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Inverter sizing principles and selectivity analysis for a high-powered energy storage system

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HUTTUNEN, MATIAS:
Vaihtosuuntaajan mitoitusperiaatteet ja selektiivisyyden tarkastelu suuritehoiselle energiavarastojärjestelmälle

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Risteilyalusten sähkönkulutus lisääntyy jatkuvasti samalla, kun maailmalla pyritään ympäristöystävällisempään suuntaan. Laivan generaattoreilla vastataan vaihtelevaan kuormitukseen muuttamalla koneiden säätöä. Kuormituspiikkeihin voidaan kuitenkin vastata suuritehoisella akustolla, jota ladattaisiin silloin, kun tehontarve on pienempi. Akustoa käytettäisiin myös satama-alueilla, joissa varustamo saa vähennettyä pääkoneista aiheutuvia päästöjä saaden itselleen ympäristöystävällisemmän imagon.

Paras vaihtoehto akustoteknologialle on litium-ioni akku, jonka energiatiheys ja elinikä ovat parempia kuin lyijyakuilla. Akusto liitettäisiin valvontajärjestelmään, joka valvoo akun kuntoa ja lataustasoa. Akusto vaatii vaihtosuuntaajan, jonka avulla se liitetään laivan vaihtosähköverkkoon. Tämän opinnäytetyön tarkoituksena oli tutustua suuntaajien mitoitusperiaatteisiin ja tuoda esille huomioon otettavat asiat niitä mitoitettaessa.

Vaihtosuuntaaja sisältää puolijohdekytkiminä toimivia komponentteja, joiden hilaohjauksen avulla muunnetaan tasasähkö sinimuotoiseksi vaihtosähköksi. Suuritehoisten suuntaajien tehoelektroniikan komponentteina voidaan käyttää tyristoreita, GTO-tyristoreita (Gate Turn-Off) tai IGBT-transistoreita (Insulated Gate Bipolar Transistor). Vaihtosuuntaajia ja sen komponentteja suojataan katkaisijoiden releiden lisäksi RC-suojilla ja varistoreilla varustetuilla ylijännitesuojilla.

Akuston oikosulkuvirran syöttökyky on huono. Akusto syöttää 200-kertaisesti kymmenen tunnin purkausvirtaa oikosulkuvirtana tasasähköpuolella, joka on keskijännitekiskostossa hyvin pieni oikosulkuvirta ja koituu selektiivisyydelle ongelmaksi. Akuston nimellisvirta on työssä pienempi kuin hotellijakelun nimellisvirta, jolloin suojareleiden virtaporrastusta ei saada selektiiviseksi. Selektiivisyyden saavuttamiseksi ainoa vaihtoehto on suojien laukaisuaikojen porrastus. Porrastukseen vaihtoehtoja ovat joko releiden aikaporrastus tai lukitussuojaus. Lukitussuojaus vaatii erilliset moduulit jokaiselle katkaisijalle, jotka keskustelevat toisiensa kanssa väylän välityksellä. Vyöhykeselektiivinen toiminta aukaisee aina lähimpänä vikaa olevan katkaisijan, jättäen muun verkon toimintaan.

Yksittäinen energiavaraston hankinta voi koitua kuitenkin kalliiksi, varsinkin jos toimintaa ei ole testattu riittävästi laivaverkossa. Asennettuja järjestelmiä löytyy kuitenkin jo paljon pohjoismaisista pienistä autolautoista, mutta todellisia kustannuksia on vaikea arvioida. Energiavarasto kuitenkin voisi olla varteenotettava kehitysaskel kohti energiatehokkaampia laivoja.

Asiasanat: energiavarastojärjestelmä, akusto, vaihtosuuntaaja, selektiivisyys

ABSTRACT

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Inverter sizing principles and selectivity analysis for a high-powered energy storage system

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Cruise ship loads are constantly expanding while world is moving towards ecological direction. Generators of the ship are adjusted when the loads are alternating. High-power energy storage can be used in peak load managing. Energy storage can be charged when electric usage is lower. In addition the batteries are used in harbors where the ship owners can reduce emissions caused by main engines, gaining more environmentally friendly and greener image.

Best battery technology is lithium-ion battery because of its better energy density and lifetime compared to lead-acid batteries. Batteries are connected to management system that monitors state of charge and condition of the battery cells. Batteries require inverter in order to connect them to the alternating current grid of the ship. The purpose of this thesis was to study the principles of design for inverters and to display matters to take into account.

Inverter consists of semiconductor power electronic components which are controlled with gate pulse in order to convert direct current to alternating current. Thyristors, GTO-thyristors (Gate Turn-Off) or IGBTs (Insulated Gate Bipolar Transistor) can be used as components in high-powered converter design. Inverters and power electronics are protected with RC-snubbers and surge arresters containing varistors.

The short-circuit capability of batteries is poor. Batteries feed short-circuit current of 200-times of its ten hour discharge current. Short-circuit current level is low when transformed to medium voltage bus. It causes problems to protection selectivity. The nominal currents of batteries are lower than the nominal current of the hotel distribution. Current selectivity cannot be achieved. Time selective action is the only option in order to reach selective protection. Time selective action is achieved by modifying setting of the relay or by interlocking. Interlocking requires additional module to every breaker which are connected together with bus. Zonal protection opens the circuit breaker nearest to the fault point.

Ordering a single energy storage can be expensive especially if the functions are not properly tested in the ship. Already operating systems can be found in ferries of the Nordic countries. Real expenses are hard to estimate. However energy storages could be the next step towards more energy efficient ships.

Key words: energy storage system, batteries, inverter, selectivity

CONTENTS

ABBREVIATIONS AND TERMS

AC	Alternating Current, Compressor motor
Ah	Amp-hour
BMS	Battery Management System
BT	Bow Thruster
DC	Direct Current
DG	Diesel Generator
DOD	Depth of Discharge
EMC	Electromagnetic compatibility
EMS	Energy Management System
ESS	Energy Storage System
GOOSE	Generic Object Oriented Substation Event
GTO	Gate Turn-Off
IGBT	Insulated Gate Bipolar Transistor
ISO	International Organization for Standardization
LC	Inductor-capacitor
LCL	Inductor-capacitor-inductor
Li-ion	Lithium-ion
MV	Medium Voltage
kA	Kilo-ampere
kWh	Kilowatt-hour
PAM	Pulse Amplitude Modulation
PMS	Power Management System
PWM	Pulse-Width Modulation
RC	Resistor-Capacitor
RMS	Root Mean Square
RMU	Ring Main Unit
SOC	State of Charge
ST	Stern Thruster
SOLAS	Safety of Life at Sea
VAr	Volt-Ampere reactive
ZSI	Zone Selective Interlocking

A	Initial value of the decaying component, A
$C/10$	10 hour discharge current, A
c	Voltage factor
$\cos \varphi$	Power factor
E''_M	Subtransient voltage of an asynchronous motor, V
E''_{q0}	Subtransient q-axis voltage of a synchronous generator, V
E'_{q0}	Transient q-axis voltage of a synchronous generator, V
I_{acM}	AC-component of the short-circuit current, A
I_{dcM}	DC-component of the short-circuit current, A
I_k	Short-circuit current, A
I''_k	Initial symmetrical short-circuit current, A
I''_{kd}	Three-phase subtransient short-circuit current of a synchronous generator, A
I'_{kd}	Three-phase transient short-circuit current of a synchronous generator, A
I_{kd}	Three-phase steady state short-circuit current of a synchronous generator, A
I''_{kmax}	Maximum short-circuit current, A
I''_{kmin}	Minimum short-circuit current, A
I_M	Short-circuit current of an asynchronous motor, A
I''_M	Subtransient short-circuit current of an asynchronous motor, A
I_N	Nominal current, A
I_p	Peak short-circuit current, A
I_{rM}	Rated current of an asynchronous motor, A
I_0	Pre-fault current, A
k	Factor for X/R ratio
n	Rotation speed, 1/min
P_e	Electrical power, W
P_k	Transformer load losses, W
pu	Relative per unit value
R_a	Stator resistance of a synchronous generator, Ω
r_k	Relative per unit short-circuit resistance
R_k	Short-circuit resistance, Ω
r_m	Relative resistance of an asynchronous motor

R_M	Resistance of an asynchronous motor, Ω
r_r	Relative rotor resistance
R_r	Rotor resistance, Ω
r_s	Relative stator resistance
R_s	Stator resistance, Ω
S_N	Nominal power, VA
t	Time duration from the beginning of the short-circuit, s
T'_d	Transient time constant for synchronous generator, s
T_{dcM}	DC time constant of an asynchronous motor, s
T''_M	Subtransient time constant of an asynchronous motor, s
$T/2$	Half periodic time, s
u_k	Relative short-circuit voltage
U_N	Nominal voltage, V
U_{rM}	Rated voltage of an asynchronous motor, V
U_0	Pre-fault voltage, V
x''_d	Relative d-axis subtransient reactance of synchronous generator
X''_d	Subtransient reactance of a synchronous generator, Ω
x'_d	Relative d-axis transient reactance of synchronous generator
X'_d	Transient reactance, Ω
x_d	Relative d-axis reactance of synchronous generator
x_k	Relative short-circuit reactance
X_k	Short-circuit reactance, Ω
x''_M	Relative subtransient reactance of an asynchronous motor
X''_M	Subtransient reactance of an asynchronous motor, Ω
Z''_d	Subtransient impedance, Ω
Z'_d	Transient impedance, Ω
z_k	Relative short-circuit impedance
Z_k	Short-circuit impedance, Ω
z''_M	Relative subtransient impedance of asynchronous motor
Z''_M	Subtransient impedance of an asynchronous motor, Ω
Z_N	Nominal impedance, Ω
ω_r	Rated angular velocity, rad/s
φ	Phase angle

1 INTRODUCTION

Main engines in the ship are connected to generators which generate electricity to ship. Running main engines forms emissions which are not considered favorable image for ship owners especially near the small Caribbean islands. Zero emission is aim in the modern world. However it is impossible for large cruise ships to reach that target with current technology but improvement to that direction can be made. Using energy storages near harbors brings greener appearance for ship owners.

The aim of this thesis is to study what things must be taken into account to reach selective protection when designing a large scale energy storage integrated into the power grid of the ship. The energy storage contains chemical energy which is transformed to electrical energy. Batteries operate in DC (Direct Current) which must be converted to AC (Alternating Current) with inverter in order to be able to connect it into the AC electric distribution system. The starting point to this research is that suppliers have brought up an issue where they had to oversize an inverter to ensure the selective protection of the grid.

Research process begins by modifying the power plant single line –diagram by adding the energy storage system (ESS) into the grid. Short-circuit calculations are made to inspect the selectivity of the protection. The purpose is to study how the selectivity can be achieved and how inverter design affects selectivity. Purpose of use for this system is to feed power from the ESS in harbors providing greener and non-polluting appearance and a good image for the corporation. Regulations for power feeding to hotel distribution and propulsion of the ship are examined.

This thesis is made in co-operation with Meyer Turku Oy. Meyer Turku is shipbuilding company owned by German Meyer Werft located in Papenburg. Along with Meyer Turku, Meyer Werft owns also shipyard in Rostock Germany named Neptun Werft. Meyer Turku has operated from year 1737 with many different names. Three separate shipyards together forms a world leading shipbuilding complex. Meyer Turku improves constantly the energy efficiency of the ships with advanced working methods.

2 ENERGY STORAGE AND CONVERTERS

2.1 Energy storage system

Energy storage is needed to store the produced energy. The purpose of the energy storage system is to provide additional energy to electrical grid of the ship. Main power is generated from the main engines. Energy storage system contains BMS (Battery Management System), an energy storage and inverter which converts DC to AC. Inverter needs to be bidirectional so that power direction can be both in and out of the energy storage.

There are multiple uses for energy storage. Energy storage can be used before the main engines are started. In addition, generators can be used in constant power and let the energy storage deal with the peak load. Energy storage is charged when consumption is less than generation. The power from energy storage is mainly used to support propulsion and cover a part of the hotel load of the ship. (Siemens n.d., 57.)

Batteries are connected to BMS that monitors them for their state and performance and operates the battery protection from short-circuit and thermal impact. Cell voltages cannot be guaranteed to be equal when charging with constant current constant voltage –charger. In order to ensure Li-ion (Lithium-ion) -battery safety, BMS must prevent cell voltages from exceeding cell voltage limit. So in other words BMS must control charging so that it turns charger off when Li-ion battery reaches its full charge and also turns it on when battery voltage has decreased below set limit. BMS also needs to monitor and control the charging and discharging current. BMS ensures the maximum lifetime for Li-ion cells. (Thurner 2016, 41.)

2.1.1 Battery as energy storage

Batteries change electrical energy to chemical energy and vice versa. Batteries that can be recharged are specified as secondary batteries. Battery consists of electrolytic cells that contain positive and negative electrode, which are called cathode and anode, and electrolyte between them. Electrolyte conducts ions between positive cathode and negative anode. However the electrolyte functions as an electronic insulator so that cell would not be in internal short-circuit and self-discharge because of it. Most of used electrolytes are acids, alkalis and salts. Connecting multiple cells in series forms a battery. Figure 1 presents the operational principle of battery: when load is connected between two electrodes, electrons move from anode to cathode and current begins to flow into opposite direction. (Dell etc. 2001, 10.)

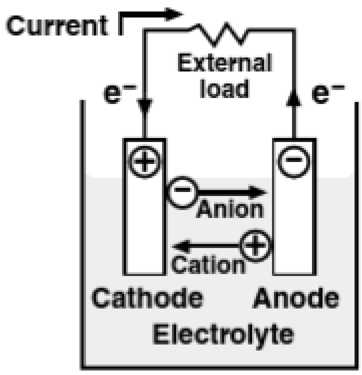

FIGURE 1. Cell chemistry (Dell etc. 2001, 11)

To form a high energy density battery, the electrodes need to be as close each other as physically is possible. A thin separator is placed between the electrodes to insulate them from each other. In order to read mΩ level for internal resistance, the separator needs to be about 1 mm thick. High internal resistances lead to massive voltage drops in high-power systems. (Dell etc. 2001, 11-12.)

