary voltage from the multi voltage transformer 3,3 – 6,6 – 13,8 kV. The last cubicle is for the 10,5 kV, which will go to the grid/resistors. A breaker (24C01.01_Q0) will take place in the generator cubicle and separators (Q1-4) in the other cubicles.

The amount of measurement transformers will be 42, of which 18 are protective measurement transformers with the accuracy class 5P10. They will be measuring before and after the generator, as well as before the grid/resistors. The rest of the measurement transformers will have the accuracy class of 0,1 %. There will be 6 measurement transformers in each cubicle. The measurement transformers are measuring the current and voltage of each phase. The measurement transformers will be connected to a power monitor unit, PMU, which will show the voltage, ampere and energy. In the switchgear there will also be an arc lightning protection relay installed, which will protect the system if an arc lightning will occur.

One advantage with this five cubicle system alternative is that it is easier to find accurate measurement transformers, since there will be a limited voltage level for each cubicle. The disadvantages are that it will require more space with five cubicles and it will require more measurement transformers compared to the other alternative. A layout of the switchgear is shown in Figure 7.

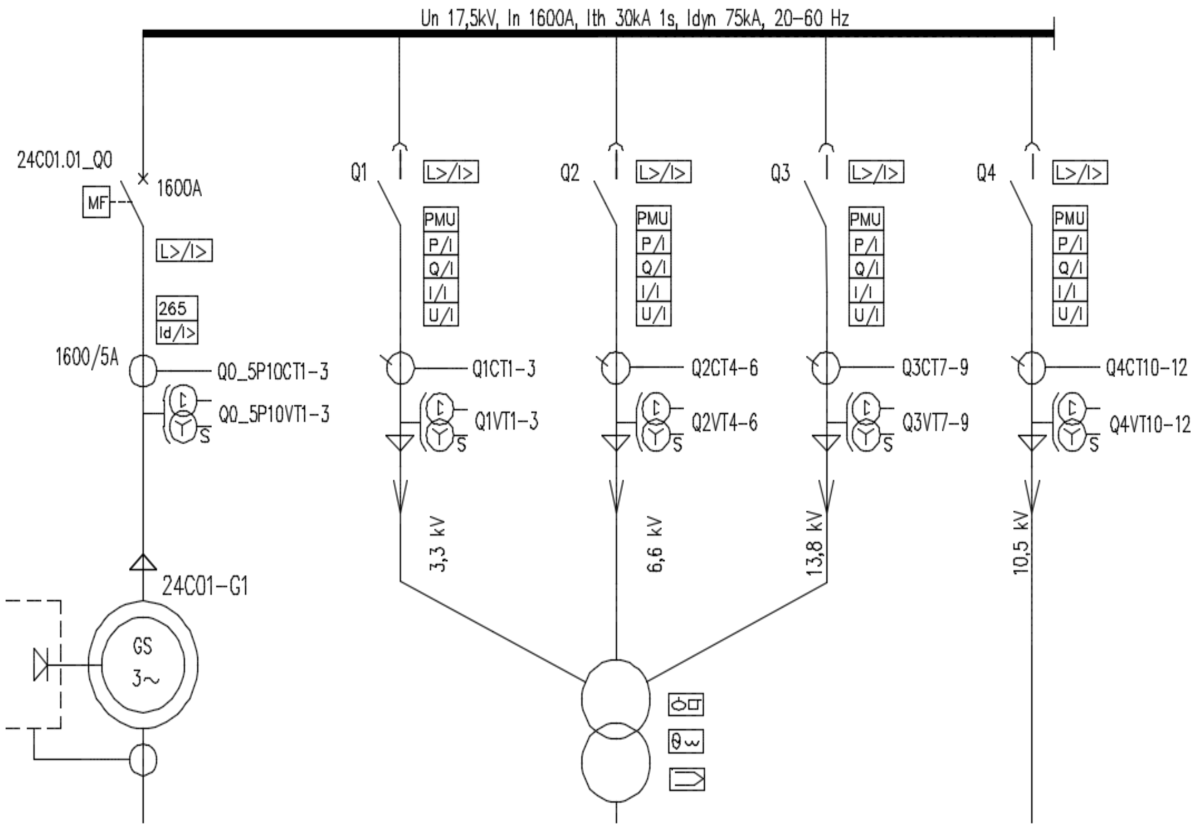

Figure 7: Layout of the five cubicle alternative

5.3.2 Alternative 2

In the second alternative, there are four cubicles, three in use and an extra spare cubicle. The first cubicle is for the generator. The second cubicle is for all the secondary voltages from the multi voltage transformer, which are 3,3 – 6,6 – 11 – 13,8 – 15,8 kV. The third cubicle is for the primary voltage 10,5 kV, which will go straight to the grid or to the resistors. The fourth and last cubicle is a spare cubicle, at least in the beginning. The spare cubicle gives an option to run the energy through the power converter unit in the future. With the power unit converter, it will be possible to change a various set of settings, such as reactive load. This is not possible if you run the test through the resistors, since it is a pure resistive load.

