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Comparison of Testing Methods for Diode Supply Modules

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Abstract

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This Bachelor's thesis was made for ABB Oy, Drives Service. The main objectives were to compare different testing methods for diode supply modules for Drive Service Workshop network. The thesis is focused on ABB's ACS800 and ACS880 product families that use diode and diode thyristor rectifiers. The purpose was to find a reliable way to test modules and to ensure they are working properly and safely. Five different module testing methods are introduced and compared.

The first chapter introduces ABB as a company. The second chapter includes the principle of diode supply module (DSU) and short explanation about diode and thyristor. Then different DSU modules that are planned to be tested with tester, are introduced. After that, the requirements of the tester are clarified, different test methods are presented and the comparison between the testing methods is made.

As a result, different test methods are compared and the most suitable one for Drive Service Workshop which seems to be testing with resistance and capacitor is recommended.

Keywords	Diode supply module, Testing method, rectifier, comparison

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Tämä insinöörityö on tehty ABB Oy Drives Servicelle. Työn päämääränä oli vertailla Drive Servicen korjaamoverkostolle erilaisia testausmenetelmiä tasasuuntaaja yksiköitä varten. Työ keskittyy ABB:n ACS800 ja ACS880 tuoteperheisiin, jotka käyttävät diodi tai diodi-tyristori -tasasuuntaajia. Testausmenetelmän tulisi toimia kaikilla edellä mainittujen tuoteperheiden tuotteilla. Tarkoitus on löytää luotettava ja turvallinen testausmenetelmä tasasuuntaaja yksiköitä varten. Työssä esitellään viisi erilaista testausmenetelmää ja niitä vertaillaan keskenään.

Työn alussa esitellään ABB yrityksenä lyhyesti. Seuraavaksi esitellään tasasuuntaajayksikön perusperiaate ja käyttötarkoitus. Tämän jälkeen esitellään lyhyt määritelmä diodista ja tyristorista, jonka jälkeen esitellään ABB:n tähän työhön liittyvät erilaiset tasasuuntaajayksiköt. Tämän jälkeen testauslaitteen vaatimukset selvennetään ja viimeisenä testausmenetelmät esitetään ja vertaillaan.

Tuloksena annetaan erilaisten testausmenetelmien vertailu ja kaikista sopivin Drives Service korjaamolle esitetään. Joka vertailun perusteella näyttäisi olevan lataus kondensaattori patterin avulla ja oikosulkua hyödyntäen.

Keywords	Tasasuuntaaja yksikkö, vertailu, testaus menetelmä

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Contents

List of Abbreviations

ABB	Asea Brown Boveri. Company that was formed after Swedish ASEA and Swiss Brown, Boveri & Cie united.
AC	Alternative current.
ACS800	ABB's Product Family.
ACS880	ABB's Product Family.
DC	Direct current.
DSU	Diode Supply Module / Diode Supply Unit
DSW	Drive Service Workshop. Workshop where DSU and AC drives are repaired.
IGBT	Insulated Gate Bipolar Transistor.
INU	Inverter Unit.
ISU	Insulated Gate Bipolar Transistor (IGBT) with this supply unit it is possible regenerate electricity back to grid.
LC	Liquid Cooling.
LV	Low voltage. Voltage in range 50-1000 AC and 120-1500 DC.
TSU	Thyristor Supply Unit with this supply unit it is possible regenerate electricity back to grid.

1 Introduction

Today, a frequency converter is a significant product in industry and in our everyday lives. Whether you are in an elevator, electric train, paper factory or in a building with air ventilation, most electric motors are controlled by frequency converters. Strömberg Oy (later ABB Oy) developed first frequency converters already in early 1980's among the first companies in the world. The first generation of the frequency converter was named SAMI (Strömberg's asynchronous motor inverter).

Frequency converters control the rotational speed of motors. Frequency converters can save electricity when motors are not rotating at full speed. These devices usually consist of a rectifier, DC-link (direct current link) and an inverter unit. Rectifier converts alternative current (AC) to direct current (DC) and the inverter converts DC back to AC at the desired frequency. When all these components are in one single frequency converter it is called single drive.

When all different units: rectifier, inverter etc. are individual modules and they are connected together in a cabinet, they are called multidrive. There are usually from one to five rectifiers connected to a larger number of inverter units that are controlling individual motors or many inverters are controlling single motor parallel. The rectifier unit in ABB is called diode supply module/unit or DSU.

This study focuses on five different testing methods for diode supply modules. Compared testing methods were decided in a meeting, that was held at the beginning of this study. The reason why this study was carried out, was to research the best possible way to reliably test diode supply modules for the Drive Service Workshop (DSW) network.

Testing of the diode supply modules is very important, because with proper testing faults can be found in the modules that are under repair and it ensures that already repaired modules will be working flawlessly and safely.

The tester should work on ABB's ACS800 and ACS880 frequency converter product families that use diode or diode/thyristor rectifiers. It would be optimal that the tester would load DSU at least at 500 A current and at the same time it should not take more than 200 A current from the power grid.

In this thesis, the first section introduces ABB. The next chapter is about the theory behind a rectifier, it’s structure and key components: diode and thyristor. After that ABB’s rectifiers are introduced and five different testing methods are explained. After reviewing these testing methods, the last chapter is the comparison of the different testing methods. The comparison lists the benefits and disadvantages for these different testing methods.

2 ABB Group

ABB was formed on 5th of January 1988, when two companies' the Swedish ASEA and the Swiss Brown Boveri, merged. At that time the company had revenues of over $17 billion and 160,000 employees all over the world. [1]

ABB Group is a world leading technology company that is creating industrial digitalization. ABB operates in more than 100 countries and nowadays employs 136,000 people all over the world. [2]

ABB's core is in power and automation technology and it is the world's largest electric grid builder. The company is divided to Corporate division and four product divisions: Electrification Products, Robotics and Motion, Industrial Automation and Power Grids. [3]

To maintain a position as one of the leading technology companies, ABB invests in research and development around $1.5 billion annually. [4]

2.1 ABB Finland

In 1889 the Finnish electrical company Oy Strömberg Ab was formed. After a fusion Strömberg changed name to Kymi-Strömberg Oy in 1983 and after that in 1987, Swedish company ASEA acquired Strömberg. [5]

ABB in Finland began when two companies merged in 1988, the Swedish ASEA that had bought Strömberg before and the Swiss BBC Brown Boveri. [1]

ABB Finland has over 2 billion euros turnover and the company has over 5000 employees in Finland, mostly in Helsinki, Vaasa, Hamina and Porvoo. [6]

2.2 ABB's Drive Service Workshop Finland

ABB's Drive Service Workshop Finland is the place where ABB's frequency converters and diode supply modules are repaired. The workshop offers an environment for workshop repair service, reconditioning service, drive exchange service, inspection and diagnostics service. Repairs are mainly available for product families: ACS600, ACS800 and ACS880.

The Drive Service Workshop Finland is part of a global network, where there are 18 ABB's authorized Drive Service Workshops that offer repair processes. [7]

The Drive Service Workshop Finland moved from Kiitoradantie in Vantaa to electronics factory in Pitäjänmäki, Helsinki in December 2017.

3 Rectifiers

In this chapter, rectifier's components, its structure and operating principle are introduced. The first section gives general information about the rectifier and explains why rectifier is needed in a frequency converter. After that, the key components diode and thyristor are introduced and at the end of the chapter different rectifier structures are presented.

A frequency converter's structure is: a rectifier, a DC-link and an inverter unit (Figure 1). First the rectifier converts alternative current (AC) to direct current (DC) to the DC-link. The DC-link usually has a coil and a capacitor to smooth DC waves and current spikes. The inverter converts DC back to alternative current (AC) for the motor. The chosen output frequency of the inverter will determine the rotating speed of the motor.

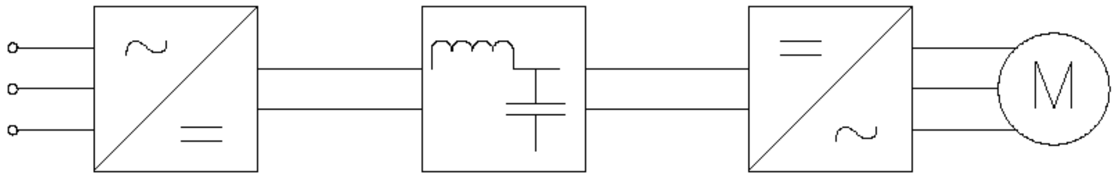

Figure 1. Single drive frequency converter's structure.

As shown in Figure 1 above from left to right there is a rectifier, DC-link, inverter and the motor. If this all is built within one module, it is called a single drive. This study will concentrate on multidrive units. In a multidrive these structures are in separate modules that are connected to each other in a cabinet. This setup makes it possible to connect multiple inverters and rectifiers in the same cabinet. In a multidrive if one module needs maintenance it can be replaced more quickly.

3.1 General

In electrical distribution, alternative current (AC) has been used for a long time because of its benefit for low power loss in long distance distribution. With high voltage and low current, distribution losses are kept at minimum.

In electronics direct current (DC) is commonly used, depending on the product. To get DC from our home socket, it needs to be converted with a rectifier. These rectifiers are very common in electronics. Most devices that have electronics and does not have battery, need a rectifier.