Each battery and each cell has its own SOC (State of Charge). BMS monitors both battery and cell SOC so that they do not exceed limited voltage levels. SOC is measured in percent from full charge that is 100 % to 0 % when it is empty. The DOD (Depth of Discharge) for battery or cell is informed as Ah (Amp-hour). It is not informed as percent because DOD is not dependent of SOC. If battery or cell capacity is decreased to 60 percent of its original capacity, SOC will still be measured from 0 % to 100 %. However DOD is more informative when its value is equal to cell actual capacity after the decrease. (Andrea 2010, 18-19.)

Battery is exposed to internal leakage. Over time the battery becomes unbalanced because of the internal leakage. The cells of the battery need to be balanced in order to maximize the usable capacity of the battery (figure 2).

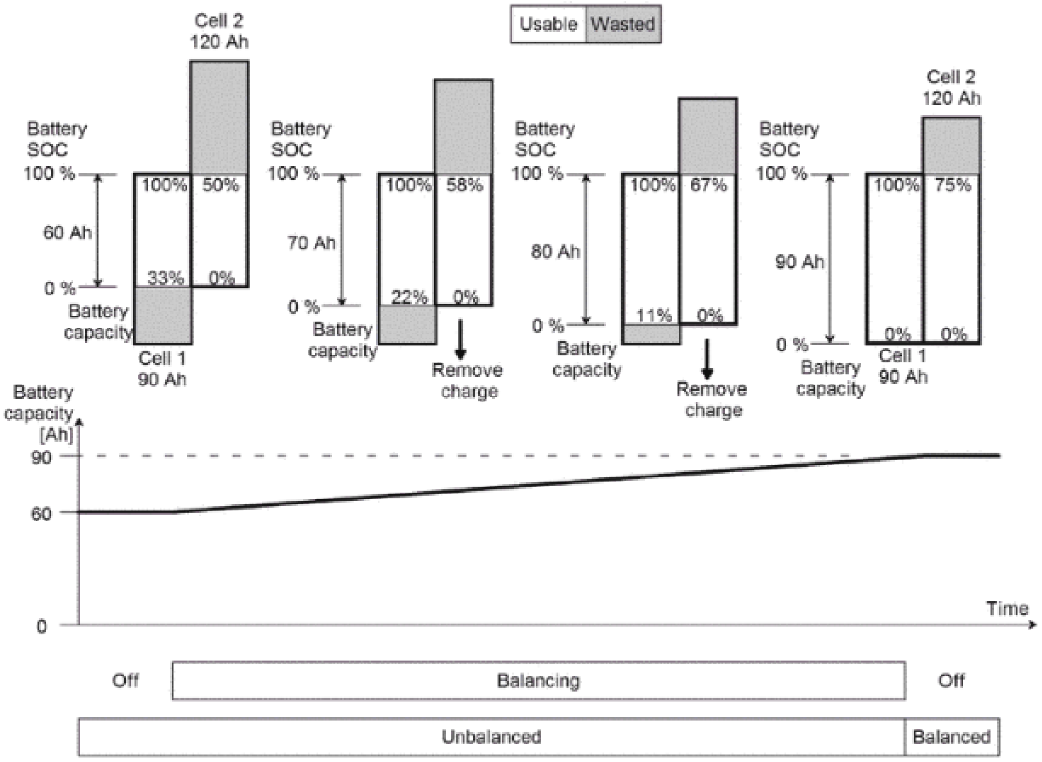

FIGURE 2. Cell balancing to maximize capacity (Andrea 2010, 27)

Balancing is usually done in 100 % SOC and by moving Ah from first cell to second cell as in figure 2. The capacity is increased because the battery 100 % SOC is limited to first cell to become full and 0 % SOC to first cell becoming empty. In the first part, there is 60 Ah capacity for the battery and the second cell limits the 0 % SOC and the first cell the 100 % SOC. The first cell is turning Ah over to second cell when its SOC is decreasing under 100 %. Second cell capacity is increased as nothing limits it. In this case, the capacity is increased by 50% when the cells are balanced. (Andrea 2010, 27.)

2.1.2 Rules and regulations by classification society

Classification society sets standards to ship installations and procedures that needs to be followed. Important and essential systems need acceptance from the classification society. Classifications are based on the SOLAS (Safety of Life at Sea) convention. Most common classification societies are DNV-GL, RINA, Bureau Veritas and Lloyd’s Register. In this thesis the focus is on DNV GL classifications.

DNV GL classification society demands that lithium cells must be tested according to IEC 62619 standard which includes safety requirements for secondary cells containing alkaline or other non-acid electrolytes. Cell tests include external short-circuit, impact, thermal abuse, overcharge and forced discharge tests. In addition, DNV GL accepts these tests to be made according to IEC 62281, UN38.3 or similar standards. Battery system is also tested according to IEC 62619. Tests include internal thermal event, overcharge with voltage, overcharge with current, overheating control, sensor failures, cell balancing SOC validation, safety function test, capacity validation, high voltage test, insulation resistance and pressure test for cooling system if the cooling is executed with liquid. For environmental tests, DNV GL requires vibration, dry heat, damp heat, flame retardant and EMC (Electromagnetic compatibility) to be tested. Flame retardant is tested according to IEC 60092-101 if flammable materials are used in installation. (DNV GL 2015, 8-9.)

For supply voltage variations, DNV GL sets limit of ±2.5 percentage variation for steady-state nominal AC voltage. This means that when the bus bars are supplied with variable DC levels, AC-side voltage variation must not exceed limits. Also for AC-side, transient state limits are set from -15 % to +20 %. For DC bus considered as main distribution board the voltage tolerances are from +30 % to -25 % for equipment connected to batteries during charging and from +20 % to -25 % for equipment connected to battery that is not charged. In addition, voltage cyclic variation is limited to 5 % and voltage ripple to 10 %. However these DC bus regulations are considered for DC distribution. Frequency variation is limited to 5 % for steady load and 10 % for transient load. A single harmonic cannot exceed 5 % of nominal frequency and total harmonic distortion cannot exceed 8 % limit according to IEC 61000-2-4. (DNV GL 2017a, 28-29.)

Battery power regulations must be followed if ESS is used to support propulsion. Larger systems than 50 kWh (kilowatt-hour) must follow battery safety regulations. Battery safety includes for example explosion, fire risk and gas development. Energy management system (EMS) is needed if battery is used for propulsion support. In propulsion use, Navigation Bridge must have remote monitoring access to EMS and remote emergency disconnection possibility. EMS may be integrated in BMS but it may also be separate system. Battery spaces must be ventilated in case of the toxic vapors of the battery. Ventilation can also be used in cooling but liquid cooling is also acceptable. Battery spaces must have fire detectors and to be integrated in fire safety system. In addition, the spaces must have water-based extinguishing system. Short-circuit and overcurrent protection is handled with switchgear. (DNV GL 2017b, 12, 17-20, 116-117.)

2.2 Inverter

Inverter converts DC to AC with frequency needed. Inverter consists of power electronics components, which need to be precise and reliable in order to operate properly. When converter is bidirectional, it operates as inverter and rectifier depending on the conversion direction. High frequency harmonics are formed from inverter switching operation. The formed output frequency is controlled with PWM (Pulse-Width Modulation). Frequency is higher when one cycle time is pulsed faster. PWM produces different width pulses so that when the pulse lines are integrated, the output voltage imitates sine wave. Larger switching frequencies produce purer sine wave. Basic circuit is presented in figure 3. (Hietalahti 2011, 87; Larminie & Dicks 2003, 344; Mohan etc. 2003. 225-226.)

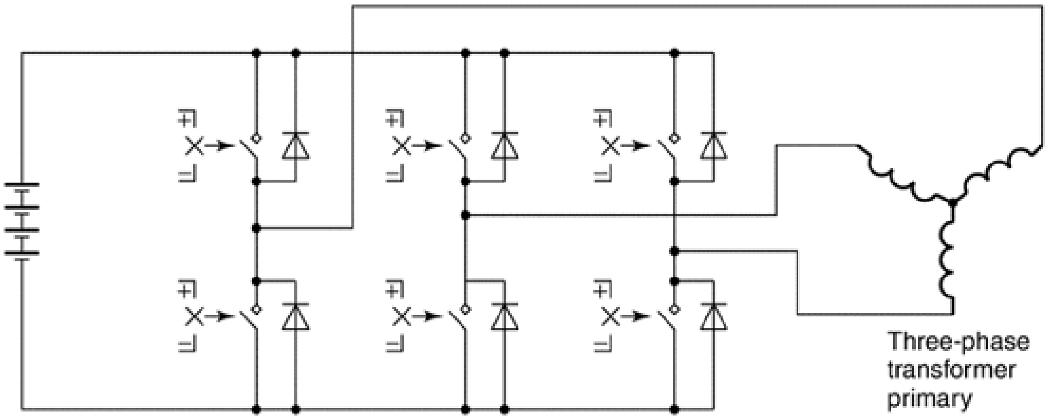

FIGURE 3. Three-phase inverter circuit (Larminie & Dicks 2003, 344)

The switches of the three-phase inverter close in specific order trying to produce sine wave into the output (figure 4).

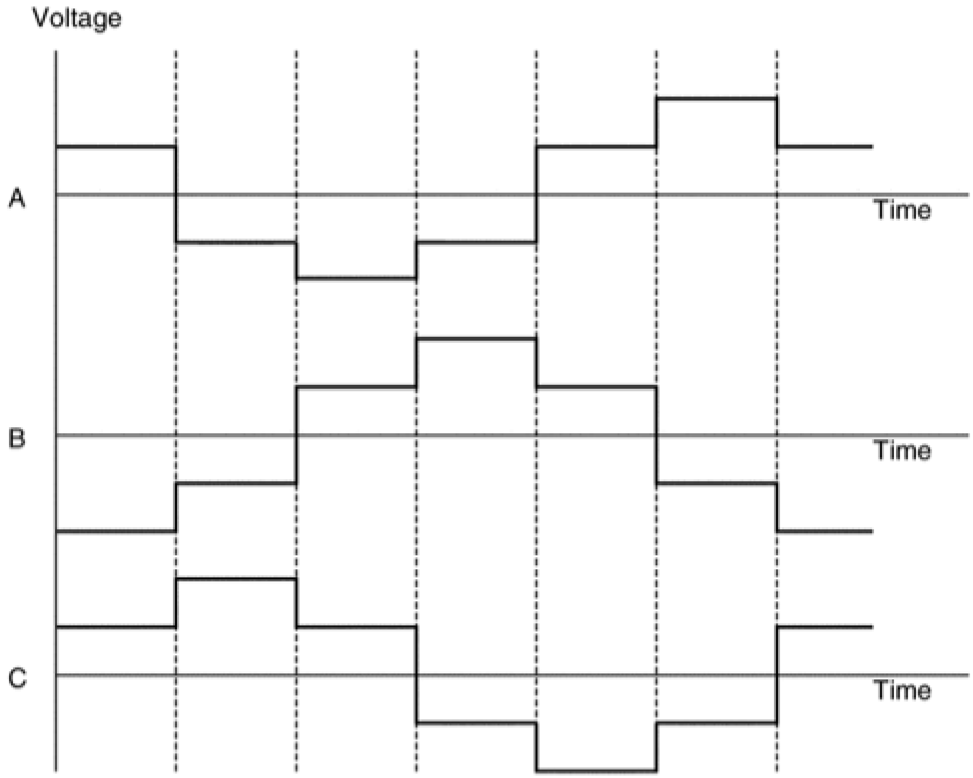

FIGURE 4. Voltage in equation of time graph for three phases (Larminie & Dicks 2003, 346)

The graph only shows the basic operation. The switching frequency is very low so the output voltages are not very close to sine wave. The amplitude of the wave can be controlled with PAM (Pulse Amplitude Modulation). This PAM is done by controlling the input voltage. Switch converters can easily change between inverter and rectifier mode. (Mohan etc. 2003. 243-245.)

Adding capacitive voltage divider to inverter circuit, can switches provide either minus, plus or zero to the output. It adds the different possible combinations up to 27 that is three to the third power. The waveform can be modelled closer to sine wave form than in two level concept. Multiple levels can be added to provide purer sine wave. (Hietalahti 2011, 93-94.)

3 SHORT-CIRCUIT

Short-circuit happens when some part of the grid or components are faulty. There is a very small impedance route for current in the fault point. Typically the faults are results for insulation failure. The insulation might have been weakened or the voltage limits are exceeded. When short-circuit appears, active sources such as motors and generators feed short-circuit current into the fault circuit. Short-circuit current is almost pure reactive current because the impedance during the fault is mostly reactance. The maximum short-circuit current appears in three-phase short-circuit and the current withstand values of the components must not be exceeded. In electric installations of ships and offshore units the calculations are based on IEC 61363-1 publication. Circuit breakers are sized based on the two-phased minimum short-circuit current. The calculations for two-phased minimum short-circuit currents are calculated based on IEC 60909 publication. Basic Short-circuit graph is presented in figure 5. (Tleis 2008, 4, 397-398; ABB 2007, 1.)

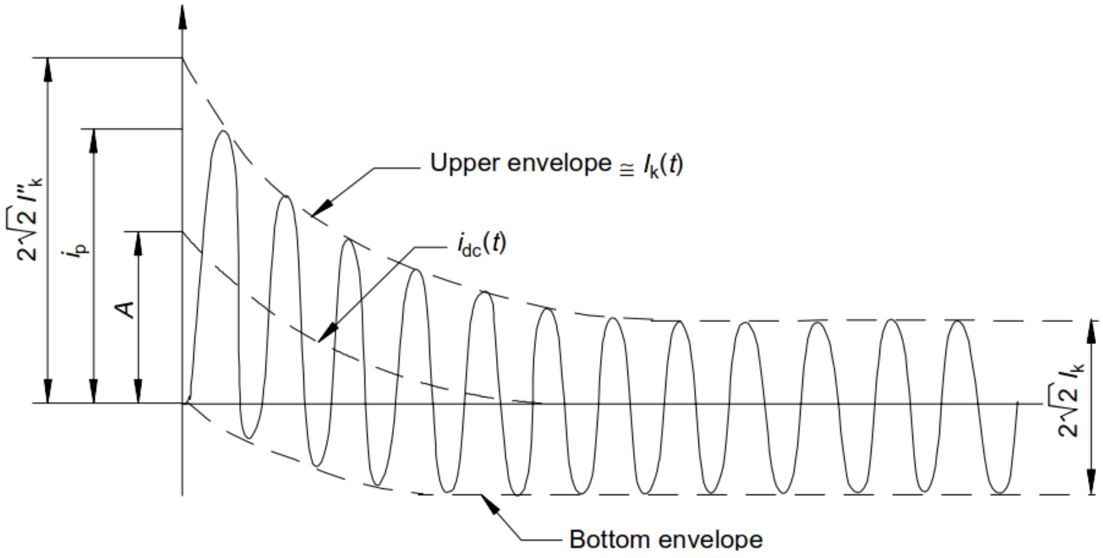

FIGURE 5. Short-circuit characteristic (IEC 61363-1 1998, 17)

In figure 5 I''_k is initial symmetrical short-circuit current, I_p is peak short-circuit current, I_k is steady-state short-circuit current, I_{dc} is DC-component of short-circuit current and A is initial value of the decaying component. In the graph presented in figure 5 phase is at zero point when short-circuit appears. In practice, the phase can be at any value and it affects peak shot-circuit current. (IEC 61363-1 1998, 17.)