The amount of measurement transformers will be 30, of which 18 are protective measurement transformers with the accuracy class 5P10. They will be measuring before and after the generator, as well as before the grid/resistors. The rest of the measurement transformers will have the accuracy class of 0,1 %. They will be measuring in the secondary voltage and the primary voltage. They are connected to a PMU, which will show the voltage, ampere and the energy.

One advantage with the second alternative is that it will require less space with only four cubicles. Another advantage is that it will require less measurement transformers. This alternative might therefore be cheaper than the first alternative. The disadvantage with this alternative is the measurement accuracy. It is uncertain if it is possible to measure the wide current range and voltage range in the secondary voltage cubicle. If it is possible, then this is the ideal way to construct the switchgear for the flexible test cell project. Figure 8 shows the four cubicle alternative.

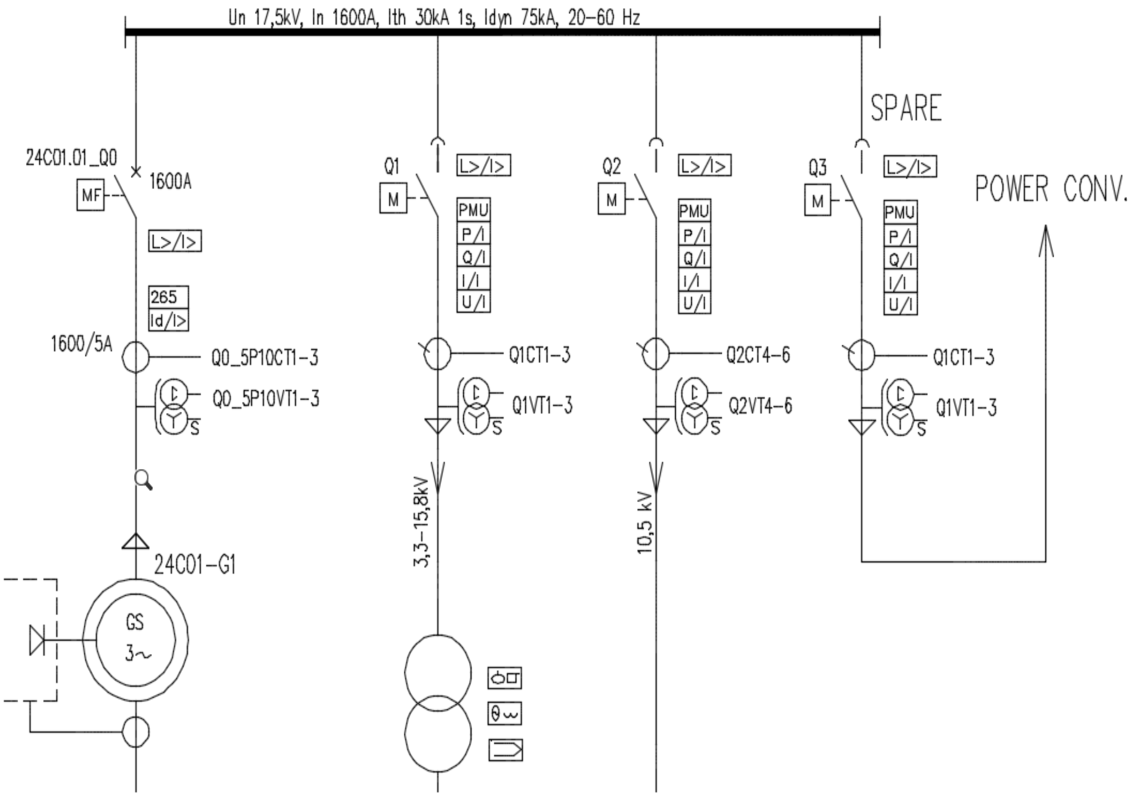

Figure 8: Layout of the four cubicle alternative

5.4 Voltage measurement transformers

Burden:	7,5 VA
Rated voltage, primary:	3,3 kV, 6,6 kV, 13,8 kV
Rated voltage, secondary:	110 V
Insulation level:	According to IEC 61869-3
Rated frequency:	20-60 Hz
Accuracy:	Class 0.1 @20-60 Hz

This chapter discusses the voltage measurement transformers. The measurement transformer is important for this project, since it will be measuring the voltage in each phase. With the measurement transformer's accuracy class of 0,1%, it can measure the voltage in the cable with a fault error of 0,1%. The voltage measurement transformers will be connected to the PMU and the generator protection relay as well as the differential relay.