The rectifier is the part that converts AC to DC. In low power systems this is done usually with diodes. In high power electronics thyristors, diodes or both of them. This thesis focuses on rectifiers that use diodes or thyristors and diodes. Next diodes and thyristors are explained. It is crucial to understand these first, before moving to more advanced structures, like rectifiers.

3.2 Diode

A diode is an electric component that passes current only in one direction. It has two terminals: anode and cathode (Figure 2). When current is flowing from anode to cathode, the diode's resistance is almost zero. This state is called forward biased. However, diodes need a certain amount of voltage before they start to conduct. That is called the cut off voltage of the diode. Ideally, the cut off voltage would be as close to zero as possible. [8]

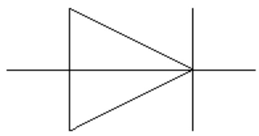

Figure 2. Diode's electric symbol. On the left-side is Anode and on right-side Cathode. The current passes from left to right.

A diode blocks current flow in the opposite way when voltage is positive in cathode and negative in anode. This state is called reverse biased. When reverse biased the diode has a very high resistance. Ideally in this situation the diode's resistance is infinite. When reverse biased, a diode passes some leakage current and if voltage is raised enough, the diode breaks down and starts to conduct again (Figure 3 below). [8]

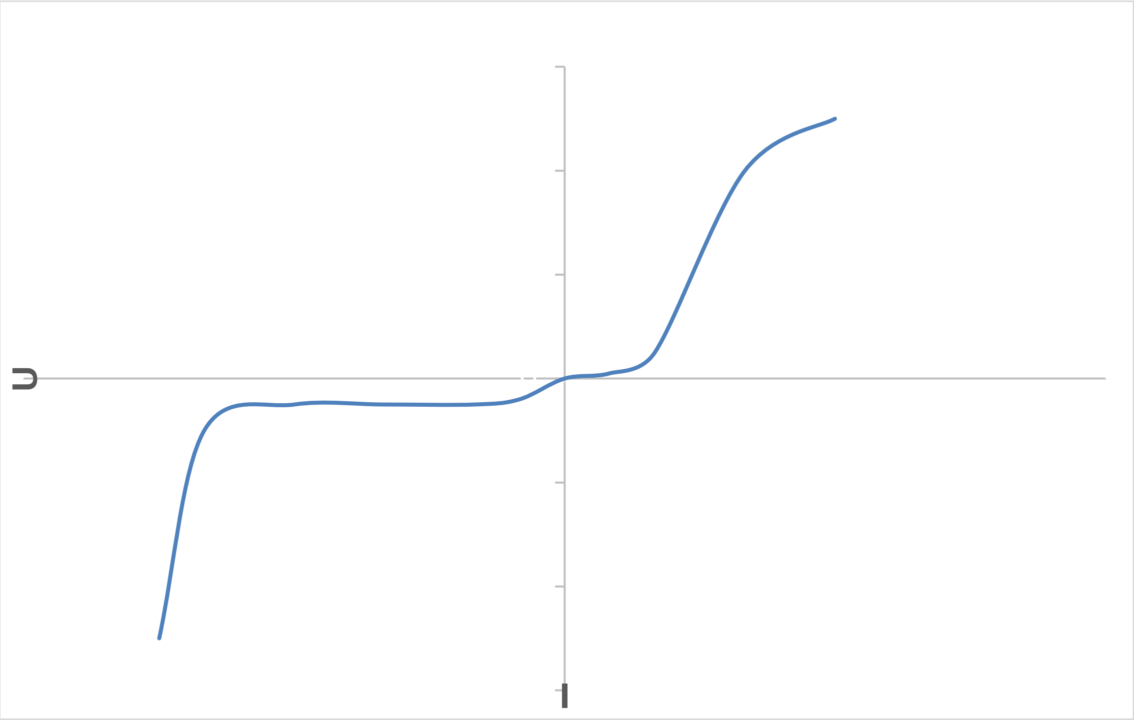

Figure 3. The static diode characteristic.

Diodes are commonly used in electronics, for example, in rectifiers, to block current flow in the wrong direction and to keep the circuit voltage under the cut off voltage.

Today most of the diodes are semiconductors, but before inventing semiconductor there were vacuum tubes that were used like diodes. These days they are used almost only in some high-fidelity (Hi-Fi) sound technology.

3.3 Thyristor

A thyristor is an electric component with three terminals: anode, cathode and gate. Thyristor works like a "controlled diode". Thyristor can start conducting at the desired time and that ability is used for an example to lower voltage on one sine wave during capacitor loading (see 3.5 Thyristors Loading Ability in DSU).

Thyristor works like a diode it also passes current in one direction, see Figure 4 below. However, if there is a positive voltage in forward direction, thyristor needs also a positive voltage pulse in to the gate, to start conducting. The thyristor stays in conduct mode as long as there is enough voltage in anode to get over cut off voltage. [8]

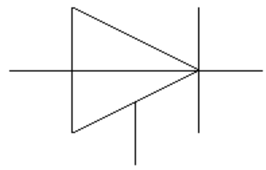

Figure 4. Thyristor’s electric symbol. The current passes from left to right. On the left side is anode, in the middle facing down the gate and on the right side the cathode.

A thyristor can operate in three different ways: forward blocking, when there is a positive voltage on anode, but there hasn’t been a voltage pulse to the gate; backward blocking, where thyristor’s diode is blocking voltage from cathode to anode; forward conduction, where thyristor is conducting voltage from anode to cathode. [9]

A thyristor is also a semiconductor and it has the highest power tolerance of all semiconductors. That’s why it is commonly used in high power electronics. A thyristor’s backward blocking and forward blocking endurance are high and the component can handle high current. Ideally, when the thyristor is conducting, the cut off voltage should be as close to zero as possible and when the thyristor is backward blocking the leaking voltage should be as small as possible.

It is quite rare that thyristor’s leaking voltage would be a problem, but the cut off voltage can be around 1 - 4 V. In some cases, that could lead to problem. Another noticeable thing is, that when the thyristor is switching from blocking to conducting mode, there can be a momentary power loss. [8]

Power control with a thyristor can be done by adjusting thyristor's fire angle. This means that when a single-phase sine wave, that remains positive for 180° in one sine wave cycle, is inputted trough thyristor, it starts to conduct at a certain point. That point can be controlled by the fire angle **α**. For example:

- If the fire angle is 0° the thyristor works like a diode and the whole positive side of the sine wave is conducted.

- When the fire angle is 180° the thyristor doesn't conduct at all.

- When the fire angle is 90° the thyristor conducts half of the positive sine wave.

In most cases this fire angle can be controlled only from 0° to 90°, which means that voltage can be controlled from 100% to 50%. Increasing the fire angle will cause more ripple current, but it will not have a big effect on the sine voltage peak value. [8]

The following equation shows voltage drop when increasing thyristors fire angle. [8]

$$U_{\mathrm{AV}} = \frac{2\sqrt{2}}{\pi}\frac{\hat{u}\alpha}{\sqrt{2}}\cos\alpha \qquad (1)$$

Û = Voltages peak value

α = Thyristor's fire angle

3.4 Rectifier's Structures

Rectifying means converting AC to DC. Rectifying often causes some problems such as ripple voltage, the remaining cyclic variation of the power supply's DC voltage, which has been rectified from AC source. The ripple is caused by incomplete suppression of alternating sine wave following the rectification. [8]

There are many different types of rectifiers. In single-phase systems there are for example half wave rectifier, four-diode full wave rectifier and a two-diode full wave rectifier.

Rectifiers composed from at least four diodes are called diode bridges. In power electronics three-phase systems are usually used six-pulse rectifier and a twelve-pulse rectifier being the most common rectifier types.

A single-phase half wave rectifier consists of only one diode. It passes current in the positive side of the sine wave and blocks on the negative side (or if the diode is reversed it passes the negative side and blocks the positive side). These half wave rectifiers are easy to make because there is only one diode in them.

A Half wave rectifier makes much more ripple current and 5^{th} and 7^{th} harmonics to AC input than full wave rectifiers. Also, half wave rectifier loads the grid unstably because of its ability to produce DC only half of the time, see Figure 5 below. Because of these problems, half wave rectifiers are not used in power electronics. [8]

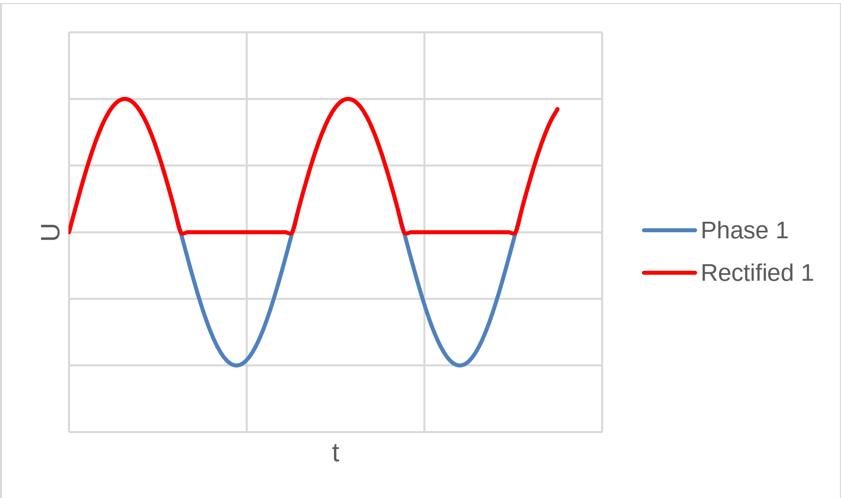

Figure 5. Example of input AC and rectified output. As shown, negative side of sin wave is left out in single phase half wave rectifier.