Marine systems are usually operating in IT-grid, which means that the neutral point is insulated from the hull. The reason for using neutral insulated grid in ships is that the neutral point is floating and the earth fault -protection is not tripped in a single earth fault leaving the necessary navigation and communication equipment working properly. Only the double earth fault trips the earth fault –relay. (IEC 61363-1 1998, 13.)

3.1 Batteries

Batteries are capable of feeding 150-200 times 10-hour discharge current during short-circuit when fully charged. Short-circuit current can be calculated from equation 1 (ST-käsikirja 20 2005, 165-166.)

$$I_k = 200 \cdot \frac{C}{10}, \tag{1}$$

where *C*/10 is 10 hour discharge current.

For AC-side the short-circuit current can be evaluated from equation (2)

$$I''_k = \frac{c \cdot U_N}{\sqrt{3} \cdot Z_k}, \tag{2}$$

where *c* is voltage factor which is 1,1 when calculation maximum short-circuit currents and 1 when calculating minimum short-circuit currents for 11 kV voltage level. (IEC 60909-0 2016, 43.)

3.2 Transformers

For two winding transformers the nominal impedance Z_N is calculated from equation (3)

$$Z_N = \frac{{U_N}^2}{S_N}, \tag{3}$$

where U_N is the nominal voltage and S_N is nominal power. (IEC 60909-0 2016, 25.)

Relative per unit short-circuit resistance r_k is calculated from equation (4)

$$r_k = \frac{P_k}{S_N}, \tag{4}$$

where P_k is transformer load losses. (IEC 60909-0 2016, 25)

Manufacturers usually inform the relative short-circuit voltage u_k which can be considered as the same as the relative short-circuit impedance z_k. With relative short-circuit impedance and relative short-circuit resistance, relative short-circuit reactance x_k can be calculated from equation (5)

$$x_k = \sqrt{{z_k}^2 - {r_k}^2}. \tag{5}$$

Equation 4 gives percentage per unit result which needs to be multiplied with nominal impedance to get the actual short-circuit reactance. General equation (6) for transferring per unit relative value to actual quantity is

$$Value = pu \cdot Z_N, \tag{6}$$

where *Value* is the actual quantity, *pu* is the given relative value.

3.3 Asynchronous motors

For time dependent calculations, IEC 61363-1 provides relative values for large motors that can be used (table 1).

TABLE 1. Relative values for large motors (IEC 61363-1 1998, 28)

z''_M	0,160	pu
x''_M	0,150	pu
r_s	0,033	pu
r_r	0,021	pu
r_m	0,055	pu

In table 1 z''_M is relative subtransient impedance of asynchronous motor, x''_M is relative subtransient reactance of an asynchronous motor, r_s is relative stator resistance, r_r is relative rotor resistance and r_m is relative resistance of an asynchronous motor.

Using the given relative per unit values and nominal impedances, all calculations of an asynchronous motor can be calculated from equation 6.

Time constants can be determined using the calculated values of an asynchronous motor. Subtransient time constant of an asynchronous motor T''_M, which relates to the rapid decay of the AC-component, is calculated from equation (7)

$$T''_M = \frac{X''_M}{\omega_r \cdot R_r} = \frac{X''_M}{2\pi \cdot \frac{n}{60} \cdot R_r}, \tag{7}$$

where X''_M is subtransient reactance of an asynchronous motor, ω_r is rated angular velocity, n is rotation speed and R_r is rotor resistance. (IEC 61363-1 1998, 20)

DC time constant of an asynchronous motor T_{dcM} relates to the decay of the aperiodic component. It can be calculated from equation (8)

$$T_{dcM} = \frac{X''_M}{\omega_r \cdot R_s} = \frac{X''_M}{2\pi \cdot \frac{n}{60} \cdot R_s}, \tag{8}$$

where R_s is stator resistance. (IEC 61363-1 1998, 20)

Subtransient voltage of an asynchronous motor E''_M is calculated from equation (9)

$$E''_M = \frac{U_{rM}}{\sqrt{3}} - I_{rM} \cdot Z''_M, \tag{9}$$

where U_{rM} is rated voltage of an asynchronous motor, I_{rM} is rated current of an asynchronous motor and Z''_M is subtransient impedance of an asynchronous motor. (IEC 61363-1 1998, 21)

Subtransient short-circuit current of an asynchronous motor I''_M is calculated from equation (10)

$$I''_M = \frac{E''_M}{\sqrt{{R_M}^2 + {X''_M}^2}}, \tag{10}$$

where R_M is resistance of an asynchronous motor. (IEC 61363-1 1998, 21)

AC-component of the short-circuit current I_{acM} is calculated from equation (11)

$$I_{acM}(t) = I''_M \cdot e^{-t/T''_M}, \tag{11}$$

where t is time duration from the beginning of the short-circuit. (IEC 61363-1 1998, 21)

DC-component of the short-circuit current I_{dcM} is calculated from equation (12)

$$I_{dcM}(t) = \sqrt{2} \cdot (I''_M + I_{rM} \cdot \sin\varphi) \cdot e^{-t/T_{dcM}}, \tag{12}$$

where φ is phase angle which can be calculated from the power factor cos φ. (IEC 61363-1 1998, 21)

Total time depending short-circuit current of an asynchronous motor I_M is calculated from equation (13)

$$I_M(t) = \sqrt{2} \cdot I_{acM}(t) + I_{dcM}(t). \tag{13}$$

Peak value of the short-circuit current can be determined with the same equation (13) evaluated at time $t=T/2$, which is half periodic time. (IEC 61363-1 1998, 20-21)

3.4 Synchronous generators

Subtransient impedance Z''_d for synchronous generators is calculated from equation (14)

$$Z''_d = \sqrt{{R_a}^2 + {X''_d}^2}, \tag{14}$$

where R_a is stator resistance of a synchronous generator and X''_d is subtransient reactance of a synchronous generator. Transient impedance Z'_d is calculated from the same equation (14) but by changing the subtransient reactance to transient reactance X'_d. (IEC 61363.1 1998, 18.)

Subtransient q-axis voltage of a synchronous generator E''_{q0} is calculated from equation (15)

$$E''_{q0} = \frac{U_0}{\sqrt{3}} + I_0 \cdot Z''_d, \tag{15}$$

where U_0 is pre-fault voltage and I_0 is pre-fault current. When calculating the maximum short-circuit currents, pre-fault conditions are rated values. Transient q-axis voltage of a synchronous generator E'_{q0} is calculated from the same equation (15) but instead of subtransient impedance, transient impedance Z'_d is used. (IEC 61363.1 1998, 18.)

Three-phase subtransient short-circuit current of a synchronous generator I''_{kd} is calculated from equation (16)

$$I''_{kd} = \frac{E''_{q0}}{Z''_d}. \tag{16}$$

Three-phase transient short-circuit current of a synchronous generator I'_{kd} is calculated from the same equation (16) but with transient q-axis voltage and transient impedance of the synchronous generator. Three-phase steady state short-circuit current of a synchronous generator I_{kd} is obtained from manufacturer. (IEC 61363.1 1998, 18.)

Time depending AC-component of the short-circuit current is calculated from equation (17)

$$I_{ac}(t) = (I''_{kd} - I'_{kd}) \cdot e^{-\frac{t}{T''_d}} + (I'_{kd} - I_{kd}) \cdot e^{-\frac{t}{T'_d}} + I_{kd}, \tag{17}$$

where T''_d is subtransient time constant and T'_d is transient time constant for synchronous generator. (IEC 61363.1 1998, 17)

Time depending DC-component of the short-circuit current is calculated from equation (18)

$$I_{dc}(t) = \sqrt{2} \cdot (I''_{kd} - I_0 \cdot \sin\varphi) \cdot e^{-\frac{t}{T_{dc}}}. \tag{18}$$

Unlike the equation (12) for DC-component of an asynchronous motor, pre-fault current is decreased from the subtransient current. (IEC 61363.1 1998, 18)

With the AC- and DC-components, time depending upper envelope short-circuit current I_k is calculated. Calculations can be made with the same equation (13) as for asynchronous motors. Peak short-circuit current can be calculated also with the same equation evaluated at time $t=T/2$.

4 PROTECTION

4.1 Short-circuit protection and protection selectivity

Protection selectivity is achieved when fault is bounded in small area so that the rest of the grid works as it should. To reach selective protection it is important that in faulty operations only the closest circuit breaker to fault opens leaving rest of the grid working properly. If the protection is not selective, the fault will affect larger area and unnecessary areas black out. It can also mean that the circuit breaker does not work at all and causes a safety issue for equipment and for people. (Hietalahti 2013, 246; ST 53.13 2017, 2-3.)

Total selectivity is achieved when any overcurrent value possible is separated from the grid. Manufacturers provide necessary time and current curves for their circuit breakers in order to verify the selective protection. Serial curves are inserted to time and current coordinates for further inspections. If two circuit breakers are not selective after specific value, the grid will be only partial selective. In coordination it means that two curves cross each other. (ABB n.d.)

In the medium voltage of the ship, the protection is implemented with protection relays including current transformers and vacuum circuit breakers. Relays are connected to automation system that operates the circuit breakers. Arc protection is also applied by monitoring switchboards with optical sensors.

4.1.1 Time selectivity

Protection is time selective when the operating time of the circuit breaker has been stepped so that the closer protection works faster than higher-level protection. In figure 6 both circuit breakers detect the fault but only the closer circuit breaker opens because of time selectivity.

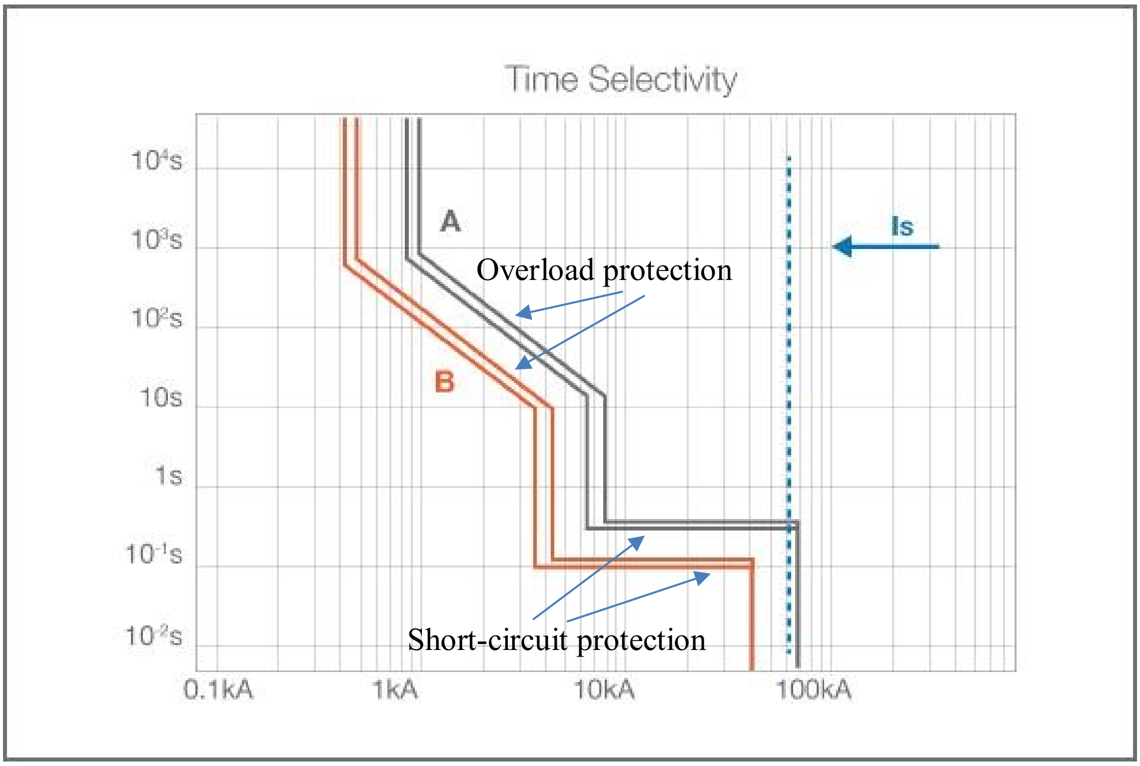

FIGURE 6. Time selectivity graph (ABB n.d.)

In the graph presented in figure 6 the A curve is higher level protection and B is closer to short-circuit and works faster. Time selectivity prevents that higher-level circuit breaker does not work faster than circuit breaker that is closer to short-circuit. The operating time of the circuit breaker and tolerance must be taken into account. Difference depends on used circuit breakers but normally the time between two curves has to be around 40-170 ms tolerances taken into account. (ST 53.13 2017, 2.)

4.1.2 Current selectivity

Short-circuit current is higher in the supply side and therefore circuit breakers can be set to work in the calculated short-circuit currents in their operating area. For example if the short-circuit current in the load side bus bar is under 1 kA (kilo ampere) and supply side is 3 kA, circuit breaker A will clear the supply side short-circuits and breaker B will clear load side short-circuits. Circuit breakers are current selective to a specific point where their curves cross (figure 7).