The measurement transformers will be placed in the switchgear cubicles and there will be a voltage measurement transformer for each phase in each cubicle. The frequency range 20-60 Hz is needed, since some tests are simulating a propeller of a ship and these tests need the frequency range of 20-60 Hz. The burden 7,5 VA is chosen, since the voltage transformers are more accurate when the components are consuming about 25-100 % of the total burden. The burden is chosen according to the VA consumption of the components, which are connected with the transformer. /10/21/

The burden 7,5 VA is calculated to be enough for this project, even if the system is being expanded. The calculation looks like this.

The voltage transformer ratio is:

$$\frac{11000\text{V}}{110\text{V}} = 100$$

If the primary voltage level is 10500 V, the secondary voltage level will be 105 V.

$$\frac{10500V}{100} = 105\ V$$

Two protection relays, Vamp 210, Vamp 265 and the PMU Vamp 260 will be connected to the voltage transformer. The relays will consume about 1 VA each. With this information it is possible to calculate the current:

$$\frac{3VA}{105V} = 0{,}029\ A$$

With the current, it is now possible to calculate the burden in the cable, which is 30 m of MMJ 3x2,5. It has an impedance of 0,00877 Ω/m at 80 C°. The cable burden is added with the relays VA drop. /11/

$$3\ VA + 0{,}029^2 A * \left(30\ m * 0{,}00877 \frac{\Omega}{m}\right) = 3VA$$

$$\frac{3\ VA}{7{,}5\ VA} * 100 = 40\ \%$$

According to the IEC standard, the voltage measurement transformers may start to give inaccurate measurements if the burden is below 25 %. In this case, the burden would have to be below 1,875 VA, before giving inaccurate measurements. This voltage transformer will still give accurate measurements for this project. /10/

$$7{,}5\ VA * 0{,}25 = 1{,}875\ VA$$

In the first construction alternative with 5 cubicles, it will be easy to scale the voltage measurement transformers for each cubicle, since they are limited to a certain voltage level. In the second construction alternative, there are only 3 cubicles in use. In two of the cubicles, there will occur voltage levels from 3,3 – 15,8 kV. It would therefore be essential to have a 17,5 kV voltage measurement transformer that is able to measure down to 3,3 kV with the accuracy of 0,1 %. This is still under investigation and it is depending on the suppliers if they are able to produce these kind of transformers or not.

5.5 Current measurement transformers

Burden:	15 VA
Nominal Voltage:	17,5 or 24 kV
Primary nominal current:	600 – 1600 A
Secondary nominal current:	5 A
Frequency:	20-60 Hz
Accuracy class:	0,1 % or 5P10

This chapter discusses the current measurement transformers. The current measurement transformer will be very important for this project, since the transformer measures the current in each phase. Depending on which accuracy class the measurement transformer has, it will be connected to different components, such as protection relays or power monitoring units, PMU. If the measurement transformer has an accuracy of 0,1 %, it will be connected to a PMU. With the PMU, it will be possible to read the current, voltage and energy that is going through the cable.

If the accuracy class is 5P10, it can measure a current 10 times the primary current, with an accuracy of 5 %. These measurement transformers will be connected to the protection relays, such as generator protection, differential protection and arc lightning protection relays. This accuracy class can measure high current peaks, which the other accuracy class would not notice. The frequency range 20-60 Hz is needed, since some tests are simulating a propeller of a ship and these tests need the frequency range of 20-60 Hz. The current measurement transformers will be placed in the switchgear. The burden of 15 VA is calculated to be enough, even if the system will be expanded.

The current transformers will be connected to a PMU or four protection relays, depending on the accuracy class. Each PMU or protection relay is consuming about 1 VA each. The cable that will connect the transformers with the PMU or the protection relays, is an MMJ 3x2,5. It has an impedance of 0,00877 Ω/m at 80 C°. This will also consume power. Finally, the calculation looks like this: (In this example there are four protection relays)

$4\ VA + 5^2 A(30\ m * 0{,}00877\ \Omega/m) = 10{,}5775 \approx 10{,}6$ VA

This leaves a burden of 4,4 VA in the transformer, which will make it possible to expand the system in the future.