A single phase full wave rectifier with two diodes has quit simple structure. In consist of two diodes and a transformer. One of the rectifier’s benefits is, that there is only one diode in serial for both positive and negative side. That way the cut off voltage is lower. One of its disadvantages is that rectifier needs transformer with center-tapped secondary winding (Figure 6).

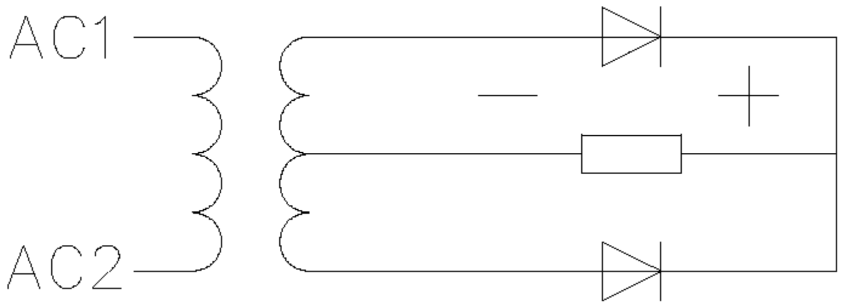

Figure 6. Full wave rectifier with two diodes.

A single phase full wave rectifier can be built from four diodes. This is probably the most commonly used rectifier in low power electronics, although it has a higher threshold voltage than a full wave rectifier, with two diodes.

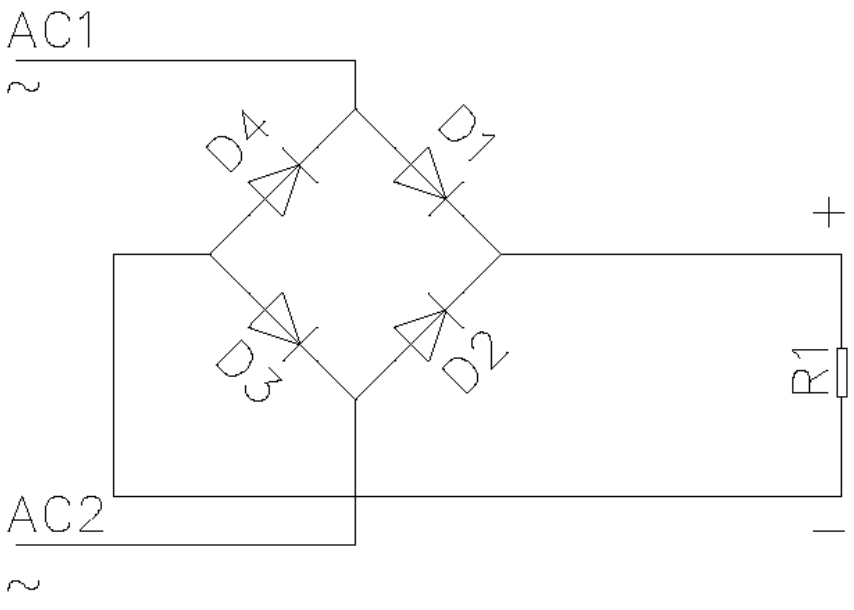

Figure 7. Four-diode full wave rectifier.

In a four-diode full wave rectifier there are always two diodes in series. It passes current through, on two different routes depending on the sign of the input sine wave. When AC1 is on the positive side of the sine wave, current goes through the diode D1 to the resistor R1 and then back through the diode D3 to the neutral AC2. Then in the opposite phase, when the AC1 is on the negative side of the sine wave, current flows from neutral AC2 to the diode D2 to the resistor R1 and then back through the diode D4 to the negative AC1, see Figure 7 above.

Without any filtering, rectifier's DC voltage is very wavelike and looks not pure direct current at all, see Figure 8 below. Therefore, a filtering capacitor is connected next to the diode bridge to smoothen the DC voltage.

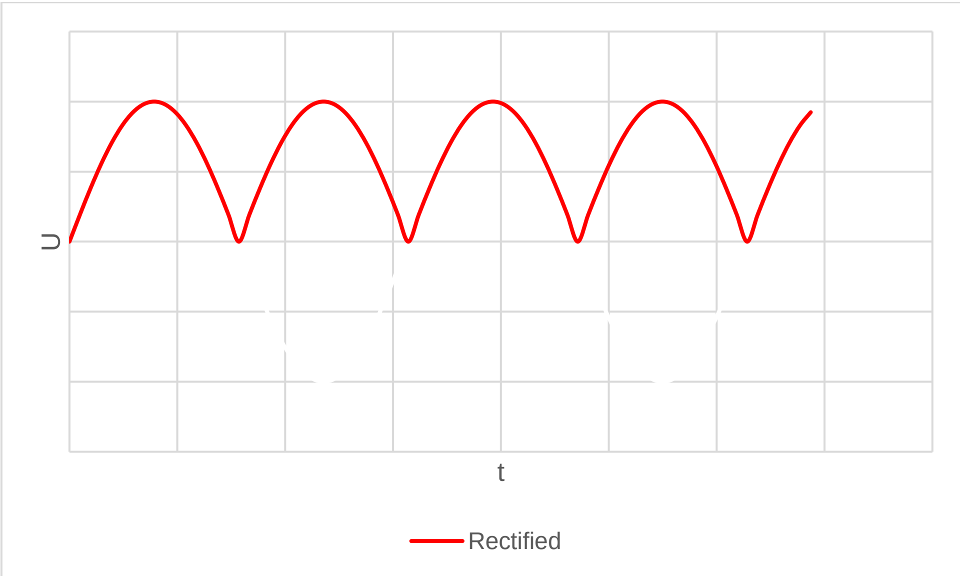

Figure 8. Unfiltered rectified DC output is very wavelike. This can be smoothened with filtering capacitor and choke.

A four-diode full wave rectifier is commonly used in low-power electronics, but in industrial applications which demands high-power electronics, mainly three-phase systems are used. 3-pulse-, 6-pulse- or 12-pulse rectifiers with higher power tolerance and more stable output DC, makes them more suitable for high-power systems.

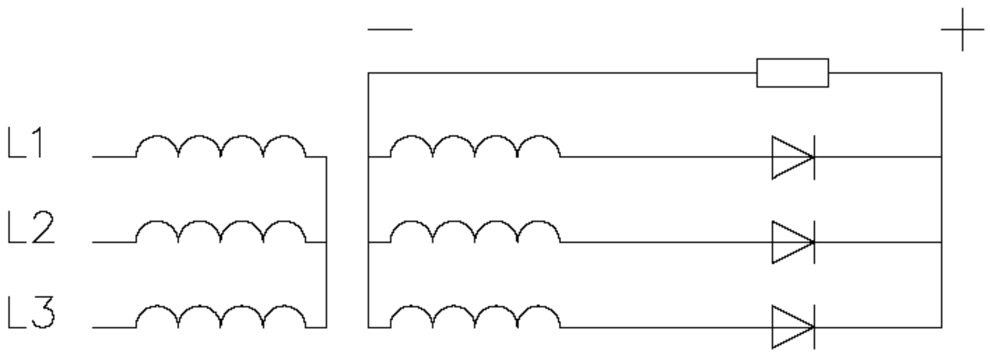

Figure 9. 3-pulse rectifier.

A 3-pulse rectifier consists of three diodes, one for each phase (Figure 9). 3-pulse rectifier needs an extra neutral wire to be connected to the transformers zero point. 3-pulse rectifier causes much more ripple and 5th and 7th harmonics than the 6-pulse version. Also, the DC output is much wavier compared to the 6- or 12- pulse versions. One of 3-pulse rectifiers benefits is, that there is only one diode in serial on each phase and the cut off voltage is then lower than in 6-phase and 12-phase rectifiers. On the downside, 3-pulse rectifier needs an extra neutral wire. [8]

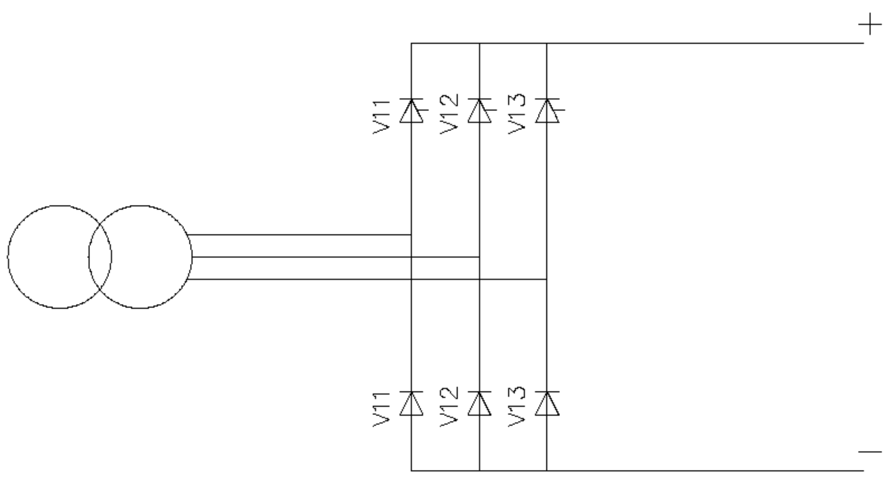

Figure 10. 6-pulse semi-controlled rectifier.