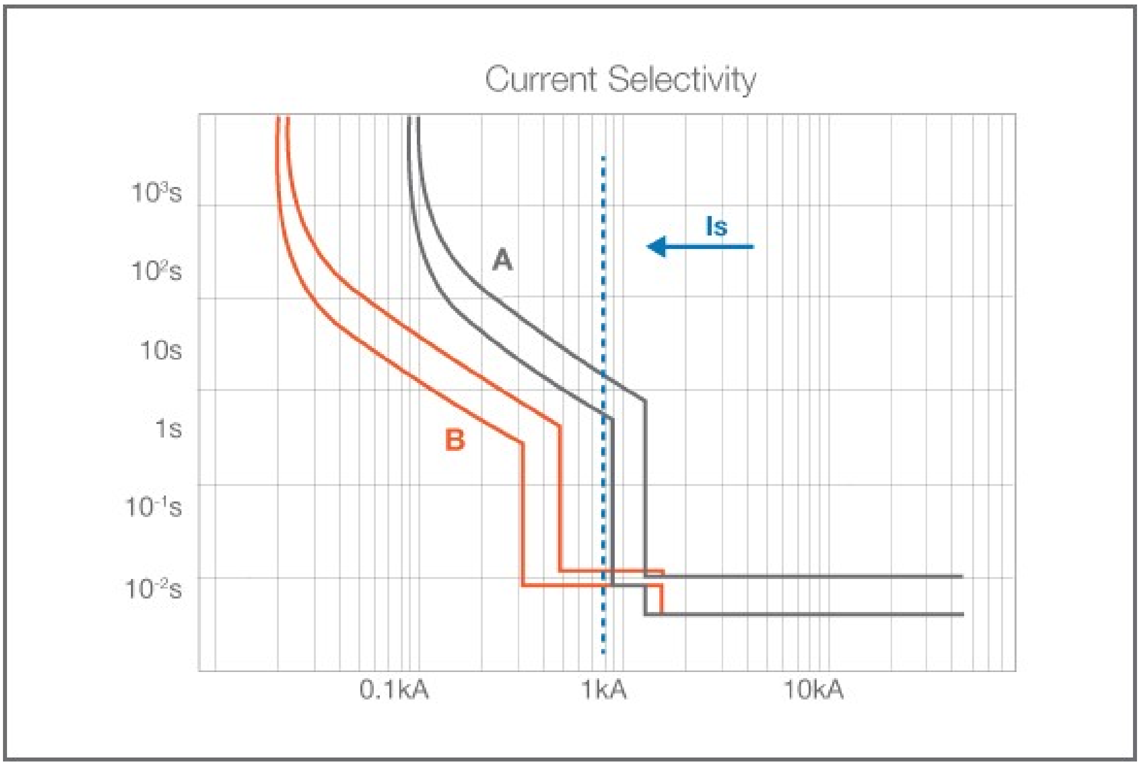

FIGURE 7. Current selectivity graph (ABB n.d.)

Circuit breaker A clears supply side short-circuits and breaker B can be set to handle short-circuits less or equal to 2 kA. Circuit breaker A is set to handle short-circuit currents from over 2 kA to its calculated short-circuit current. Then the protection is current selective. In the protection curves of the graph the horizontal base line is for short-circuit protection and the corner to corner angled part is overload protection. (ABB n.d.)

4.1.3 Zone selectivity

Zone selectivity is an option if time and current selectivity cannot be achieved. Zone selectivity functions need an external ZSI-relay module (Zone Selective Interlocking). Zone selective protection means that if circuit breaker senses short-circuit, the breaker will send a signal to upstream breakers and it begins to time out its selected short-time delay. If breaker does not receive locking signal, it will open and clear the fault. Locking rises trip times a bit higher. Clearing the fault as fast as possible will reduce the mechanical and thermal stress of the bus bar. However short clearing times do not guarantee selectivity and may end up opening higher level circuit breakers. Zone interlocking is compromise for reducing mechanical stress and avoiding blackouts. The ZSI-modules of the last zone breakers are set to delay time of zero and every other breaker for at least additional 50 ms. Figure 8 presents an example of ZSI-function. (Siemens 2010, 2, 8-15.)

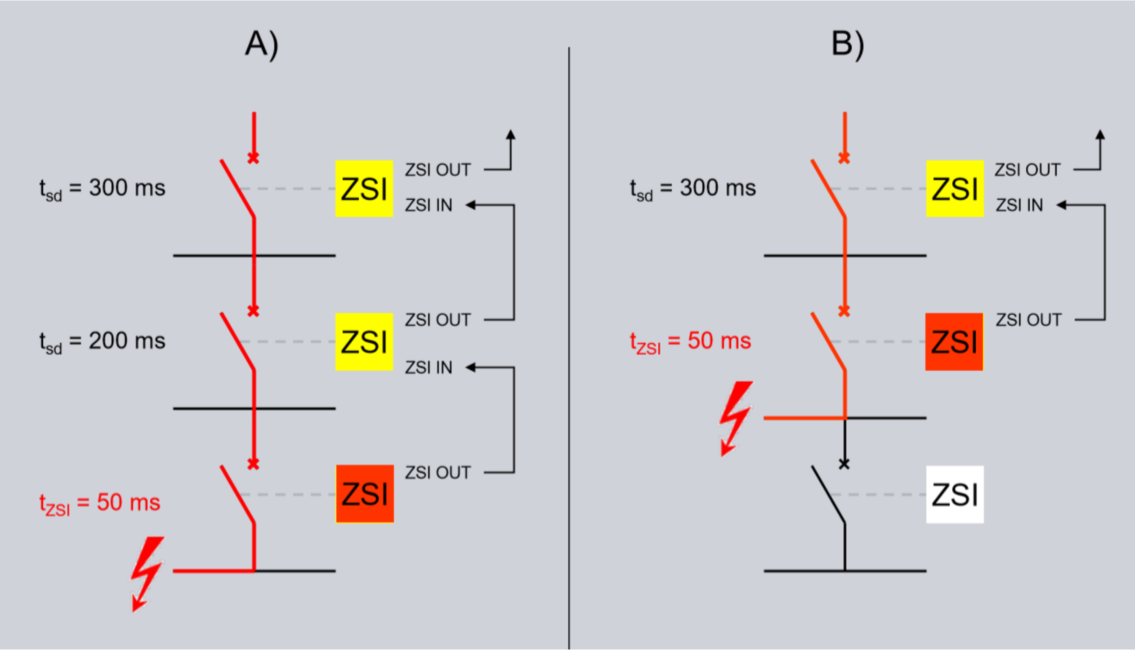

FIGURE 8. ZSI-function example (Siemens 2010, 31)

In the A scenario of figure 8, short-circuit appears in the last bus bar. All three ZSI-modules detect the fault and send locking signal from ZSI OUT –channel to the higher level ZSI IN –channel of the ZSI-module. If the module does not receive locking signal, it will trip after 50 ms time delay. If the breaker is unable to clear the fault, in case A after time delay of 200 ms the higher level breaker will open the circuit. In the scenario B, short-circuit appears in the second bus bar and the last ZSI module does not detect the fault. All modules that have detected the fault send locking signal. Second ZSI-module trips in 50 ms and if not, then the higher level breaker clears the fault after its time delay. Short time delays ensure that higher-level breakers do not unnecessarily open. Mechanically all the breakers can quench the arc in under 35 ms. Tripping time is typically for short-circuit between 80-100 ms which means 50 ms delay time and mechanical operating time. Usually 150 ms difference between operating times of the relays safe margins taken into account can be considered as selective protection. With interlocking the time difference can be even smaller. Possible return currents must be taken into account when using interlocking. That is why directional relay may also be needed. Protection function times depend on manufacturer and user settings. (Schneider electric 2014, 3; ABB n.d.; ABB 2011, 9; Siemens 2010, 2, 8-15.)

4.1.4 GOOSE

The protection of the grid may contain devices from multiple manufacturer so communication needs to work between them. Transferring message from device to a device from different manufacturer needs data conversion unless GOOSE (Generic Object Oriented Substation Event) is used. GOOSE is determined in IEC 61850-standard. Generic in GOOSE means that it can handle any data type including measuring and alarm signals. It allows data to move faster from one device to another without time-consuming data conversions to manufacturer-specific data type. GOOSE-message transfers locking signals faster than usual and allows faster operating time for protection. Time critical info is transferred under 4 ms so the ZSI-module can be set to work even faster than normally. GOOSE-signal takes priority from Ethernet switch and therefore it overtakes other signals. (ABB 2010; Hakala-Ranta etc. 2009, 1-4.)

4.2 Power electronics protection

The function of the power electronics protection is to prevent components from breaking. Protection needs to take external faults into account. When operating in normal conditions, power electronics must be protected from device turn-on currents (di/dt). Turn-on currents appear when the switch is turned on. The switch is in forwarding state, which means that it lets the current flow through it. In forwarding state, the overvoltage does not cause harm to power electronics. Protection against the rising of the turn-off voltage (du/dt) must be also be observed. These switching action stresses can be protected against with RC-snubbers (Resistor-Capacitor). RC-snubber is connected parallel with semiconductor switch. RC-snubbers protect against du/dt, di/dt and overvoltage. However these RC-snubbers increase power losses. (Hietalahti 2011, 24-26; Khanna 2003, 26; Mohan etc. 2003, 669.)

Thryristor protection is easier than transistor protection. As the IGBT goes to blocking state, exceeding the isolation voltage between collector and emitter could break the IGBT-module. Usually the supply voltage is limited to less than 80% of the rated breakdown voltage given to the IGBT-module. Voltage protection circuit is also connected parallel with IGBT. The voltage protection circuit contains surge arrester and varistors. Surge arrester diverts the surge current in order to limit the surge voltage. The resistance of the varistor changes when voltage starts to rise. Varistor gives a short-circuit path to overvoltage when it appears. After that the circuit returns to its normal state. Surge arrester is capable of diverting the surge current multiple times. RC-snubbers are enough protection for thyristors. (ABB 2018, 7; Hietalahti 2011, 26; Khanna 2003, 26.)

IGBT junction heats up to 150 degree Celsius when switching. If the environment temperature is higher than usual, junctions may heat up more than that. The nominal current of the IGBT is the continuous current that does not heat up the IGBT more than the limited junction temperature. If overcurrent appears, the control circuit will reduce the gate voltage and in some cases turns off the IGBT. Thermal fuses are used to secure the thermal protection. IGBT produces much power losses, which appear as heat as in all power electronics devices. Cooling is very important in order to keep the process running. (Khanna 2003, 26-27.)

5 ESS INTEGRATED IN THE POWER GRID OF THE SHIP

5.1 Different scenarios

Two different scenarios are examined for the use of the ESS. One where the ESS is used to support the propulsion of the ship and one where the ESS is used to supply hotel load. Switching is executed with transfer switch. When supporting the propulsion system located in 11 kV switchboard, the battery power regulations of the DNV GL must be followed. Batteries can be used to hotel load in seas and for 11 kV AC-compressors in harbors. This way the power regulations can be avoided because propulsion is not in use when the ship is in harbor. The life cycle of the batteries may be much shorter if they are constantly used in cycles.

When the ESS is used only to cover a part of the hotel load, the battery power regulations do not need to be followed. The settings for protection relays are easier to implement when propulsion is not supplied. It might be practical to integrate the BMS into the PMS (Power Management System) of the ship. The only differences between the two scenarios are connection point, regulations and the protection relay settings.

The single line for the inverter use is presented in appendix 1. Transfer switch is used to switch the connection from the 11 kV propulsion switchboard to RMU (Ring Main Unit). This ensures that batteries do not supply motors connected to propulsion switchboard. Supplying hotel load near harbors is probably the main use for the energy storage.

5.2 Inverter design

Inverter switching action produces power losses, which appear in form of heat. Also passive components in inverter cause losses. Inverter must be designed to operate in voltage and current areas that cannot be considered harmful for the power electronics. Cooling is important part of the inverter preventing thermal damage. Undersized cooling will lead to thermal stress and thermal protection device tripping. (Kaboli & Oraee 2016, 65.)

To minimize the losses formed in the switching action, the circuit control must be well designed. For this high-powered design it is recommended to use either thyristors, GTO (Gate Turn-off) thyristors or IGBTs (Figure 9). (Mohan etc. 2003, 30-31.)

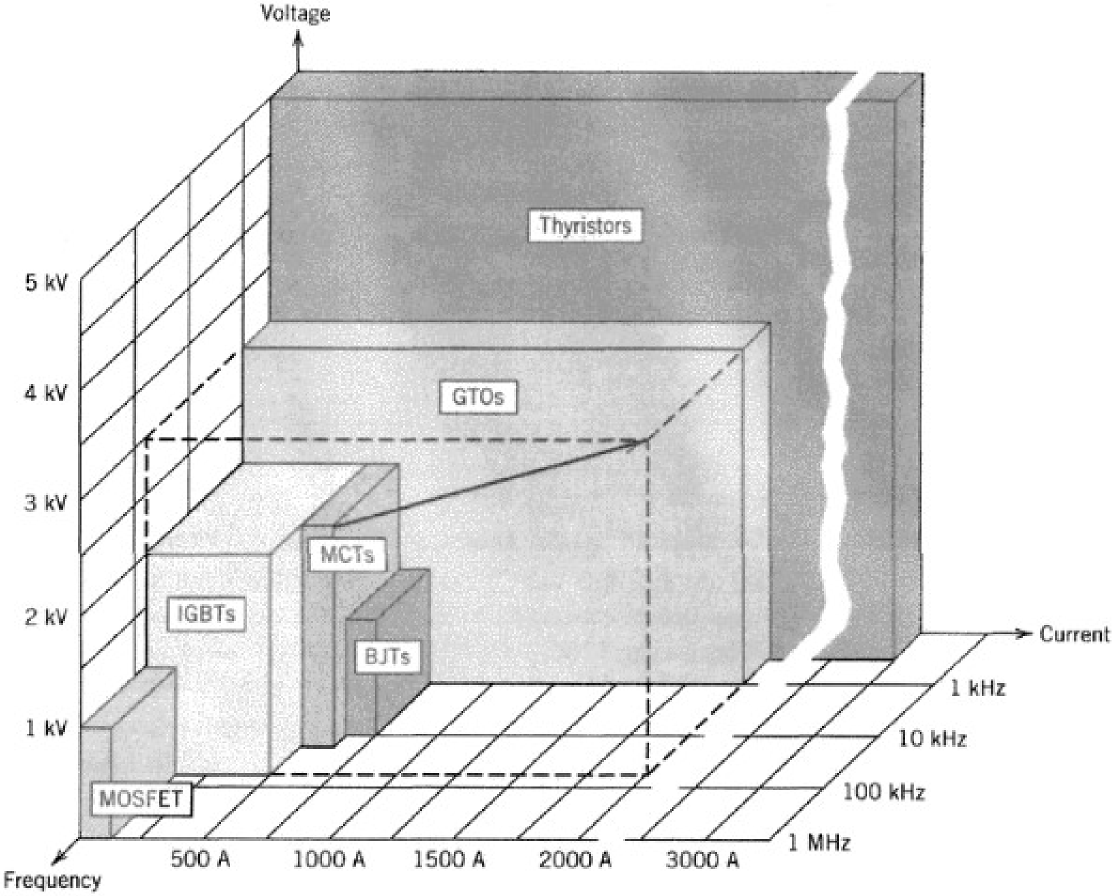

FIGURE 9. Semiconductor comparison (Mohan etc. 2003, 30)

Figure 9 shows a good scale for which purpose can power electronic components be used. Even though the figure old information, it shows that the suitable components for the high-power inverter are thyristors or GTOs. Components are controlled by triggering pulse to the gate of the thyristors or transistor. IGBT technology has evolved during those years and it can be considered for high-power inverter use. Still thyristors are more suitable than IGBTs but they are also more expensive than IGBTs. As the voltage and current durability rises, component price will rise in proportion. It is recommendable to use components in parallel to divide the current. Preferred design is dry, air-cooled converter. For transformer installed to either supply or load side of the converter, IEC publication 60092-303 needs to be followed. (IEC 60092-304, 9.)