If the burden of the cable and protection relays would have been under 3,75 VA it might result in inaccurate measurement, since it is recommended that the burden is between 25-100 % of the transformers burden for accurate measurements.

$$15\ VA * 0,25 = 3,75\ VA$$

If the burden is too high, it is recommended to use current transformers with a secondary current of 1 A instead of 5 A. This will reduce the burden in the conductor by 96 %, in comparison with a 5 A as secondary current. For example:

$$5^2 A * \left(30\ m * 0,00877\ \frac{\Omega}{m}\right) = 6,5775\ VA = 100\ \%$$

$$1^2 A * \left(30\ m * 0,00877\ \frac{\Omega}{m}\right) = 0,2631\ VA = 4\ \%$$

It can also be solved by increasing the thickness of the conductor, which will reduce the conductor's impedance. The impact will not be as big as a reduction of the secondary current. Below Figure 9 shows the impact of the secondary current as well as the thickness of the conductor. /6/10/

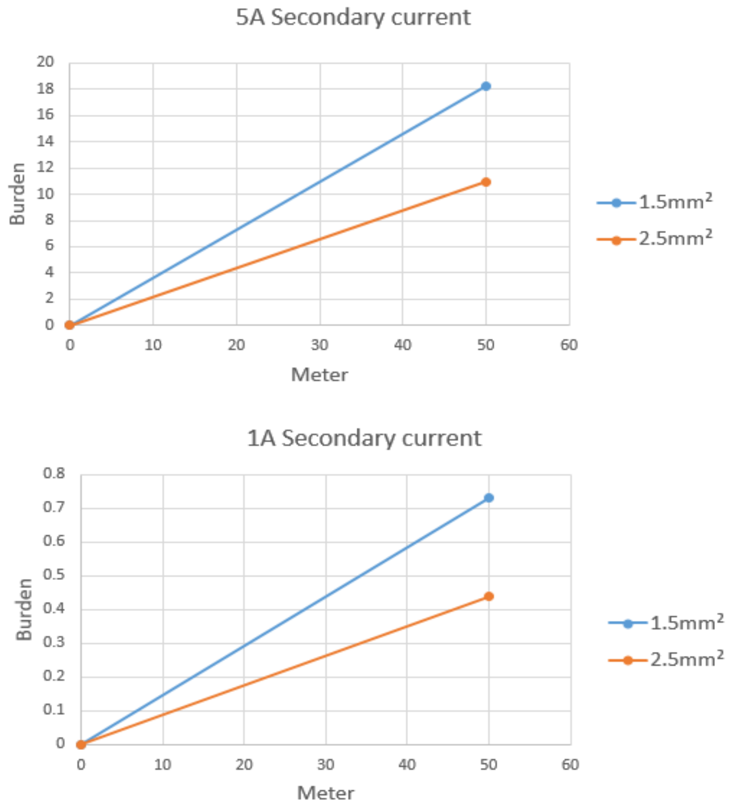

Figure 9: Burden according to secondary current and thickness of conductor

5.5.1 Measurement accuracy

The measurement accuracy of the transformers is very important in this project and for the laboratory in general. It is according to these measurements, the PMUs will show an accurate value and the protection relays will detect faults in the system. Most of the measurement transformers are made to be approved by the IEC 60044-1 standard. In Table 4 are the IEC standards required values of a current measurement transformer with the accuracy class 0,1 % shown. /10/

Class	For burdens [1)]	Limits of errors			Application
		at % rated current	Ratio error %	Phase displacement minutes	
0.1	25-100% of rated burden	5	0.4	15	Laboratory
		20	0.20	8	
		100	0.1	5	
		120	0.1	5	

Table 4: Accuracy class values according to IEC 60044-1

The chart says when there is a 25-100 % of the rated burden and a current of 5 % of the primary current, the transformer will have a measurement accuracy of 0,4 %. At 20 % of the primary current, the accuracy will be improved to 0,2 %. First at 100-120 % of the primary current, the accuracy will have improved to 0,1 %, which is needed in this project. Therefore, is this standard not that suitable for the measurement transformers in this project, since it will be needed to have better accuracy, even though the current may be less than 100 % of the rated primary current. /3/4/

Siemens states that they are able to produce current measurement transformers able to have an accuracy of 0,1 %, even when the current going through the conductor is only 5 % of the rated primary current. This accuracy will have a huge impact on the project, since the current measurement transformers will be able to measure accurately at a wide current range. Table 5 is a test report, from Siemens, it shows that their current transformers are accurate both at 16,7 Hz and 60 Hz, as well as with only 5 % of the rated primary current up to 120 %.