A 6-pulse rectifier uses three thyristors and three diodes or six of either one. When there is three of both, they are called semi-controlled rectifiers (Figure 10). In the Figure 10 above, there are three thyristors in the positive side of the rectifier and three diodes on the negative side. In a solid state when there is a continuing current, each diode or thyristor carries current for period of 120°.

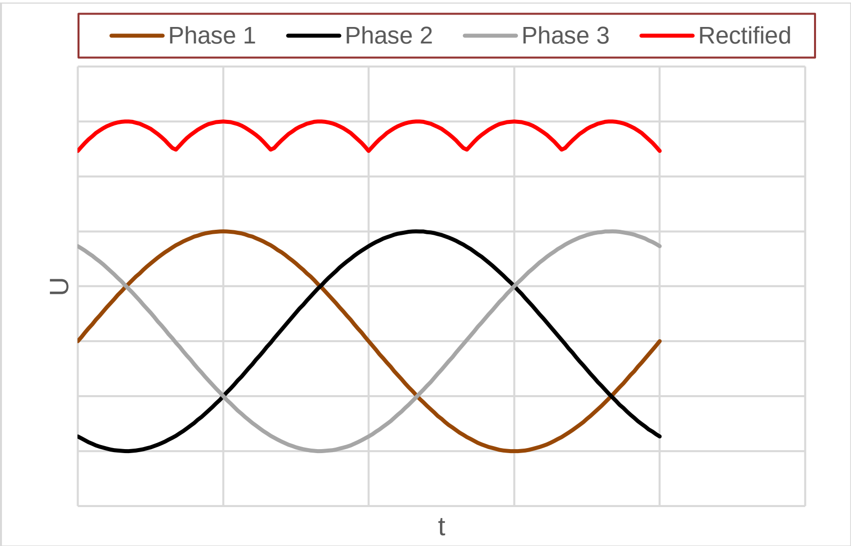

Figure 11. Example of 6-pulse rectifier output and input. A three-phase AC input and above the unfiltered output are shown.

6-pulse rectifiers are very commonly used in DSU's. They have two 3-pulse rectifiers in series, inside of them. They output the double amount of DC, compared to 3-pulse rectifier and they output less ripple current and 5th and 7th harmonics than 3-pulse, but more than 12-pulse rectifier (Figure 11). [10]

12-pulse rectifiers are more advanced and they have double the amount of sine wave inputs. As a result, the output DC is much more stable and less wavy (Figure 12). 12-pulse rectifier is commonly used when high supply is needed or total harmonic distortion is needed to be decreased.

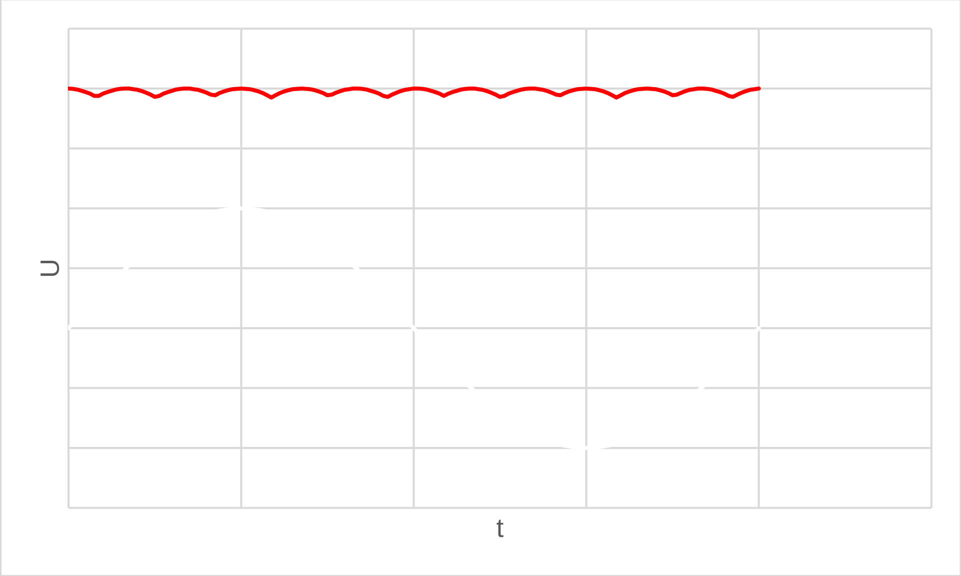

Figure 12. 12-pulse rectifier unfiltered output

12-pulse rectifiers are made of two 6-pulse rectifiers in parallel. 12-pulse rectifier has six inputs and they are connected to multiple winding transformer. With one primary coil that is connected to grid and two secondary coils that are connected to delta and to the star. These connections are made to get 30° phase difference between 12-pulse rectifier's two different 6-pulse rectifiers. With this connection DC output is much more stable and connection reduces greatly the ripple current and the 5th and the 7th harmonics that are fed back to the supply network (Figure 13). [10]

12-pulse rectifier can be also connected to transformer without multiple windings, but then 12-pulse rectifier will run as two 6-pulse rectifiers in parallel and DC output will be also like in 6-pulse rectifier.

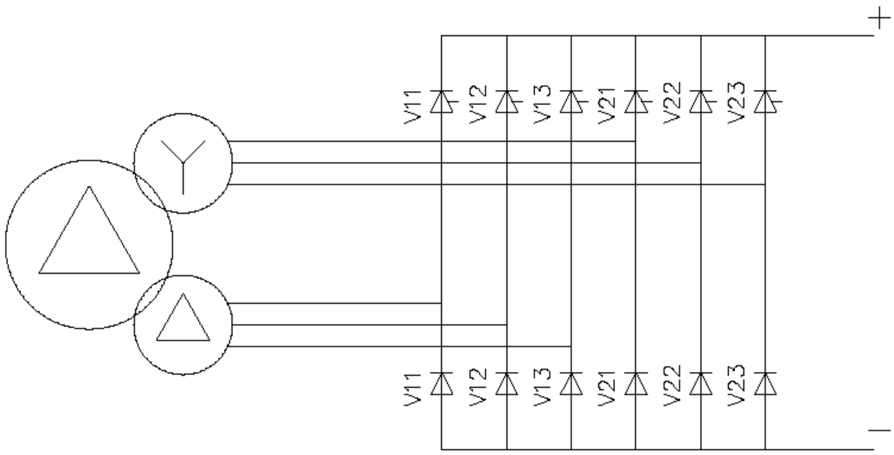

Figure 13. 12-pulse rectifier connected to delta and star coils.

ABB uses two 6-pulse rectifiers in parallel on 12-pulse rectifies. They could also be connected in series, that way it would double the output voltage. In ABB common DC voltage in multimode DC-link is 1000 V DC. So, there is no need to double the output voltage. Benefit for the parallel connection is power tolerance for components.

3.5 Thyristors Loading Ability in DSU

Half-controlled rectifiers can load capacitors on DC-link in a controlled matter. Loading happens right after DSU is started, loading usually takes about two to ten seconds and during that time the rectifier slowly lifts DC voltage up to its nominal. This helps conductors to stay unharmed and extends lifetime.

Here is example of how DSU can load capacitor in a controlled matter by controlling thyristor’s fire angle:

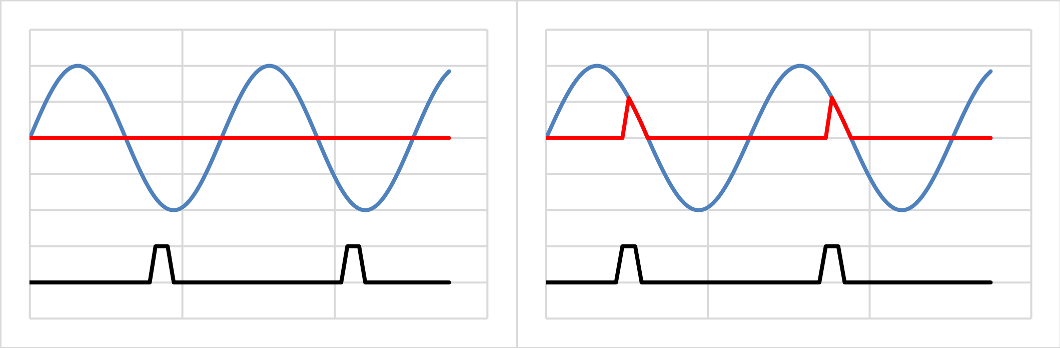

Figure 14. Thyristor gate control 1 in single phase, the blue line is sine wave, the red line is sinewave after the thyristor and black line is the pulse coming to the thyristor’s gate.