Energy storage nominal voltage is probably going to be between 690-1000 V. Formed currents are very high and will lead to large inverter. The best solution would be to use multiple smaller inverters to form smaller complexes. The components used are smaller and cheaper than if only one high-powered inverter would be used. Components can be connected serial in order to rise the voltage endurance. Serial components share the voltage affecting over them. Parallel components divide the currents so that the single components can be smaller. However the serial connection can lead to unbalanced voltage share because of the differences between switching actions, lead currents or cutting time. Using same components will reduce the tolerances mentioned above. If thyristors are used, the gate pulse can be enlarged so that the tolerances between switching actions are smaller. Other option is to use RC-snubbers to protect against overvoltage formed from different switching actions. For serial connection, IGBT and GTO can be exposed to larger stress than normal thyristors. Temperatures also affect to actions so best way to ensure balanced action is to use same components and same cooling. (Hietalahti 2011, 26.)

Maximum overcurrent capability of the power electronics must be taken into account when designing the inverter. For example, the IGBT-module can handle 2-3 times nominal current before the component breaks down. Components have to stand the short-circuit current and it grows the component size. Protection is important for power electronic components but if the components are sized too small, the inverter is not working and protection opens the circuit all the time. With correct turn-on and turn-off protection, the components can be sized cost-efficiently. Protection reduces the turn-on currents and turn-off voltages so that the components are not needed to oversize. These are the reasons inverters had to be oversized. Protection must be sized to cut the current before components are damaged. Inverters must be able to withstand the short-circuit current without damage. Figure 10 presents an example of 1 MW ABB central inverter. (Hietalahti 2011, 27; Nuutinen 2015, 58.)

FIGURE 10. ABB 1 MW central inverter (ABB 2017a, 3)

The central inverter in figure 10 is designed for photovoltaic solutions but it can also be used as regular high-powered inverter. The cabinet in the left is the control cabinet that monitors the inverter data. The second cabinet from the left is the DC input cabinet. Three next cabinets are single-phase converters forming a three phase complex following the last two AC-side cabinets. Figure 11 presents an example of two modular inverter stations and their circuit diagrams.

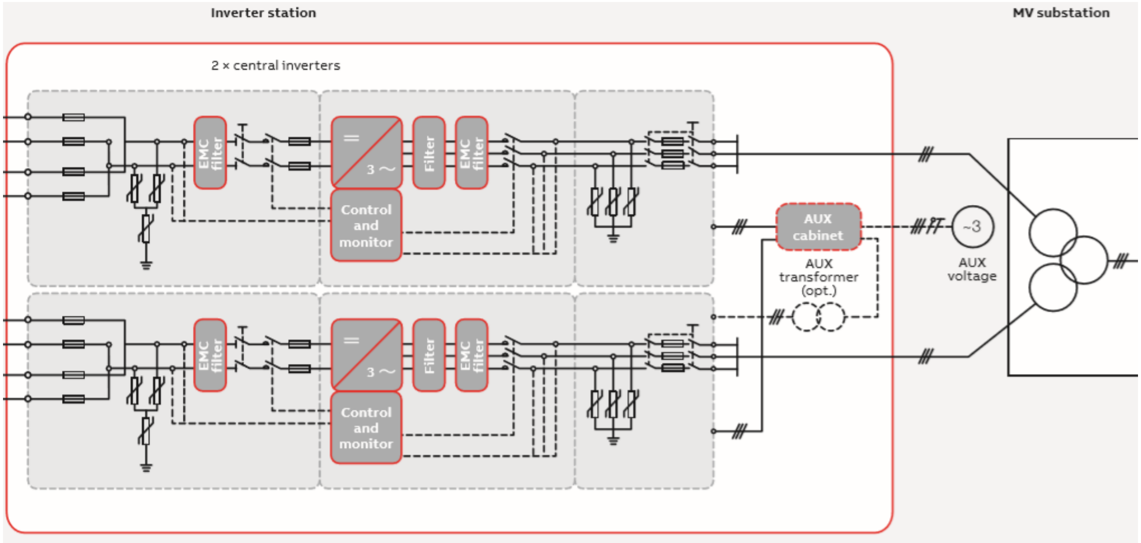

FIGURE 11. An example of inverter station design (ABB 2017b, 3)

The design has been divided in two central inverters. DC input cabinet contains surge arresters, EMC-filter and protection devices. Converter cabinets consist of three single-phase inverters, control- and monitoring system and filters for EMC and harmonics. AC-side have also surge arresters and circuit breakers. Two inverter outputs are connected to multiple winding step-up transformer connected to MV-grid (Medium Voltage). Lifetime for these inverters are promised around 20 years but it depends on the usage. (ABB 2017a, 2; ABB 2017b, 3.)

EMC must be examined when connecting power electronics to distribution. EMC is based on EMI (Electromagnetic Interface) standard EN50081. Based on EMI-standard the converters need filters in order to confirm the electromagnetic compatibility. LC- or LCL-filter needs to be installed to filter the harmonics from used inverters. Filter is placed next to the power electronics. (Hietalahti 2011, 103-104.)

Power factor can be controlled with capacitors supplying lagging VArs (Volt-Ampere reactive) to the circuit. The idea is the same as the idea of the compensation gear in industries. This can be used in advantage if the power factor needs to be kept in specific value. (ABB 2017a, 2; Sueker 2005, 181.)

5.3 Short-circuit calculations

Maximum short-circuit current appears when energy storages are in use and all generators and medium voltage motors are running. All breakers are also closed and all transformers are connected.

A few assumptions have to be made to simplify the calculation. The short-circuit path remains unchanged during short-circuit. The generators are operated at their rated values. Generators produce short-circuit current proportionally. Arc impedance and system capacitances are neglected. All circuit components are reacting linearly which means that the surge arresters are not taken into account. The fault point of one phase at the start of short-circuit is zero and only positive sequence components are taken into account. The secondary motor load of the transformer does not affect to primary circuit faults. Bus connections and generator cables are considered negligible so they do not affect circuit impedance. Batteries are feeding constant short-circuit current. (IEC 61363-1 1998, 14.)

Propulsion motors are drive-fed motors and unless the drives are set to bidirectional use, they do not feed short-circuit current to the 11 kV switchboard. In this case, the drives are considered one way only so the propulsion motors do not feed short-circuit current. (IEC 60909-0 2001, 36.)

5.3.1 Transformers

Necessary data of used transformers is presented in table 2.

TABLE 2. Data for transformers

	B1T sec.	T1.sec.	T71 sec.	T71 sec.
S_N (kVA)	6300	2250	850	850
U_N (V)	11000	690	690	400
P_k (kW)	48	21,1	12,3	12,3
z_k (%)	7,2	7	5,25	5,25

Nominal impedances in the secondary side of the transformers are calculated from equation (3)

$$Z_N = \frac{{U_N}^2}{S_N} = \frac{(11\ 000\ \text{V})^2}{6\ 300\ 000\ \text{VA}} \approx 19{,}2\ \Omega.$$

Relative per unit short-circuit resistance is calculated from equation (4)

$$r_k = \frac{P_k}{S_N} = \frac{48\ 000\ \text{W}}{6\ 300\ 000\ \text{VA}} \approx 0{,}0076\ \text{pu}$$

Calculated relative short-circuit resistance is used to calculate relative short-circuit reactance with equation (5)

$$x_k = \sqrt{{z_k}^2 - {r_k}^2} = \sqrt{0{,}072^2 - 0{,}0076^2} \approx 0{,}0716\ \text{pu}$$

Per unit value is transformed to actual short-circuit reactance with equation (6)

$$Value = pu \cdot Z_N \leftrightarrow X_k = x_k \cdot Z_N = 0{,}0716 \text{ pu} \cdot 19{,}2\ \Omega \approx 1{,}375\ \Omega$$

All calculated transformer values are gathered in table 3. Values are all calculated in the secondary side of the transformer.

TABLE 3. Calculated transformer values

	B1T sec.	T1 sec.	T71 sec.	T71 sec.
Z_N (Ω)	19,2	0,2116	0,5601	0,1882
r_k (%)	0,0076	0,0094	0,0145	0,0145
z_k (%)	0,0716	0,0694	0,0505	0,0505
Z_k (Ω)	1,383	0,0148	0,0294	0,0099
X_k (Ω)	1,375	0,0147	0,0283	0,0095
R_k (Ω)	0,146	0,0020	0,0081	0,0027

In table 3 Z_k is short-circuit impedance, X_k is short-circuit reactance and R_k is short-circuit resistance.

For short-circuit calculations either short-circuit reactance or short-circuit impedance can be used because main part of short-circuit current is reactive. (Tleis 2008, 440)

5.3.2 Battery short-circuit

Samsung SDI manufactures batteries used in this calculation. Their brochure for smart battery systems provides the data of table 4 for cells.

TABLE 4. Battery rack specifications (Samsung SDI 2017, 9)

Rack	M2-R084
Cell capacity	94 Ah
Energy	84 kWh
Operating voltage	774-1004 V
Weight	670 kg
Nominal voltage	1000 V

Calculations are made with energy quantity given by Samsung. Total energy needed is to be determined by customer when making the contract. Single rack short-circuit current can be calculated from equation (1)

$$I_k = 200 \cdot \frac{C}{10} = 200 \cdot \frac{94\ \mathrm{Ah}}{10} = 1{,}88\ \mathrm{kA}.$$

To get 5 MW continuous power from the batteries for half an hour, 30 racks are needed to install. Capacity of single cell is multiplied by the amount of total cells installed using equation (1)

$$I_k = 200 \cdot \frac{C}{10} = 200 \cdot \frac{94\ \mathrm{Ah} \cdot 30\ \mathrm{pcs}}{10} = 56{,}4\ \mathrm{kA}.$$

The result is theoretical maximum short-circuit current that the ESS can feed. Battery modules include their own fuses to protect against internal short-circuits so the current is limited. Battery short-circuit current varies depending on the level of charge. When the level of charge is only half-full, the short-circuit current is decreased to 70-80% of the maximum. (ABB 2016a, 5; Samsung SDI 2017, 6; ST-käsikirja 20 2005, 165.)

Assuming the DC bus nominal voltage U_N to be 1 kV, the DC-side impedance Z_k for the batteries is

$$Z_k = \frac{U_N}{I_k} = \frac{1000\ \mathrm{V}}{56400\ \mathrm{A}} \approx 0{,}0177\ \Omega$$

DC-side impedance is converted to 11 kV voltage level with transformation ratio

$$Z_k' = Z_k \cdot \left(\frac{U_2}{U_1}\right)^2 = 0{,}0177\ \Omega \cdot \left(\frac{11000\ \mathrm{V}}{1000\ \mathrm{V}}\right)^2 \approx 2{,}15\ \Omega.$$

Maximum short-circuit current I''_{kmax} is evaluated from equation 2 using voltage factor of 1,1

$$I''_{kmax} = \frac{c \cdot U_N}{\sqrt{3} \cdot Z_k} = \frac{c \cdot U_N}{\sqrt{3} \cdot (Z_k + Z_{B1T})} = \frac{1{,}1 \cdot 11\,000\ \mathrm{V}}{\sqrt{3} \cdot (2{,}15\ \Omega + 1{,}383\ \Omega\,)} \approx\ 1980\ \mathrm{A}$$

Peak short-circuit current is evaluated from equation (19)

$$I_p = k \cdot \sqrt{2} \cdot I''_k = 2 \cdot \sqrt{2} \cdot 1980\ \mathrm{A} \approx 5600\ \mathrm{A}, \tag{19}$$

where k is factor for X/R ratio and factor of 2 can be used to calculate the maximum peak short-circuit current. (IEC60909-0 2016, 49)

Minimum short-circuit current appears when batteries are in low charge. As mentioned before, in half charge short-circuit current decreases to 70-80 % of its full charge value. Assuming that the batteries are kept between half and full charge, DC-side minimum short-circuit current would then be 39,5 kA. Calculating impedances with the same methods, minimum short-circuit current can be evaluated from equation (2) with voltage factor of 1

$$I''_{kmin} = \frac{c \cdot U_N}{\sqrt{3} \cdot Z_k} = \frac{c \cdot U_N}{\sqrt{3} \cdot (Z_k + Z_{B1T})} = \frac{1 \cdot 11\,000\ \mathrm{V}}{\sqrt{3} \cdot (3{,}07\ \Omega + 1{,}383\ \Omega)} \approx 1428\ \mathrm{A}$$

Nominal current for one battery energy storage in AC-side with power factor of 0,92 is

$$I_N = \frac{P_e}{\sqrt{3} \cdot U_N \cdot \cos\varphi} = \frac{5\,000\,000\ \mathrm{W}}{\sqrt{3} \cdot 11\,000\ \mathrm{V} \cdot 0{,}92} = 285{,}3\ \mathrm{A}.$$

Calculated values are presented in table 5.