16,7 Hz

Fabriknummer Serial No	Klemmen Terminals	Übersetzung Ratio	Leistung Power	5 %I_n		20 %I_n		100 %I_n		120 %I_n	
				F_i [%]	δ_i [min]	F_i [%]	δ_i [min]	F_i [%]	δ_i [min]	F_i [%]	δ_i [min]
30896266	1S1-1S2	500/5	2,5 VA	0,076	2,41	0,072	1,23	0,078	0,22	0,08	0,14
			10 VA	-0,006	2,73	0,022	0,77	0,054	-0,16	0,048	0,29
	2S1-2S2	500/5	10 VA					-0,066	1,52		

60 Hz

Fabriknummer Serial No	Klemmen Terminals	Übersetzung Ratio	Leistung Power	5 %I_n		20 %I_n		100 %I_n		120 %I_n	
				F_i [%]	δ_i [min]	F_i [%]	δ_i [min]	F_i [%]	δ_i [min]	F_i [%]	δ_i [min]
30896266	1S1-1S2	500/5	2,5 VA	0,09	1,36	0,088	1,08	0,087	0,67	0,087	0,62
			10 VA	0,05	1,84	0,053	1,2	0,065	0,44	0,067	0,35
	2S1-2S2	500/5	10 VA					-0,038	0,91		

Messdatum / Measuring date: 14.06.2013

Table 5: Siemens' test report of the current measurement transformer

5.5.2 Different types of current transformers

This chapter discusses three different types of current transformers. The wound transformer, the toroidal transformer and the bar transformer. Depending on the transformer there may be some benefits over the others.

Wound transformer

The wound transformers' primary and secondary windings are physically wounded on top of each other. The first half of the secondary winding is wound around the core. Then the primary winding is wound on top of that. Then the second half of the secondary winding is wound on top of the primary winding. These transformers are often used in high voltage stations, where the current is quite low. /22/23/

Figure 10: Wound transformer

Toroidal transformer

In the toroidal transformer, the conductor or bus-bar is working as the primary winding when it goes through the window of the transformer. Some of the toroidal transformers are designed in a way that they are able to be opened. This will make it easy to assemble the transformer around the conductor or bus-bar. These kind of transformers are called split core transformers. /7/

Figure 11: Toroidal transformer

Bar transformer

With the bar transformer, the cable is connected to the bar. This kind of transformers are counted as a single turn primary winding, since the bar is going through a toroidal core window. These transformers are therefore quite alike the toroidal transformers. /20/

Figure 12: Bar transformer

5.5.3 Current transformer ratio

This chapter will discuss the different current transformer ratios that may be useful in this project. In Table 6, there will be values according to the Siemens current measurement transformers. According to the tests their transformers are able to measure current accurately, although there is only 5 % of the nominal primary current in the conductor. The transformers do also have taps, which will allow half of the winding to be used, to make the primary current 50 % smaller. The different settings are shown as CT1 and CT2. The minimum is 5 % of the primary current and the maximum is 120 % of the rated primary current.

Voltage / kV	Max Current/A	CT1	CT1_max	CT1_min	CT2	CT2_max	CT2_min
3,3	1575	1600	1920	80	800	960	40
6,3	1470	1600	1920	80	800	960	40
6,6	1400	1200	1440	60	600	720	30
10,5	880	800	960	40	400	480	20
11	840	800	960	40	400	480	20
13,8	670	600	720	30	300	360	15
15,8	585	600	720	30	300	360	15

Table 6: Min max value with accurate measurement

According to this, it is theoretically possible to manage with a current transformer that has a ratio of 1600/5 A, since the maximum nominal current is calculated to be 1575 A and the minimum nominal current is calculated to be 585 A. A current of 585 A is equal to

$\frac{585}{1600} * 100 = 35{,}5\ \%$ of the nominal current, which will make it possible to show accurate measurements. Theoretically, the transformer is able to measure a current of 80 A, with an accuracy of 0,1 %. With a transformer using taps, the transformer will give even more accurate measurements, since the tap will make the primary rated current from 1600 A to 800 A. This will make the current of 585 A equal to 73 % of the rated primary current

$\frac{585}{800} * 100 = 73{,}125\ \%$, which will give more accurate measurements.