First gate pulse hits negative wave form of the sine wave. So, the thyristor does not fire at all. Second pulse on the right side of the Figure 14, is the first pulse that hits positive side of the sine wave and the thyristor starts to conduct. The thyristor stays conducted as long as the sine wave stays on the positive side. [11]

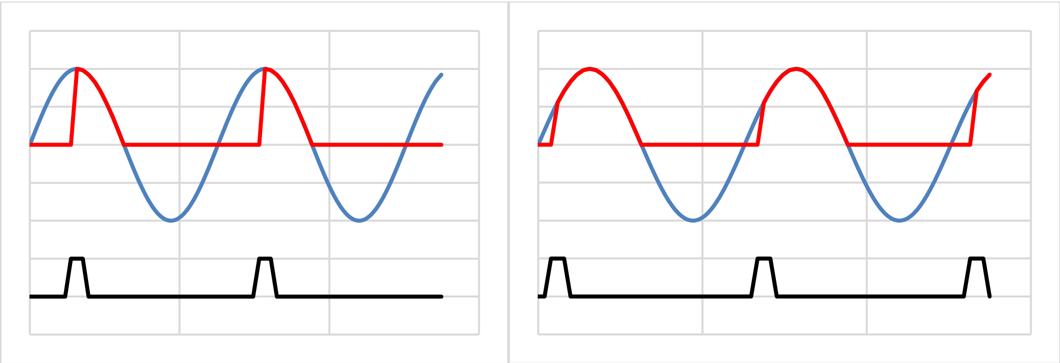

Figure 15. Thyristor gate control 2 in single phase

On every new positive sine wave the thyristor starts to conduct more. As shown in Figure 15 above, thyristor conducts half of the sine wave with 90° fire angle on left and almost hole sine wave on the right side of the figure. [11]

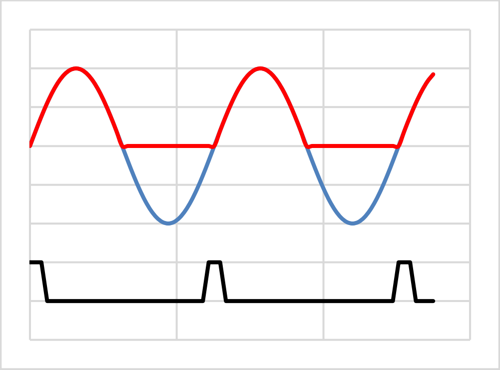

Figure 16. Thyristor gate control 3 in single phase

In Figure 16 the thyristor is working on fire angle 0° and the whole sine wave is conducted in the same way as the diode. [11]

With thyristor gate control some DSUs can also lower DC voltage constantly on DC-link. This happens in the same way as shown above, but with constant gate control on specific angle so that the DC voltage will lower on the desired level.

4 ABB’s Diode Supply Modules

This chapter introduces all the different ABB’s diode supply modules, that are considered in this study. These modules are half-controlled thyristor-diode rectifiers and diode bridge rectifiers from ABB’s product families ACS800 and ACS880.

The diode supply module/unit (DSU) is a 6-pulse or a 12-pulse rectifier. They can be made from diodes, thyristors or both of them. This thesis considers only those DSUs that are built from diodes or diodes and thyristors.

The issue with testing is the variety of modules. It can be harder to find a reliable tester for so many different modules at a low cost.

Some modules have a choke in them, which is used to smoothen the DC-link voltage and to prevent current spikes.

Some modules also include contactors. The main contactors are used in emergency stop and in some DSUs capacitor loading is connected through loading resistor so that the capacitor loading will happen in limited current.

The volume of DSU repairs in single workshop is in year bases about 30 modules. In future the volume may increase since ACS880 production will increase and at some point, post-manufacturing will begin with DSUs and they will be tested at DSW test site.

Here are few ABB’s abbreviations that are needed to know to fully understand some of the testing methods:

- ISU (IGBT Supply Unit) is used to regenerate electricity back to grid. (IGBT is high power bipolar transistor. IGBT’s advantage is current endurance when in contacting mode and voltage endurance when blocking mode. IGBT also has very low voltage- and power losses.)

- TSU (Thyristor Supply Unit) is thyristor made rectifier that has ability to regenerate electricity back to grid.

- INU (Inverter Unit) is used to control motor.

- LCL (inductor - capacitor – inductor) filter that is used to filter voltage.

4.1 Multidrive

In ABB, most of the industry’s frequency converters come in multidrive. In these cabinets the common voltage is up to 1000 V DC.

A benefit of multidrive is that energy can flow via the DC-link from one generating motor to another driving one. This can happen, without braking chopper or the regenerative supply unit. This can save some energy. It also helps to save at installation, cabling and maintenance costs.

4.2 ACS800

In the ABB’s ACS800 product family, there are two different rectifier frame sizes (This means the actual power of the module) D3 and D4. One to five DSU modules can be installed in parallel to multidrive, depending on the need of power. Within these frame sizes there are 6-pulse rectifiers that are all frame sizes D3 and bigger 12-pulse rectifiers that are all D4.

ACS800-704

ACS800-704 DSU comes with 690 V voltage class only. If lower voltage is needed, it can be done just by lowering the input voltage at desired voltage. This DSU does not have any controlling ability.

ACS800-704 is a “Basic model” with a 12-pulse rectifier, it has two 6-pulse rectifiers in it. These both work individually or in parallel. With only one rectifier it runs in 6-pulse mode or with two rectifiers in parallel it runs in 12-pulse mode. This DSU comes with two sizes 640 kW and 910 kW.

ACS800-304

ACS800-304 DSU is the “Half model” of ACS800-704. It is basically the same DSU as the 704, but there is only one 6-pulse rectifier in it. There is only a 690 V model with two sizes 320 kW and 450 kW.

ACS800-304/704 +V992

ACS800-304/704 +V992 DSU is basically the same as ACS800-304 and ACS800-704, but with a control board. This helps it to control the thyristors fire angle and to limit current.

ACS800-304LC D3LC

ACS800-304LC D3LC is a liquid-cooled 6-pulse DSU with diode bridges. It doesn’t have any controlling ability.

ACS800-704LC D4LC

ACS800-704LC D4LC is a liquid-cooled 12-pulse DSU with diode bridges. It doesn’t have any controlling ability.

4.3 ACS880

ACS880 DSUS have three different frame sizes 6, 7 and 8. In the ACS880 product family the last three characters of the model’s name will tell: the frame size and the bridge’s key components. Here are some examples:

- D6D = Diode, frame size 6, diode. This DSU is frame size 6 and has a diode bridge in it.

- D7T = Diode, frame size 7, thyristor. This DSU is frame size 7 and it has a half-controlled diode thyristor bridge.

In the ACS880 product family most DSUs are 6-pulse models. Two DSUs can be installed in parallel on multiple winding transformer to get a 12-pulse mode (Figure 13 above).

In ABB's DSUs have plus codes and here are meanings of different pulses:

- +A003 6-pulse, uncontrolled diode bridge
- +A018 6-pulse, half controlled diode bridge
- +A004 12-pulse rectifier [12]

ACS880-304+A003 DXD

ACS880-304+A003 modules are manufactured in three different frame sizes 6, 7 and 8. They are all uncontrollable diode bridge DSUs.

These rectifiers power range is from 55 kVA to 850 kVA

ACS880-304+A018 DXT

ACS880-304+A018 modules are manufactured in two different frame sizes 7 and 8. They both have controllable diode and thyristor bridges with the capacitor loading ability.

These rectifiers power range is from 450 kVA to 5 445 kVA

5 Workshop Testing Procedure

Every time a new module is taken to repair there are a few standard steps that need to be taken care of in the first place. Visual inspection, basic measurements, insulation resistance test, water pressure test (on water cooled units only) and main circuit test are crucial and are performed every time. After these tests, comes the loading test where DSU is loaded with high current. This will ensure that DSU will endure high current.

5.1 Visual Inspection

The first step is to visually inspect that everything looks normal and module has not taken any damage from shipping. After that module is opened and ensured there is not too much dirt or dust inside the module, to prevent components from overheating. Then all the wire connections must be ensured that they don't have any bad connections. Also, to visually check that the module has no corrosion in it and if the module is water cooled, that water hose connections are undamaged.

All the detected faults will be entered in the repair report.

5.2 Basic Measurements

After the visual inspection, basic measurements are carried out. These are done by using a multimeter. Most of the faults in components/modules are found during these basic measurements. The following components are part of the basic measurements with the multimeter:

- Rectifier's diodes and thyristors
- Thyristor's gates
- Onboard fuses
- Power converters and thermostats

- Contactors

Sometimes faults can be hidden and basic measurements will not reveal them. Because of the hidden faults the testing method is crucial.

5.3 Insulation Resistance Test

In the insulation resistance test, ground leaking is tested. Before the test can begin, all inputs and outputs are short circuited and resistance is measured between all inputs/outputs and the module frame, see Figure 17 below.

An insulation resistance tester has two DC outputs that are used in this testing. There is a positive wire and a negative wire, the positive wire is connected to all inputs and outputs that are short-circuited and the negative wire is connected to the module's frame. This measurement is done by ramping the voltage slowly up to 1000 V DC and at the end the tester will measure the resistance between the positive and the negative wire. This resistance should be more than 50 MΩ.