TABLE 5. Calculated values for batteries

I_k in 1 kV DC	56400 A
Z_k in 1 kV DC	0,0177 Ω
Z_k' in 11 kV AC	3,528 Ω
I''_{kmax} in 11 kV AC	1980 A
I''_{kmin} in 11 kV AC	1428 A
I_p in 11 kV AC	5600 A
I_N in 11 kV AC	285,3 A

Values are calculated only for a single battery energy storage. If a single DC circuit breaker is used, it must withstand 56,4 kA short-circuit current. However if every cell is protected with fuse it is impossible to tell short-circuit current value without exact information of cell fuses. Constant short-circuit value can be used in time depending calculations because battery short-circuit behavior is unknown.

5.3.3 Asynchronous motor short-circuit

There are total of seven medium voltage asynchronous motors connected in the 11 kV main bus bar. Nameplate values are presented in table 6.

TABLE 6. Nameplate values for asynchronous motors

	ST	BT	AC
P_e (kW)	3000	3600	920
U_N (V)	11000	11000	11000
cosϕ	0,85	0,79	0,89
sinϕ	0,527	0,613	0,456
I_N (A)	192	249	57
n (1/min)	717	717	3585

In table 6 ST is stern thruster, BT is bow thruster, AC is compressor motor, I_N is nominal current and P_e is electrical power. Nominal impedance is calculated from equation (3)

$$Z_N = \frac{{U_N}^2}{S_N} = \frac{{U_N}^2}{\frac{P_e}{\cos\varphi}} = \frac{(11\,000\ \mathrm{V})^2}{\frac{3\,000\,000\ \mathrm{W}}{0{,}85}} \approx 34{,}3\ \Omega$$

Motor impedances and resistances are calculated from equation 6 using the nominal impedance and relative values presented in table 1. Calculated values are presented in table 7.

TABLE 7. Calculated impedances and resistances of the asynchronous motors

	ST	BT	AC
Z_N (Ω)	34,3	26,6	117,1
Z''_M (Ω)	5,49	4,25	18,73
X''_M (Ω)	5,14	3,98	17,56
R_s (Ω)	1,15	0,89	3,91
R_r (Ω)	0,72	0,56	2,46
R_M (Ω)	1,89	1,46	6,44

According to IEC 61363-1 (1998, 20) the subtransient time constant depends on the damping effect of the rotor circuit and the DC time constants depend on the damping effect of the stator circuit. Subtransient time constant can be evaluated from equation (7)

$$T''_M = \frac{X''_M}{\omega_r \cdot R_r} = \frac{X''_M}{2\pi \cdot \frac{n}{60} \cdot R_r} = \frac{5{,}14\ \Omega}{2\pi \cdot \frac{717\ \frac{1}{\mathrm{min}}}{60} \cdot 0{,}72\ \Omega} = 0{,}09513\ \mathrm{s} = 95{,}13\ \mathrm{ms}.$$

Changing the rotor resistance to stator resistance, the DC time constant can be evaluated from equation (8)

$$T_{dcM} = \frac{X''_M}{\omega_r \cdot R_s} = \frac{X''_M}{2\pi \cdot \frac{n}{60} \cdot R_s} = \frac{5{,}14\ \Omega}{2\pi \cdot \frac{717\ \frac{1}{\mathrm{min}}}{60} \cdot 1{,}15\ \Omega} = 59{,}81\ \mathrm{ms}.$$

Subtransient voltage of an asynchronous motor is needed for calculating the subtransient short-circuit current. According to IEC 61363-1 (1998, 21) Subtransient voltage is depending on the terminal voltage, load current and power factor of the motor during short-circuit. Subtransient voltage is calculated from equation (9)

$$E''_M = \frac{U_{rM}}{\sqrt{3}} - I_{rM} \cdot Z''_M = \frac{11\ 000\ \mathrm{V}}{\sqrt{3}} - 192\ \mathrm{A} \cdot 5{,}49\ \Omega = 5297{,}7\ \mathrm{V}.$$

Motor terminal voltage drops to half of nominal voltage in the subtransient phase of short-circuit. Subtransient short-circuit current is calculated from equation (10)

$$I''_M = \frac{E''_M}{\sqrt{{R_M}^2 + {X''_M}^2}} = \frac{5297{,}7\ \mathrm{V}}{\sqrt{(1{,}89\ \Omega)^2 + (5{,}14\ \Omega)^2}} = 967{,}2\ \mathrm{A}.$$

Calculated values are presented in table 8.

TABLE 8. Calculated values for asynchronous motors

	ST	BT	AC
T''_M (ms)	95,13	95,13	19,03
T_{dcM} (ms)	59,81	59,81	11,96
E''_M (V)	5297,7	5293,0	5283,3
I''_M (A)	967,2	1247,7	282,5

AC-component of the short-circuit current is calculated from equation 11 using table 8 values. The equation is time depending so it is calculated to running time values. In this example the AC-component is calculated in the half cycle time which is 8,33 ms when frequency is 60 hertz

$$I_{acM}(t) = I''_M \cdot e^{-\frac{t}{T''_M}} = 967{,}2\ \mathrm{A} \cdot e^{-\frac{8{,}33\ \mathrm{ms}}{95{,}13\ \mathrm{ms}}} \approx 886{,}1\ \mathrm{A}.$$

The DC-component is calculated in the same time as AC-component from equation (12)

$$\begin{aligned} I_{dcM}(t) &= \sqrt{2} \cdot (I''_M + I_{rM} \cdot \sin\varphi) \cdot e^{-\frac{t}{T_{dcM}}} \\ &= \sqrt{2} \cdot (967{,}2\ \mathrm{A} + 192\ \mathrm{A} \cdot 0{,}527) \cdot e^{-\frac{8{,}33\ \mathrm{ms}}{59{,}81\ \mathrm{ms}}} \approx 1314{,}4\ \mathrm{A}. \end{aligned}$$

Total upper envelope short-circuit current is evaluated from equation (13)

$$I_M(t) = \sqrt{2} \cdot I_{acM}(t) + I_{dcM}(t) = \sqrt{2} \cdot 886{,}1\ \mathrm{A} + 1314{,}4\ \mathrm{A} = 2567{,}5\ \mathrm{A}.$$

The result is peak short-circuit current of a single stern thruster. Other values are calculated in precision of one millisecond and presented as a function of time in figure 12.

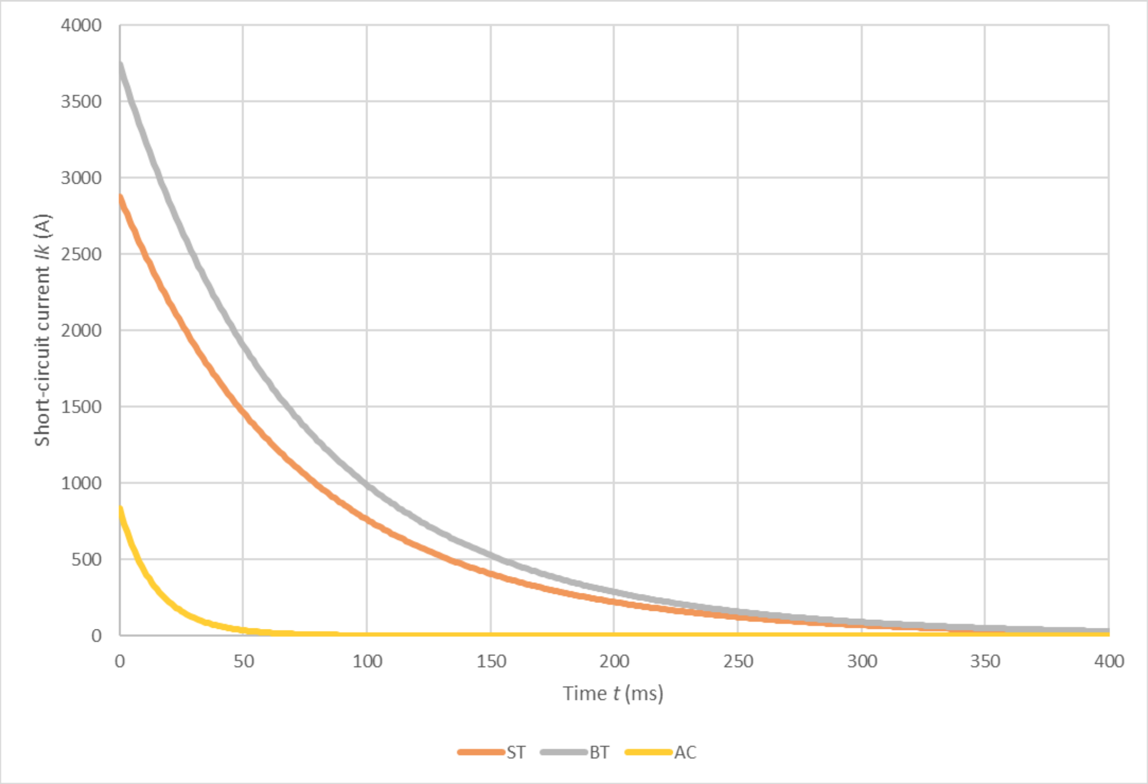

FIGURE 12. Short-circuit currents of the medium voltage motors in 11 kV bus bar

Curves in figure 12 are presented for a single motor of a kind. Thrusters feed a lot of higher short-circuit current than AC motors. Damping short-circuit is near zero after 400 ms for all motors.

5.3.4 Generator short-circuit

Technical data for generators is presented in table 9.

TABLE 9. Generator technical data

	DG1, DG3	DG2, DG4
S (kVA)	15183	10153
U (V)	11000	11000
I_N (A)	797	553
I_{kd}	2391	1659
$\cos\phi$	0,92	0,92
$\sin\phi$	0,392	0,392
x''_d (%)	20,6	20,1
x'_d (%)	35,1	32,0
x_d (%)	201,8	167,0
T''_d (ms)	19,29	14,48
T'_d (ms)	1557	1279
R_a (Ω)	0,0296	0,0602
T_{dc} (ms)	142,3	101,0

In table 9 x''_d is relative d-axis subtransient reactance of synchronous generator, x'_d is relative d-axis transient reactance of synchronous generator and x_d is relative d-axis reactance of synchronous generator.

Nominal impedances are calculated with equation (3)

$$Z_N = \frac{{U_N}^2}{S_N} = \frac{(11\,000\ \mathrm{V})^2}{15\,183\,000\ \mathrm{VA}} \approx 7{,}97\ \Omega.$$

Using relative subtransient and relative transient impedances and nominal impedance, actual reactance values are calculated using equation (6)

$$Value = pu \cdot Z_N \leftrightarrow X''_d = x''_d \cdot Z_N = 0{,}206 \cdot 7{,}97\ \Omega \approx 1{,}64\ \Omega.$$

Subtransient and transient direct-axis impedances are evaluated from equation (14)

$$Z''_d = \sqrt{{R_a}^2 + {X''_d}^2} = \sqrt{(0{,}0296\ \Omega)^2 + (1{,}64\ \Omega)^2} \approx 1{,}64\ \Omega.$$

Using the same procedure, values for other generators can be evaluated. All calculated values are presented in table 10.

TABLE 10. Calculated generator impedances and reactances

	DG1, DG3	DG2, DG4
Z_N (Ω)	7,97	11,92
X''_d (Ω)	1,64	2,40
Z''_d (Ω)	1,64	2,40
X'_d (Ω)	2,80	3,81
Z'_d (Ω)	2,80	3,81

Subtransient q-axis voltage is evaluated from equation (15)

$$E''_{q0} = \frac{U_0}{\sqrt{3}} + I_0 \cdot Z''_d = \frac{11\ 000\ \text{V}}{\sqrt{3}} + 797\ \text{A} \cdot 1{,}64\ \Omega \approx 7660\ \text{V}.$$

Transient q-axis voltage is calculated with same equation (15) but with transient impedance. Subtransient d-axis short-circuit current can be evaluated from equation (16)

$$I''_{kd} = \frac{E''_{q0}}{Z''_d} = \frac{7660\ \text{V}}{1{,}64\ \Omega} \approx 4665\ \text{A}.$$

Transient direct-axis short-circuit current is calculated with same equation (16) but with transient quadrature-axis voltage and transient impedance. Calculated values for q-axis voltages and d-axis short-circuit currents are presented in table 11.

TABLE 11. Calculated q-axis voltages and d-axis short-circuit currents.

	E''_{q0} (V)	I''_{kd} (A)	E'_{q0} (V)	I'_{kd} (A)
DG1, DG3	7660	4665	8580	3067
DG2, DG4	7676	3203	9391	2462

Steady-state short-circuit current is assumed to be three times nominal current. AC-component of the generator short-circuit current is evaluated with equation (17)

$$I_{ac}(t) = (I''_{kd} - I'_{kd}) \cdot e^{-\frac{t}{T''_{d}}} + (I'_{kd} - I_{kd}) \cdot e^{-\frac{t}{T'_{d}}} + I_{kd}$$
$$= (4665\ \mathrm{A} - 3067\ \mathrm{A}) \cdot e^{-\frac{8{,}33\ \mathrm{ms}}{19{,}29\ \mathrm{ms}}} + \big(3067\ \mathrm{A} - (3 \cdot 797\ \mathrm{A})\big) \cdot e^{-\frac{8{,}33\ \mathrm{ms}}{1557\ \mathrm{ms}}}$$
$$+ (3 \cdot 797\ \mathrm{A}) = 4094{,}4\ \mathrm{A}.$$

DC-component is evaluated from equation (18)

$$I_{dc}(t) = \sqrt{2} \cdot (I''_{kd} - I_0 \cdot \sin\varphi) \cdot e^{-\frac{t}{T_{dc}}} = \sqrt{2} \cdot (4665\ \mathrm{A} - 797\ \mathrm{A} \cdot 0{,}392) \cdot e^{-\frac{8{,}33\ \mathrm{ms}}{142{,}3\ \mathrm{ms}}}$$
$$= 5805{,}2\ \mathrm{A}.$$

Total short-circuit is calculated with AC- and DC-components using equation (13)

$$I_k(t) = \sqrt{2} \cdot I_{ac}(t) + I_{dc}(t) = \sqrt{2} \cdot 4094{,}4\ \mathrm{A} + 5805{,}2\ \mathrm{A} = 11595{,}6\ \mathrm{A}.$$

The result is same as peak short-circuit current calculated in half periodic time. Functions drawn in figure 13 are evaluated from the beginning of short-circuit to 1500 ms with equation 13.