5.6 Conductor

This chapter will focus on the conductor. The conductor that will be used in this project is an AHXCMK-WTC 20kV 1x800/35 mm^2. It is an aluminium conductor. Aluminium conductors are easier to place and bend compared to copper conductors. There are also other benefits with the aluminium conductors over the copper. In Table 7 the benefits of the conductors are shown. The main factors, which decided why aluminium was chosen over copper, were weight and price. The benefits with copper conductors are that they are not as fragile and does not start to oxide as quickly as aluminium. /3/

Material properties	Copper	Aluminium
Market price raw materials (2014)	3	1
Weight	3	1
Resistivity per volume	3	5
Resistivity per mass	2	1
Cost per ampere	6	1

Table 7: Benefits according to the conductor

According to the information about the conductor gotten from the supplier, the conductor is able to conduct a current of 1010 A. There are, though, different factors that will decrease the amount to be conducted. With the calculated factor of 0,8, the final current that can be transferred is $1010 * 0{,}8 = 808\ A$. Therefore, there has to be two conductors per phase, when a current greater than 808 A occurs. With two conductors per phase, a current of $808 * 2 = 1616\ A$ will be allowed. This will be enough to cover the flexible test cell's needs. /2/3/

Power (kVA)	Voltage (kV)	Ampere (A)
16000	15.8	585
16000	13.8	670
16000	10.5	880
16000	6.6	1400
9000	3.3	1575

Table 8: Table showing which cubicle will need two conductors per phase

5.6.1 Alternative 1

In the first alternative, there will be a five cubicle system in the switchgear. In cubicles where a current higher than 808 A may occur, there will be two conductors per phase. The generator cubicle has a voltage range of 3,3 – 13,8 kV, which will give a nominal current range of 670 – 1575 A. Because of this, the generator cubicle will need two conductors per phase. The secondary voltage cubicles 3,3 kV and 6,6 kV will need two conductors per phase, since the nominal current in them is 1575 – 1400 A. The primary voltage cubicle 10,5 kV will also need two conductors per phase, since the nominal current is calculated to 880 A. The only cubicle that will manage with a single conductor per phase is the 13,8 kV cubicle, were the nominal current is calculated to be 670 A.

5.6.2 Alternative 2

The second alternative is a four cubicle system. Three of the cubicles are in use and the last cubicle is an extra spare cubicle. In all of these cubicles there might occur higher currents than 808 A. In the generator cubicle, the voltage range is 3,3 – 15,8 kV, which will give a current range of 1575 – 585 A. The second cubicle is for all the secondary voltages 3,3 – 6,6 – 11 – 13,8 – 15,8 kV, where a current range of 585 – 1575 A may occur. The last cubicle is for the primary voltage 10,5 kV. In this cubicle the calculated current is 880 A. Therefore, will two conductors per phase be needed in all of the cubicles.

5.7 Protection relays & Measurement equipment

To make the flexible test cell work as mentioned, advanced components will be needed. Therefore, it is important to protect these components. In this project, there will be three types of protections relays. The protection relay brand that will be used is Vamp and the measurement equipment that will be used is a power monitor unit, PMU.

5.7.1 Protection relays

The flexible test cell will use three protection relays. The first protection relay is a Vamp 210, which is a generator protection relay. The relay will protect the generator from different faults, such as overvoltage, overcurrent, reverse power, loss of reactive power and voltage or current to earth. If any of these faults occurs, the relay will shut down the system.

The second protection relay is a Vamp 221, which is an arc lightning protection relay. This relay will protect the switchgear cubicles from continuous arc lightning in the cubicles. If an arc lightning would appear in the cubicles, a sensor from the relay would notice the lightning and shut down the system. There will only be one Vamp 221 relay, since it is possible to install multiple sensors to it.

The third protection relay is a Vamp 265, which is a differential protection relay. Vamp 265 will mainly protect the generator and multi voltage transformer from differential currents. The relay will measure the current before and after the generator as well as the multi voltage transformer. If there are any differences in the measurements, it means that the current is going elsewhere. This will make the relay trip and shut down the system. /16/19/20/

5.7.2 Measurement unit

The flexible test cell will also use a Vamp 260, which is a power monitor unit, PMU. With the PMU, it is possible to read the voltage, current and energy in each phase. The PMU is connected to the measurement transformers. /18/

Figure 13: Vamp 260, power monitor unit

Freja 306

Before the relays are connected to the system they have to be tested so that they work according to the configurations. This is done with a tool called Freja 306. With Freja 306 it is possible to simulate different faults that will make the relays trip. It is possible to check if the relay trips correctly and in time. It is important to check and possibly reconfigure the relays before a new engine comes to the laboratory for tests. /9/

Figure 14: Freja 306, relay testing tool

VEO & Arqtec

Recently, VEO & Arcteq have produced and introduced a new type of relay with multiple functions which is called Generator commander. The Generator commander consists of generator protection, differential protection, synchronizing, as well as an automatic voltage regulator, AVR. It is a brand new innovation from the Finnish companies.