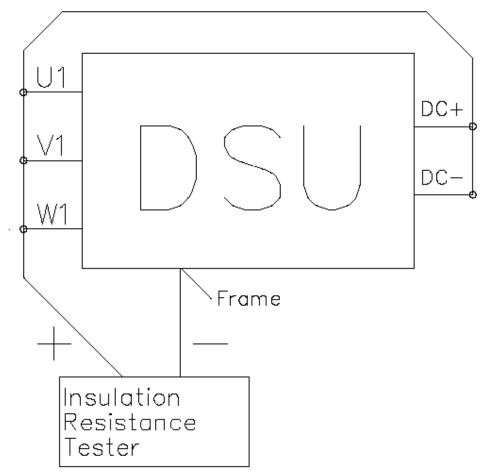

Figure 17. Insulation resistance test

5.4 Water Pressure Test

The water pressure test is done only to water-cooled modules. The purpose of this test is to make sure that modules are waterproof.

First the module is filled up with in water such way that there are no air bubbles in it. Then pressure is raised up to 10 bars (must not exceed that) and the pressure is held for 30 minutes. Pressure should not drop more than two bars, during that time. If pressure has not dropped over two bars in 30 min, the module is rated waterproof.

5.5 Main Circuit Test

Before the actual loading test, main circuits need to be tested that the module will endure voltage. This is done by lifting voltage slowly up to modules nominal, without any load. After voltage is at module's nominal, DSU's DC voltage is measured. If DC voltage is at nominal, then voltage is lowered back to zero and next step is to test with a load.

6 Requirements of Testing

The testing of the modules is crucial because, with the right kind of testing, it can be ensured that: hidden faults in modules can be found, the modules are repaired properly and modules are safe to use.

The testing should expose hidden faults, that cannot be revealed by visual inspections or basic measurements, like loose joints or wires with bad connection. These kinds of faults occur over time or during repairs due to human error, and they must be exposed through the testing.

Tester should also save testing data to the cloud or in to the PC automatically, so it would be easier to investigate failure rates and overall testers working in future.

Requirements for the tester:

- Tester should be able to load DSU at least 500 A
- Tester should not take more than 200 A from the grid
- Tester should work with both thyristor/diode and diode rectifiers
- Tester should reveal DSU's hidden faults
- Tester should save testing data to cloud or in PC
- Target price should be under 30 000€

7 Different Testing Methods

All the different testing methods, are first introduced here.

1. Testing with motors is a test where two motors are connected mechanically together. First motor is rotating loaded and second motor is braking and converting rotating energy to electricity.

2. Testing with resistance is a test where DSU module's output is connected to short circuit and another module is limiting current to around 500 A.

3. Testing with capacitor is test where capacitors are loaded with DSU and graphic illustration is taken from the charging time.

4. Testing with resistance and capacitor includes two tests where first test is the same as testing with capacitor and second test is where modules output is connected to short circuit, but on the input side voltage is lowered with stepdown transformer to 12 V.

5. DxT full load tester is a test where DSU's DC output is converted back to AC and with step up transformer it is lifted back to DSUs input.

The comparison is in the next chapter.

7.1 Testing with Motors

This testing is also known as the back-to-back test. This testing method needs:

- One DSU, that is being tested

- One thyristor supply unit (TSU)

- Two inverters that are working as the inverter unit (INU)

- One IGBT supply unit (ISU)

- Two motors, one working as a motor and another working as a generator

The first DSU rectifies DC voltage for the Inverter unit. That inverter runs the motor that is mechanically connected to the generator. This generator generates electricity while it brakes the spinning motor. The generated electricity flows to the ISU which is converting AC back to DC. After that, the breaking TSU pushes the electricity back to the grid. That way the current cycles through all the modules and the load is possible to get to the nominal point. The only limitation is that the motor's nominal current cannot be exceeded, see Figure 18.

To run this testing method first, motor is slowly lifted to nominal speed (rounds per minute) whiteout any breaking from generator. After nominal rotation is reached and if everything seems to be fine, DC generation from ISU can began. Carefully ISU's DC generation is lifted to that point that DSUs current is 500 A. After 500 A is reached it should be held for one hour.

A benefit of this test is that only the losses from the motors are taken from the grid. A problem with this testing method is that it is very expensive because it requires two very large motors to achieve the required DSU load of around 500 A.

Below the losses calculated with two 500 kW motors that were used in the old Kiitoradantie Drive Service Workshop.

$$P_N = 500\ kW$$

$$P_{Motor} = \sqrt{3} * U_N * I_N * Cos\varphi = \sqrt{3} * 690\ V * 505\ A * 0{,}86 = 519\ kW \qquad (2)$$

$$P_{Loss} = 2 * (P_{Motor} - P_N) * t = 2 * (519\ kW - 500\ kW) * 1\ h = 38\ kWh$$

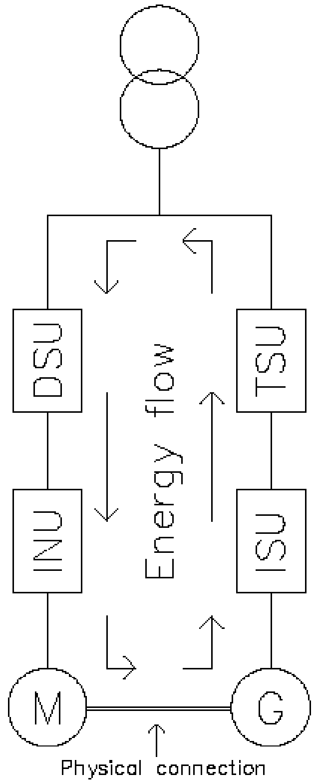

Figure 18. Back to back motor generator system.

This testing method is the most expensive one of the comparison. One 500 kW motor will cost around 30 000€ and after cabling and installation costs the whole testing method would cost over 100 000€.

7.2 Testing with Resistance

Testing with resistance is a testing method, where DSU's input is connected to current limiter and output is connected to a short circuit. At the beginning of the test, the current is limited to almost zero and voltage is raised to nominal point at the DSU's input. Then current is slowly lifted to the desired point (around 500A) and when this is achieved, actual current measurements are done. This test will reveal hidden faults like loose joints.

This testing method is currently only tested with DC frequency converters (frequency converters that controls DC motors) that have control ability, but in theory this testing method should work on DSUs that have control ability. (Figure 19).

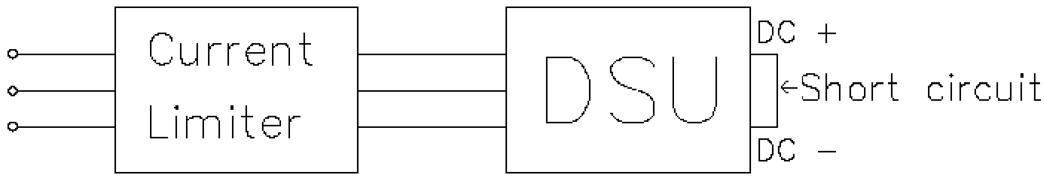

Figure 19. Testing with Resistance.

This testing method will get to the desired current load, but it is not energy efficient so testing time should be very short. Also, this testing method will take high current from the grid which means that the cabling costs would be substantial.

7.3 Testing with Capacitor

In this testing method the DSU module loading capacitors and a resistor connected in series. The purpose is to measure how long it will take for the DSU to load the capacitors. This loading will only take about 0.5 second and the tester will print a result as graphic illustration on a computer screen, see Figure 22 below.

Like in Figure 20 shown below:

- The blue and the red curves present currents that are compared to each other's. Both from DSUs different diode bridges (12-pulse rectifier). Ideally, they are the same.

- The violet curve present capacitors charging time as voltage.

- Black curve presents the RMIO's (RMIO is ACS800 product family's control card) analog input. It detects possible earth fault. This should be always zero.

- The graphic illustration is taken from a working DSU. There is no current oscillation and the voltage raises smoothly.