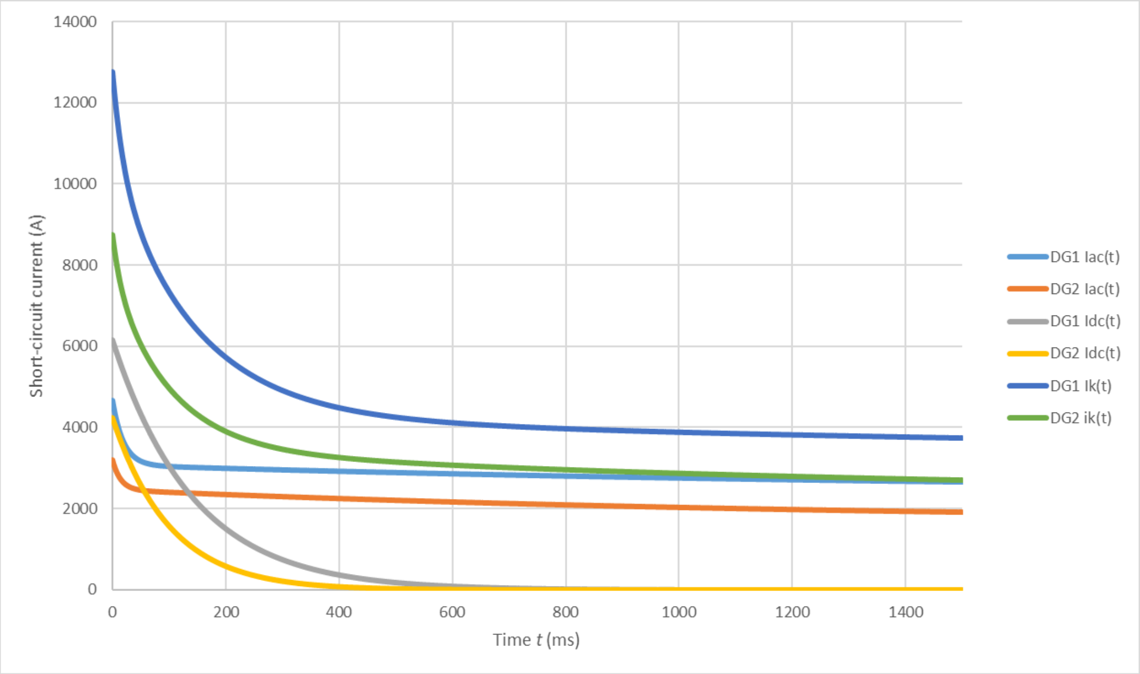

FIGURE 13. Short-circuit currents and -current components of two generators

Yellow and grey DC-components form the decaying waveform for the total short-circuit current in the beginning of short-circuit. After the DC-component has decayed, orange and light-blue AC-components hold the short-circuit current value. Calculation values for the first 58 ms are presented in appendix 2.

5.3.5 Short-circuit in 11 kV bus bar

Short-circuit current in 11 kV bus bar contains short-circuit currents of four parallel generators, seven parallel running medium voltage motors and two battery energy storages. 11 kV bus bar short-circuit current can be evaluated by adding together the currents from previous calculations. Total time depending short-circuit current in 11 kV bus bar is presented in figure 14.

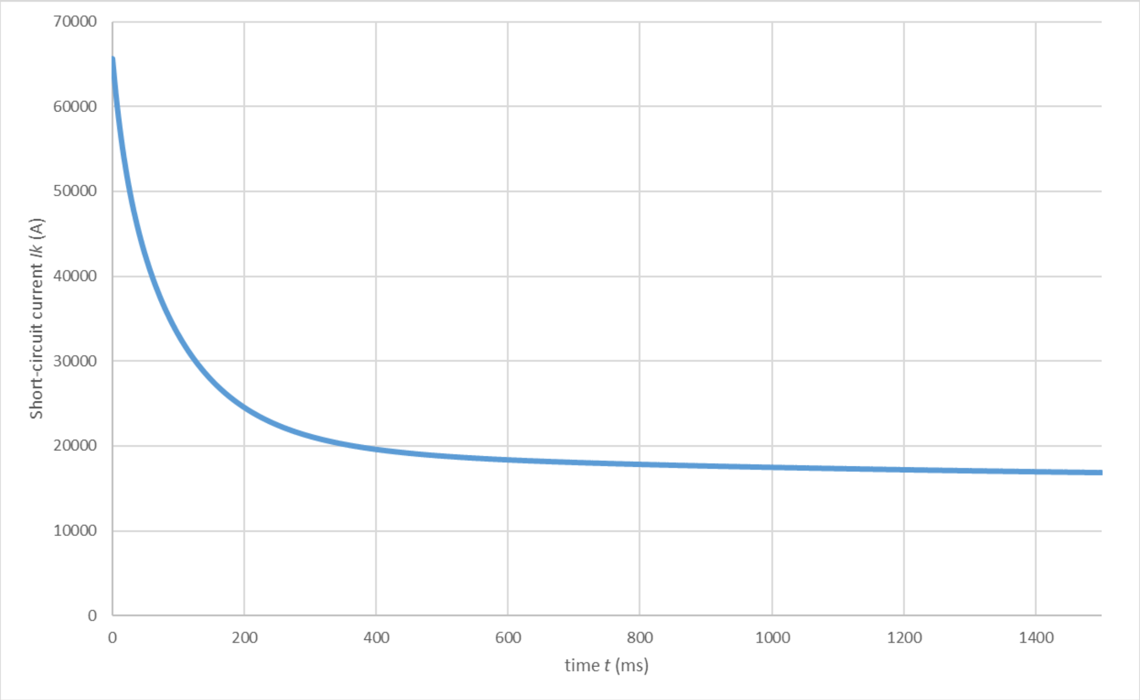

FIGURE 14. Total time depending upper envelope short-circuit current in 11 kV bus bar

Short-circuit current curve behavior is the same as upper envelope behavior in figure 5. Essential values of function in figure 14 is presented in table 12.

TABLE 12. Short-circuit current values in 11 kV bus bar

I_p	59,2 kA
$I_{AC(T/2)RMS}$	19,5 kA
A	27,6 kA
I_k	16,5 kA

Table 12 presents peak short-circuit current calculated in half periodic time, AC-component RMS-value (Root Mean Square) in half periodic time, initial value of decaying component and steady-state short-circuit current. Calculated values are also presented in appendix 2 for the first 58 ms. Bus bar needs to withstand the effects of short-circuit current. All short-circuit current sources have their own circuit-breaker.

5.3.6 Short-circuit in lower buses

Transformers change time constants and smooth the peak short-circuit current. Subtransient and transient time constants are increased and the DC time constant is decreased. If the secondary side short-circuit current will not cause the primary voltage to drop over 20 %, it is unlikely that the generators will react to short-circuit. In that case, transformer must be considered to be connected in to an infinite bus and calculations can be made with transformer impedance only. If the voltage drop is more than 20 %, new time constants need to be calculated and the impedances of passive components are added to generator impedances. (IEC 61363-1 1998, 36)

In this thesis it is assumed that the voltage drop limit is not exceeded and maximum short-circuit current I''_{kmax} in the secondary of the transformer can be evaluated from equation (2)

$$I''_{kmax} = \frac{c \cdot U_N}{\sqrt{3} \cdot Z_k} = \frac{c \cdot U_N}{\sqrt{3} \cdot \left(\frac{1}{Z_{T1}} + \frac{1}{Z_{T1}}\right)^{-1}} = \frac{1{,}1 \cdot 690\ \mathrm{V}}{\sqrt{3} \cdot \left(\frac{1}{0{,}0148\ \Omega} + \frac{1}{0{,}0148\ \Omega}\right)^{-1}} \approx 29{,}5\ \mathrm{kA}$$

Peak short-circuit current I_p is calculated with equation (19)

$$I_p = k \cdot \sqrt{2} \cdot I''_k = 2 \cdot \sqrt{2} \cdot 29{,}5\ \mathrm{kA} \approx 83{,}7\ \mathrm{kA}$$

Minimum short-circuit current I''_{kmin} is evaluated from equation 2 using voltage factor of 1

$$I''_{kmin} = \frac{c \cdot U_N}{\sqrt{3} \cdot Z_k} = \frac{1 \cdot 690\ \text{V}}{\sqrt{3} \cdot \left(\frac{1}{0{,}0148\ \Omega} + \frac{1}{0{,}0148\ \Omega}\right)^{-1}} \approx 26{,}9\ \text{kA}$$

Calculated short-circuit values for lower bus bars are presented in table 13.

TABLE 13. Calculated short-circuit values for lower buses

	MS01 690 V	RMU 690 V	RMU 400 V
I''_{kmin}	26,9 kA	13,5 kA	23,4 kA
I''_{kmax}	29,5 kA	14,9 kA	25,7 kA
I_p	83,7 kA	42,1 kA	72,7 kA

Circuit breakers and bus bars must be designed to withstand the peak short-circuit current and circuit breakers must be able to clear the minimum short-circuit current.

5.4 Selectivity analysis

Battery energy storage has a low nominal current in the AC-side. Nominal current is approximately 285 A with 5 MW feeding power. RMU-distribution has a nominal current of 389 A. 630 A vacuum circuit breakers with electronic relays can be used for both. Figure 15 presents selectivity graphs for both breakers.

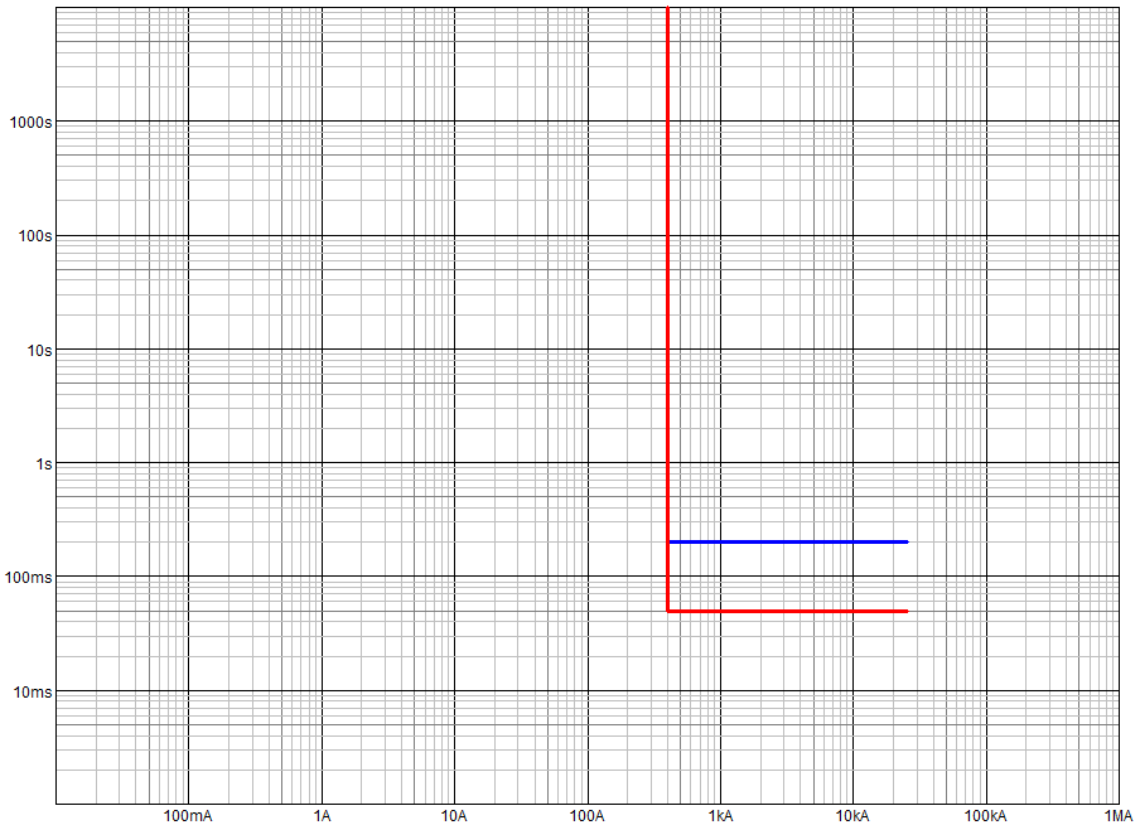

FIGURE 15. Selectivity graph of battery energy storage and RMU circuit breakers

Red line is circuit breaker of the RMU and blue line is circuit breaker of the battery energy storage. Relays allow setting to be modified but only time selective actions are allowed because of the low nominal and short-circuit –currents of the battery energy storage.

The protection relay after transformer must have at least thermal overcurrent protection, short-circuit protection and earth fault protection. Relay needs to be bidirectional protection relay. The relay has same conditions than generator relay when short-circuit appears in 11 kV bus. The transfer feeder between two buses is opened first and then if the fault was not in the other 11 kV bus, the protection relay of the energy storage is opened. This ensures that the whole system is not blacked out when only the other 11 kV bus is in short-circuit.

In figure 15 the relay settings are set to 150 ms time difference between two curves. Time difference includes two times 25 ms tolerance of the operating time, circuit breaker operating time (50 ms), retardation time of 30 ms and safety margin of 20 ms. (ABB 2011, 9)

Short-circuit protection can be considered selective with 150 ms time difference between the operating times of the breakers. However interlocking ensures that the protection relays operate in right order. One solution could be that components are sized to withstand the short-circuit currents calculated to lower level buses and devices. The battery energy storage protection would only trip if short circuit appears internally or in the 11 kV bus.

In DC-network, the protection is usually executed with 2-pole breakers. Breakers containing thermomagnetic protection relay can be used in DC protection. (ST 53.45 2015, 11.)

5.5 Space requirements

Space requirements are critical matter in ship. When some solution saves space in little amount of money, it is obviously considered for a better solution. Energy storage needs to be located near the switchboards they are connected to. Battery energy density and specific energy is better in Li-ion batteries which means that compared to Lead-acid batteries, Li-ion needs less storage weight and volume in the systems of same technical performance. Also Li-ion batteries have remarkably longer lifetime compared to lead-acid batteries. Li-ion batteries do not require oversizing and they have better charge and discharge rates. (Luo etc. 2014; Samsung SDI 2017, 10.)

Energy storage needs to be located near the switchboards they are connected to. Samsung SDI can fit 9,1 MWh energy storage to 40 feet ISO container so it gives a scale for the space needed to reserve for the batteries. However the customer decides the energy capacity needed. The weight of one cell is around 55 kg so the durability of the floor must be examined. (Samsung SDI 2017, 8.)