The Generator commander has the possibility to replace the Vamp relays. Vamp 210 can be replaced, since the generator commander is able to protect the generator in the same way. The current AVR, UNITROL 1020 can be replaced, since the Generator commander can work as an AVR. The Vamp 265 can also be replaced, because the Generator commander may also protect the system from differential currents. The Generator commander does also have additional functions, such as synchronizing. This is a very interesting product which fits into this project. The product is though very new and it needs further investigation. /20/

Figure 15: ARCTEQ Generator commander

6 Result

Solution 1

This solution will be a four cubicle system. Three of them will be in use and the fourth will be an extra spare cubicle. The first cubicle is for the generator, the second cubicle is for all the secondary voltages 3,3 – 6,6 – 11 – 13,8 – 15,8 kV and the third cubicle is for the primary voltage 10,5 kV. The multi voltage transformer will be using an OFAF cooling system, which will make the multi voltage transformer quite small to make it fit under the switchgear. This will make the cable route from the cubicles to the multi voltage transformer very short. Though, all of the cubicles will need two conductors per phase, since it may occur currents higher than 808 A in all of the cubicles. The amount of measurement transformers will be 30, of which 18 will have protective properties and will be connected to the protection relays.

One advantage of this solution is that it requires the least amount of components, such as cables, measurement transformers and cubicles. Another advantage is that the multi voltage transformer can be placed under the switchgear. It will also have two extra secondary voltage levels 11 kV and 15,8 kV. A disadvantage with this solution is that there is a greater risk that the measurement transformers give an inaccurate measurement. Figure 16 shows the layout of this solution.

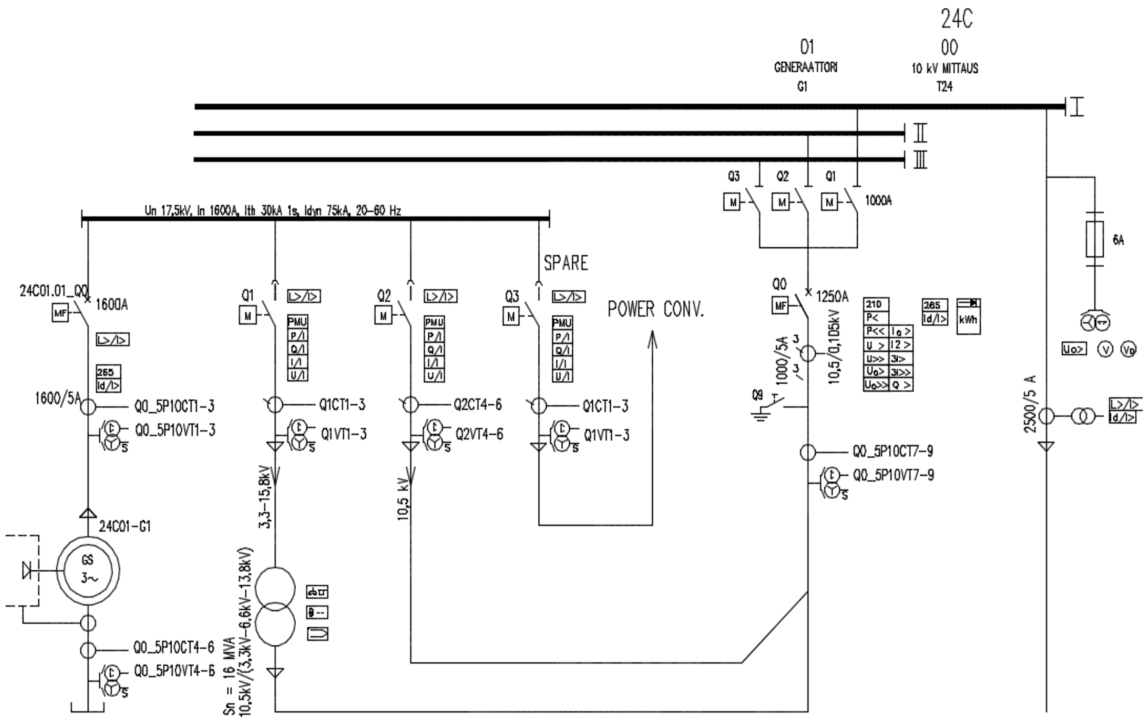

Figure 16: Layout of solution 1

Solution 2

The second solution is a five cubicle system. The first cubicle is for the generator. The next three cubicles are for the three secondary voltages 3,3 – 6,6 – 13,8 kV of the multi voltage transformer. The last cubicle is for the primary voltage 10,5 kV. The multi voltage transformer is using the ONAF cooling system, which will make it too big to be placed under the switchgear. It will therefore have to be placed at the yard. This will add extra costs for this project, such as an oil bath, longer cable route and a transformer cage. All cubicles will need two conductors per phase, except the 13,8 kV cubicle. The amount of measurement transformers is 42, of which 18 have protective properties and are connected to the protection relays.