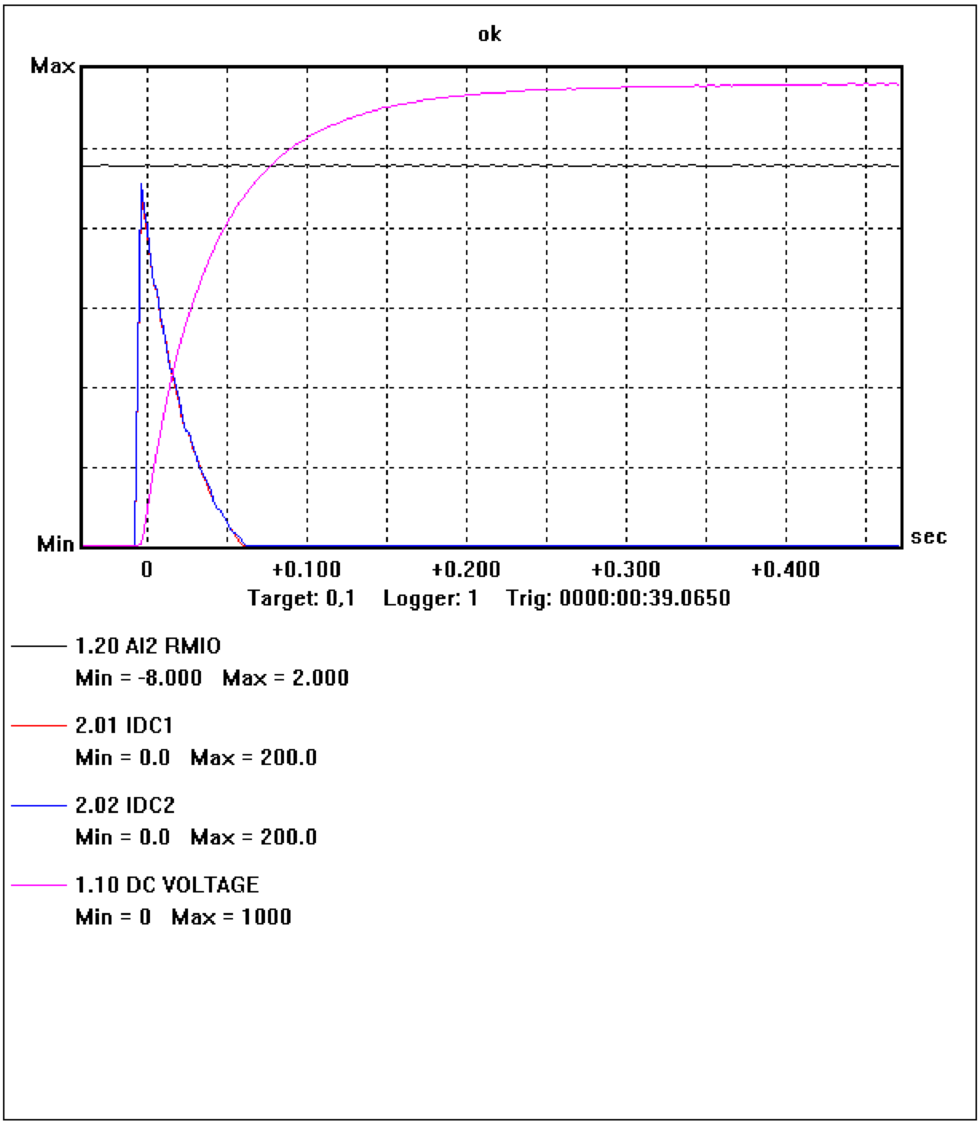

Figure 20. Testing with Capacitor Graphic Illustration

To operate this testing method first nominal voltage is given to DSU's input. Then capacitor loading test can began. First contactor is closed and capacitor loading begins. With time relay (value 0.5 seconds) this test opens contactor automatically and then prints graphic illustration. In another tester the closing time is done by measuring DC voltage, when DC voltage exceed given value it will start 0.5 seconds timer and after that opens contactors.

Figure 21 below shows a failed test on the capacitor loading test. As shown, voltage raises almost same way, but current curves and RMIO's have oscillation. This picture is taken from printed paper because this device doesn't save pictures of failed tests.

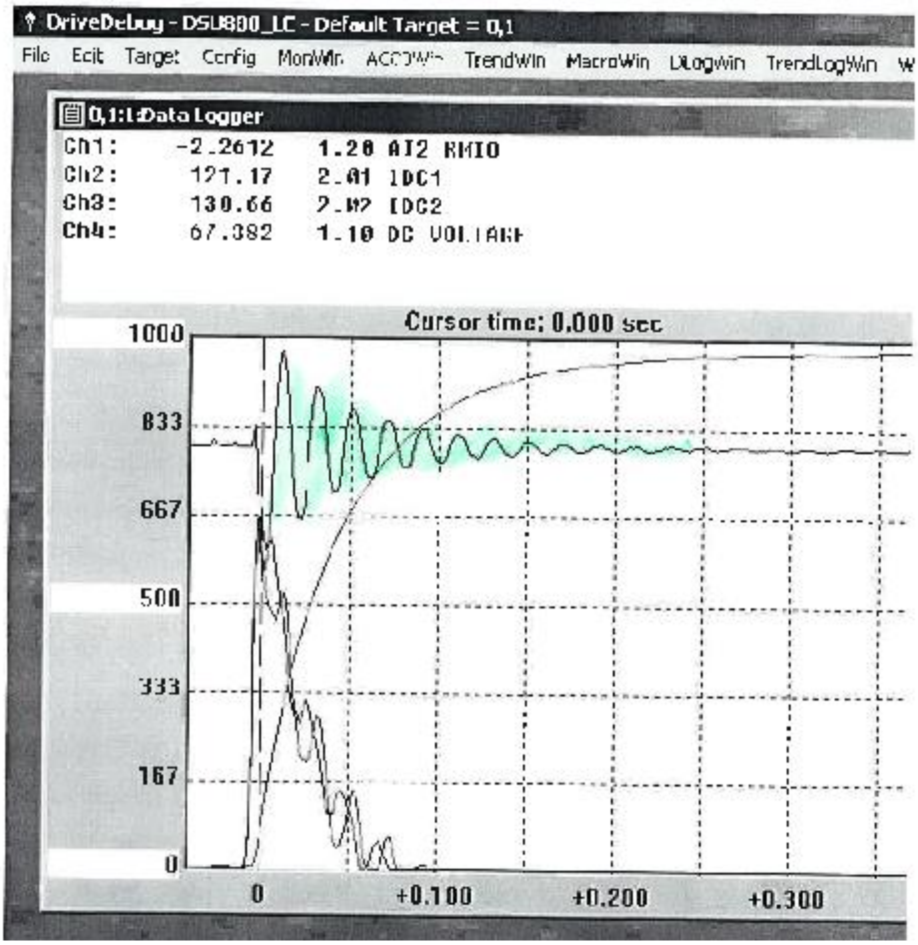

Figure 21. Testing with Capacitor Graphic Illustration 2.

In this study, there was two different testing with capacitor methods. Both of them were studied during this work. The one is for ACS800 liquid cooling (LC) modules and another is for ACS880 LC modules. They are both made for only diode bridge DSUs, but it is possible to order/build a new kind of tester that would have all the different control cards for DSUs that are to be tested.

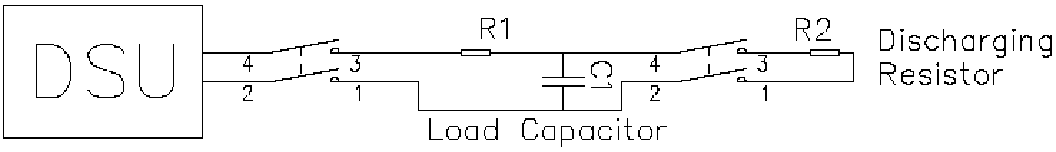

Figure 22. Testing with Capacitor.

This testing method will take only about 0.5 seconds (Figure 23). So, the losses on this testing method are very low, because the test will only take milliseconds and losses will only take place in that time.

Figure 23. Testing with capacitor.

There are two types of this tester, in other one it is up to the person who is testing to decipher this graphic illustration and to decide by analyzing it, whether the module is working or not. So, there are no limit values and no endurance testing. If lack of limit values is considered as a risk they can be inserted to the new tester.

7.4 Testing with Resistance and Capacitor

Testing with resistance and capacitor, combines two of the previous testing methods: testing with resistance and testing with capacitor, but in a little bit different way.

The purpose is, to first load the DSU with nominal voltage to test voltage endurance. After voltage is raised and DC voltage is settled, the capacitor loading test begins. As shown in the previous chapter, the capacitor loading test will be executed in the same way (Figure 22). If this test will be successful and everything looks fine, the next step is to wait for the capacitors to discharge.

After the capacitors have been discharged, the next step will be the short circuit loading test. This test is done with step down 10 kVA transformer (690V / 12V) on AC side before the DSU's input. With low voltage and high current, the DSU is loaded around 300 A, this part of the test will reveal hidden faults like loose joints (Figure 24). This part of the test will take only about one seconds and it is done by using time relay. At that time all power will be losses, but with the step-down transformer losses would not be a problem.

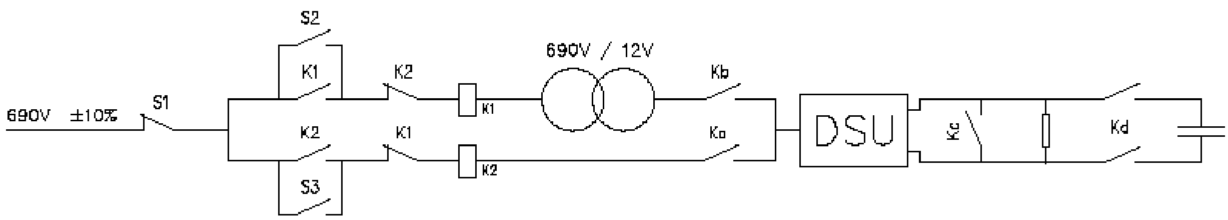

Figure 24. Testing with Resistance and Capacitor

Testing with resistance and capacitor consists of holding circuit, step down transformer, tested DSU, power resistance and capacitor as shown in Figure 24. Holding circuit will prevent from two lines to be powered on at the same time. Power resistance will work on discharging capacitors and on second test short circuit loading test.

The problem with this testing method is same as the difficulty in this study: the variety of different DSUs. This tester will not work with ACS800-304/704. The first test with the capacitor will work with all DSUs.

Second test section, short circuit test with 12 V on input side and short circuited with resistance on output side. This will work on diode bridge DSUs easily, but with half-controlled DSUs it will need a certain service program. This program will force thyristors to fire without nominal voltage on DSU's input. Whiteout this there will be no DC voltage on output side. This way the current can be reduced and losses would be much lower. This would be possible to do on nominal voltage, but the losses would be too great. This testing method will also need external control voltage for to work with half controlled DSUs.