Batteries are placed on secured space. For ships the vibration must be taken into account. Protection platform is needed to be at least the size of one cell in case of the electrolyte leaking of the cell. Batteries must be also protected against water, fire and puncture. For battery room the ventilation is necessary to keep the temperature down and to lead possible dangerous gases outside. When natural ventilation is not enough, the forced ventilation is equipped. The air removed from the battery room needs to be leaded outside. Closed battery racks need more cooling than open space batteries. The air conditioning must be sized based on the maximum charging current for the batteries. Floor material needs to be such that there is no static charge inside the distance of 1,25 m from the batteries. Also maintenance operator needs to use ESD shoes and clothes that do not generate static charge. (SFS-EN IEC 62485-2:2018, 23-25.)

6 CONCLUSIONS

Energy storage can be used to increase system efficiency by responding to peak loads. Power variation generators can be decreased with batteries. Main engines can be used in constant power and energy can be taken from the storage during peak demands. When consumption is below production, excess energy can be used to charge the battery. Energy storages can be used to give additional power to cold start of the ship. In these ways the fuel expenses are reduced slightly. Largest ESS installed to ship is 4,16 MWh lithium battery energy storage unit. It is installed to Scandlines M/F Tycho Brahe -ferry. ABB delivered 10 kV and 10 MW shore connection which is supposed to recharge 1,2 MWh during port time which is 5,5 to 9 minutes. Estimated cost of the investment was approximately 29 million euros. Cooling for batteries are implemented with sea water. (ABB 2016b; Insideevs 2016.)

Disadvantage for an investment like this is that it is tailor made and not mass production. In addition if the system is not properly tested and studied before contract, it may cause technological problems and extra work leading to unexpected costs.

In high-power solutions like this, it is necessary to divide the power for multiple inverter units. Multiple inverters divide the current so that single power electronic switch inside the inverter unit can be sized smaller and cheaper. Parallel switches divide the current and serial switches divide the voltage. However serial switches can cause high voltages because of their switching time difference. Thyristors are best components for high-power inverters but thyristors are also expensive. Power electronics protection is also necessary. Component prices and characteristics need closer look when placing an order for inverters.

The nominal current of the batteries is low in the medium voltage AC-side. In addition short-circuit current fed by the batteries is low and can vary depending on the level of charge. To ensure that lower bus faults does not trip the energy storage protection relay, relay time settings need to be modified or interlocking function needs to be adapted. Interlocking can be used to achieve selectivity. Interlocking will guarantee fast operation for protection and with GOOSE message even faster. However interlocking can be expensive option for the wide distribution network of the ship. If interlocking is not used the only way is to modify different relay timing settings to step the protection as in figure 15. Protection relay settings need to be considered separately when precise system component values are available.

Some of the values for calculations in this thesis are received from manufacturer and some are guesstimate. Usually short-circuit calculations are made with commercial programs developed to professionals. Programs can model the passive and active component operations more specific than manually calculated.

The future sights for the technology is bright. Battery technology improves all the time and every year the energy density of the cells increased. Power electronic manufacturing also develops constantly. Component current and voltage durabilities rise and prices drop. If large energy storages are installed, it is recommended to study if the distribution could be changed to DC and what are the advantages and disadvantages of the DC distribution. There are many variables in a system like this. This matter needs further research and feasibility analysis to be installed in ships.

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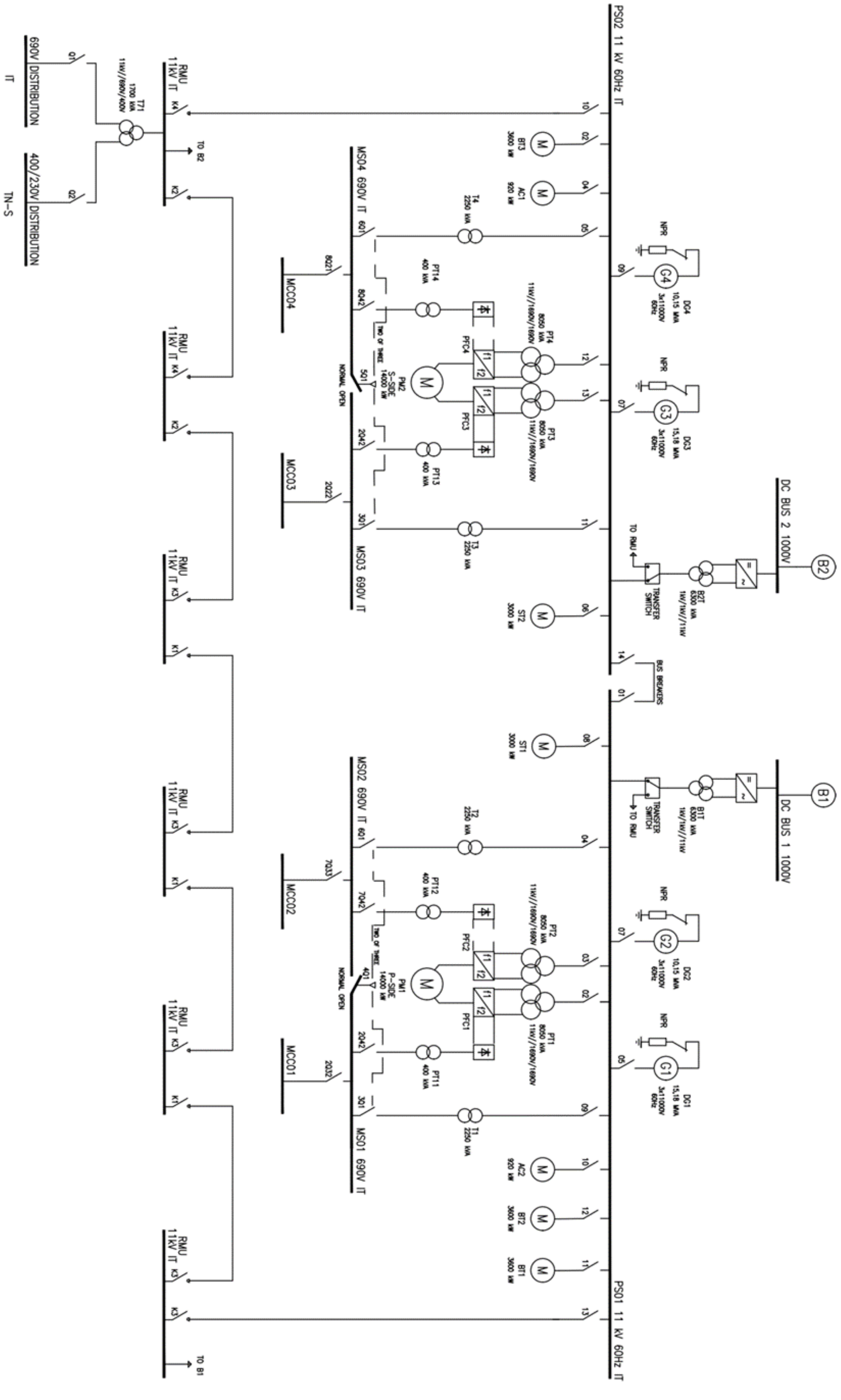
APPENDICES

Appendix 1. Single-line diagram



Appendix 2. Short-circuit current calculation values

	DG13	DG24	DG13	DG24	DG13	DG24	B12	ST	BT	AC	ST	BT	AC	ST	BT	AC	KOK
t	Iac(t)	Iac(t)	Idc(t)	Idc(t)	ik(t)	ik(t)	ik(t)	Iac(t)	Iac(t)	Iac(t)	Idc(t)	Idc(t)	Idc(t)	im(t)	im(t)	im(t)	ik(t)
0	4665	3203	6155	4224	12752	8754	1980	967	1248	283	1511	1980	436	2879	3745	836	65637
1	4583	3153	6112	4182	12593	8641	1980	957	1235	268	1486	1948	401	2839	3694	780	64749
2	4505	3105	6069	4141	12441	8532	1980	947	1222	254	1461	1915	369	2801	3643	729	63894
3	4431	3061	6027	4100	12293	8429	1980	937	1209	241	1437	1884	340	2762	3593	681	63071
4	4361	3019	5985	4060	12152	8330	1980	927	1196	229	1413	1852	312	2725	3544	636	62277
5	4294	2981	5943	4020	12015	8235	1980	918	1184	217	1390	1822	287	2688	3496	594	61512
6	4231	2944	5901	3980	11884	8144	1980	908	1171	206	1367	1791	264	2651	3448	556	60774
7	4170	2911	5860	3941	11757	8057	1980	899	1159	196	1344	1762	243	2615	3401	520	60061
8	4113	2879	5819	3902	11635	7973	1980	889	1147	186	1322	1732	224	2579	3355	486	59372
9	4058	2849	5778	3864	11517	7893	1980	880	1135	176	1300	1704	206	2544	3309	455	58705
10	4007	2821	5738	3826	11404	7816	1980	871	1123	167	1278	1676	189	2510	3264	425	58060
11	3957	2795	5697	3788	11294	7741	1980	862	1111	158	1257	1648	174	2476	3220	398	57436
12	3910	2771	5658	3751	11188	7669	1980	853	1100	150	1236	1620	160	2442	3176	373	56831
13	3866	2748	5618	3714	11085	7600	1980	844	1088	143	1216	1594	147	2409	3133	349	56244
14	3824	2727	5579	3677	10986	7533	1980	835	1077	135	1196	1567	135	2376	3090	327	55675
15	3783	2707	5540	3641	10890	7469	1980	826	1066	128	1176	1541	125	2344	3048	306	55122
16	3745	2688	5501	3605	10797	7406	1980	817	1055	122	1156	1516	115	2312	3007	287	54586
17	3709	2670	5462	3569	10707	7346	1980	809	1044	116	1137	1490	105	2281	2966	269	54064
18	3674	2654	5424	3534	10620	7287	1980	800	1033	110	1118	1466	97	2250	2926	252	53557
19	3641	2638	5386	3499	10535	7230	1980	792	1022	104	1100	1441	89	2220	2886	236	53063
20	3610	2624	5348	3465	10453	7175	1980	784	1011	99	1081	1418	82	2190	2847	222	52583
21	3580	2610	5311	3431	10374	7122	1980	776	1001	94	1064	1394	75	2160	2809	208	52115
22	3552	2597	5274	3397	10296	7070	1980	768	990	89	1046	1371	69	2131	2771	195	51659
23	3525	2585	5237	3364	10221	7020	1980	759	980	84	1029	1348	64	2103	2734	183	51214
24	3499	2574	5200	3330	10148	6970	1980	752	969	80	1012	1326	59	2074	2697	172	50780
25	3475	2563	5164	3298	10077	6923	1980	744	959	76	995	1304	54	2046	2661	161	50357
26	3451	2553	5127	3265	10008	6876	1980	736	949	72	978	1282	50	2019	2625	152	49943
27	3429	2544	5092	3233	9941	6830	1980	728	939	68	962	1261	46	1992	2589	142	49540
28	3408	2535	5056	3201	9875	6786	1980	721	930	65	946	1240	42	1965	2555	134	49145
29	3388	2526	5020	3170	9812	6743	1980	713	920	62	930	1220	39	1939	2520	126	48759
30	3369	2519	4985	3138	9749	6700	1980	706	910	58	915	1199	36	1913	2487	118	48381
31	3351	2511	4950	3107	9689	6659	1980	698	901	55	900	1179	33	1887	2453	111	48011
32	3333	2504	4916	3077	9630	6618	1980	691	891	53	885	1160	30	1862	2420	104	47649
33	3317	2497	4881	3046	9572	6578	1980	684	882	50	870	1141	28	1837	2388	98	47295
34	3301	2491	4847	3016	9515	6540	1980	677	873	47	856	1122	25	1813	2356	92	46947
35	3286	2485	4813	2987	9460	6501	1980	669	864	45	842	1103	23	1788	2324	87	46607
36	3272	2480	4779	2957	9406	6464	1980	662	855	43	828	1085	22	1765	2293	82	46273
37	3258	2474	4746	2928	9353	6427	1980	656	846	40	814	1067	20	1741	2263	77	45946
38	3245	2469	4713	2899	9302	6391	1980	649	837	38	800	1049	18	1718	2233	72	45624
39	3232	2464	4680	2871	9251	6356	1980	642	828	36	787	1032	17	1695	2203	68	45309
40	3221	2460	4647	2843	9202	6321	1980	635	819	35	774	1015	15	1672	2173	64	44999
41	3209	2456	4614	2814	9153	6287	1980	629	811	33	761	998	14	1650	2145	60	44695
42	3198	2451	4582	2787	9105	6254	1980	622	802	31	749	981	13	1628	2116	57	44397
43	3188	2448	4550	2759	9059	6221	1980	615	794	29	736	965	12	1607	2088	54	44103
44	3178	2444	4518	2732	9013	6188	1980	609	786	28	724	949	11	1585	2060	51	43814
45	3169	2440	4487	2705	8968	6156	1980	603	777	27	712	933	10	1564	2033	48	43531
46	3160	2437	4455	2679	8924	6125	1980	596	769	25	700	918	9	1544	2006	45	43252
47	3151	2434	4424	2652	8880	6094	1980	590	761	24	689	903	9	1523	1979	42	42977
48	3143	2430	4393	2626	8838	6063	1980	584	753	23	677	888	8	1503	1953	40	42707
49	3135	2427	4362	2600	8796	6033	1980	578	745	22	666	873	7	1483	1927	38	42441
50	3128	2425	4332	2575	8755	6003	1980	572	738	20	655	858	7	1464	1902	36	42179
51	3120	2422	4301	2549	8714	5974	1980	566	730	19	644	844	6	1444	1876	34	41922
52	3113	2419	4271	2524	8674	5945	1980	560	722	18	633	830	6	1425	1852	32	41668
53	3107	2417	4241	2499	8635	5917	1980	554	715	17	623	816	5	1406	1827	30	41418
54	3101	2414	4212	2475	8596	5889	1980	548	707	17	613	803	5	1388	1803	28	41172
55	3094	2412	4182	2450	8558	5861	1980	543	700	16	602	790	4	1370	1779	27	40929
56	3089	2409	4153	2426	8521	5834	1980	537	693	15	592	777	4	1352	1756	25	40690
57	3083	2407	4124	2402	8484	5807	1980	531	685	14	583	764	4	1334	1733	24	40454
58	3078	2405	4095	2378	8447	5780	1980	526	678	13	573	751	3	1316	1710	22	40222