The advantage of this solution is that it will give more accurate measurements, since the measurement transformers can be dimensioned for each cubicle separately. A disadvantage with this solution is that it will need more space and components, such as cable, measurement transformers as well as cubicles. Another disadvantage is that the multi voltage transformer will not have the secondary voltage levels of 11 kV and 15,8 kV. It will also be placed at the yard, which will add costs for this project. Figure 17 shows the layout of this solution.

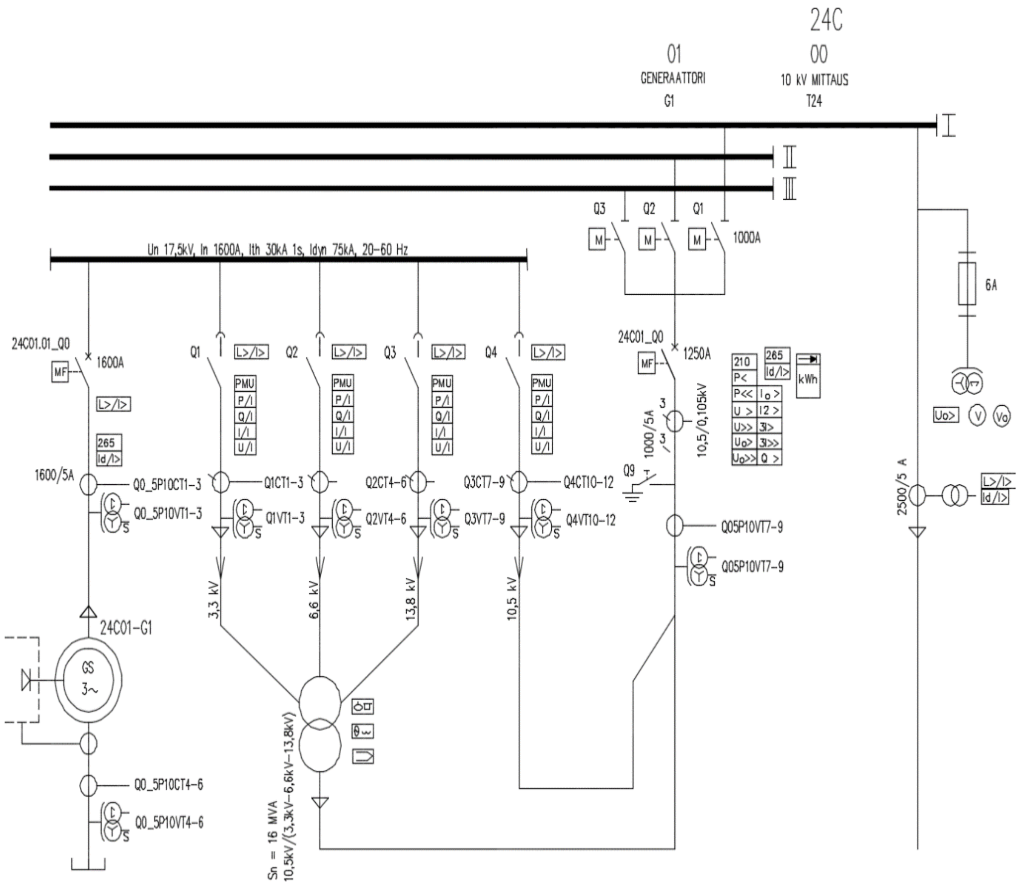

Figure 17: Layout of solution 2

7 Discussion

I personally think this bachelor’s thesis went good, although it was quite wide and there were many things to keep in mind. I think that the flexible test cell will be constructed according to one of the two solutions in this thesis. It was interesting to plan and think about what would be the best way to construct the flexible test cell, which components should benefit this project the most and how to choose them.

The lack of response from different suppliers was a setback in this project and thesis. It made it hard to know whether the supplier was able to deliver the different components or not. Because of that, there are two solutions in this thesis.

The first solution is the ideal flexible test cell, with lower cost and less labour needed to construct and maintain the flexible test cell. The second solution is intended to be a choice, possible to execute, without or with less component issues, since the components are not so restricted. This solution will require more space, more components, more labour and make the project more expensive.

It is up to Wärtsilä to decide, whether they will allow the laboratory to proceed with this project and to construct the flexible test cell according to this thesis, or not. It will be interesting to see, if the flexible test cell will be constructed and if it will work in practice according to the theory.

There is also the possibility to continue on this project and thesis, if the flexible test cell is constructed according to solution 1. In the future it might be so that the fourth cubicle will make it possible to test the engines with the power converter, which will enable more advanced tests.

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