7.5 DxT Full Load Tester

The DxT full load tester is tester that uses transformer to lift voltage back to DSU. With that tester, it is possible to test up to four supply units at the same time. The tester is built for testing manufactured supply and inverter units. DSW Finland has no need to test four supply units at the same time since the testing volumes are much lower in DSW. So, it would be easier and less expensive to make one tester for DSW Finland.

The tester works on cycling energy through the tested module, by lifting voltage up with a 630/690v transformer between the ISU and the DSU.

DSU raises DC voltage to DC-circuit. Where IGBT supply unit (ISU) converts DC voltage back to AC voltage. Voltage is smoothened with LCL filter (inductor - capacitor - inductor) and next the energy goes to the transformer, that raises voltage 630/690 V. The primary coil is at the end of the ISU's output and the secondary coil is at the input of the tested DSU module. That way the energy would cycle between circuit and only the losses would be taken from the grid. In theory, this could load testing module around 500 to 1000 A, see Figure 25 below.

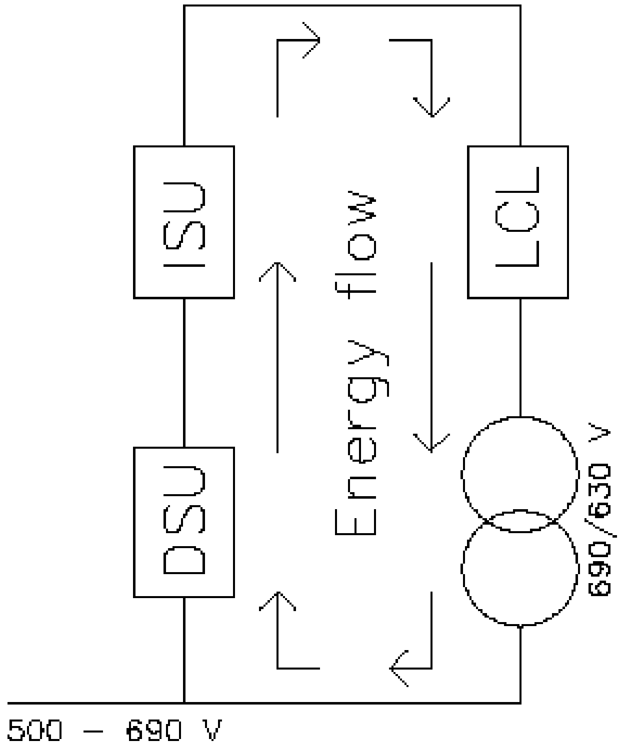

Figure 25. DxT Full Load Tester

DxT full load tester has not worked at full load, because of the ripple and harmonics that would distort other devices on the grid. On the other hand, ABB Finland's tester would be only about a quarter of original tester and ripples and harmonics would also be around a quarter of the originals.

The original DxT tester has 1.5 MVA transformer. If DSW Finland would consider this tester, much smaller transformer would be enough.

Here is calculation for apparent power for transformer.

$$Sn = \sqrt{3} * 690\ V * 500\ A = 597\ 558\ VA \quad (3)$$

For this system 600 kVA transformer would load DSU at 500 A and that transformer would cost around 15 000€.

The losses would be almost only transformers losses. There are also internal losses on the tested modules but they would be somewhere between zero to one percent. Systems total losses are counted for five percent. [13]

Losses would be around: $\sqrt{3} * 690\ V * 500\ A * 0.05 * 1h = 29{,}88\ kWh$ (4)

8 Comparison

In this chapter, the key criterions of this comparison are clarified. Then all the different testing methods are compared with all their disadvantages and benefits. Then at the end of this chapter comparison chart (see Table 1) is given.

This comparison will criterion on:

- Cost of the tester
- Testing reliability
- Energy efficiency
- Testing time
- The required space
- Compatibility with different DSU

Testing with Motors

This testing method can load DSUs to the nominal point and the losses would not be very big issue.

Positive side of this testing method is from the customer's side of view is the reliability of this test. Many customers find it very reliable to test modules with the actual motors. As a customer's point of view this would be the best solution.

The cost of this testing method is massive. There would be no interest to invest that kind of money at this volume of DSU repairs. Other issue would be cabling costs, at the ABB's factory in Pitäjänmäki, all the motors are in separate motor room and the cabling costs would easily tenfold.

Benefits of testing with motors:

- It is very reliable
- Can load DSU to nominal point
- Small losses at testing
- Works with all DSUs

Disadvantages of testing with motors:

- Very costly
- Motors would take a lot of space

Testing with Resistance

This testing method can load the DSU to nominal point, but it is not at all energy efficient. All the power will be losses, so it would be quite costly to use and it will take more from the grid than 200 A. So, there will have to be powerful feed for this one and this one will not work with most of the DSUs.

Benefits of testing with resistance:

- Can load DSU close to nominal point
- It is not very costly to build
- It will not take much space

Disadvantages of testing with resistance:

- Will take more than 200 A from the grid

- Will not work with most of DSUs
- Power losses

Testing with Capacitor

This testing method loads capacitors and takes graphic illustration of it. By collected data it seems to be quite reliable testing method and it doesn't cost much. Testing time is very short and the tester doesn't take much floor space, but it also doesn't load the DSU much and it will not reveal all hidden faults like loose joints.

Benefits of testing with capacitor:

- Cost
- It will not take much space
- It is energy efficient
- Works on every DSU

Disadvantages of testing with capacitor:

- It will not load DSU much

Testing with Resistance and Capacitor

This testing method is combination of two different tests. It will test nominal voltage on the DSU when loading the capacitors and high current with low voltage when short circuited. It doesn't take much space and it will not take much current from the grid.

Benefits of testing with resistance and capacitor:

- Cost
- It will not take much space
- It is energy efficient
- It will load DSU with 300 A

Disadvantages of testing with resistance and capacitor:

- Short circuit will not work on ACS800-304 and ACS800-704

DxT Full Load Tester

This testing method is quite massive and expensive, but it would be a reliable testing option. There have been some issues with the original tester, but DSW Finland's tester would be much smaller. That would remove some of the issues in this testing method.

Benefits of DxT Full Load Tester:

- It is reliable
- Can load DSU around 500 A
- It is energy efficient
- Works with all the DSUs

Disadvantages of DxT Full Load Tester:

- Requires much space
- Costly

Comparison chart:

Table 1. Comparison chart.

	Cost estimate	Reliability	Energy efficiency	Testing time	Required space	Different DSU combability
Testing with motors	Over 100 000€	Reliable	Good	1 Hour	Very much	All of them
Testing with resistance	Around 10 000€	Reliable	Very bad	Some seconds	One cabinet	Only controlled DSUs
Testing with capacitor	Around 20 000€	Doesn't load DSU	Good	Some seconds	One cabinet	All can be attached to this
Testing with resistance and capacitor	Around 30 000€	Reliable	Good	Two short tests	One cabinet	Resistance test works only with controlled DSUs
DxT full load tester	Over 100 000€	Reliable	Good	1 Hour	Very much	All of them

8.1 Interviews

Ten people were interviewed during this study. Interviewed people have been around in DSU testing and developing different testing methods. Everyone seems to have their own opinion on testing DSUs, but everyone seemed to agree on that some testing method for DSU is necessity.

It was also found out that there are not much problems with DSUs testing without high-power. They seem to be in most cases working, or not working at all. DSUs have quite simple structure and they don't seem to have much faults that haven't been seen at tests like loading with capacitor.

There have been few cases that these basic testing methods haven't been enough for DSU testing. For these kind of situations, the testing with resistance and capacitor is recommended. With this testing method it is possible to find out most of the hidden faults within DSUs.

9 Conclusions

The purpose of this study, was to search for the best possible way to reliably test DSUs. Possible testing methods for DSU were discussed in a meeting that was held at the beginning of this study. Four different testing methods were chosen and a fifth method came along the research.

Within this time that this study had. There was a lot from learn in DSUs and different test methods. It was hard to account for everything that will affect the testing. It is also quite hard to compare totally different testing methods to each other. Also cost of the testing methods are estimate of the cost and they are calculated for building tester in ABB, not ordering one from elsewhere.

It is important to collect data from future DSU testing methods, to keep track of the testing methods' reliability and on failure rate of the DSUs. It would be optimal that this information would download to ABB's cloud or on PC automatically.

After studying different testing methods for this study, the first conclusion is that all of these testing methods are better than not having one at all besides basic measurements. They reveal faults better than basic measurements, which will only test individual components with multimeter and that will not necessarily reveal faults.

The conclusion is that at this volume of DSU repairs, there is no need for a massive test line that can load a DSU around 500 A. Most of the faults have been seen with these tests like testing with capacitor or testing with resistance and capacitor. If volume would be higher, then I would recommend the DxT full load tester, to get current load closer to nominal point.

It is recommended that DSW Finland would build a tester that will test with resistance and capacitor. This would be the best possible way to test modules with this volume of DSUs and as well to prepare to test post-manufactured DSUs. This testing method would be much more reliable than the current testing method.

For DSW network it is recommended to build testing with capacitor or testing with resistance and capacitor depending on volume of DSUs.

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