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# GROUND ELECTRICITY INFRASTRUCTURES AND GRIDS

Prepared by:
Faculty of Maritime Studies, University of Rijeka
University of Trieste, Dept of Engineering and Architecture

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# Contents

# 1 INTRODUCTION

This report presents the results of activities carried out as a part of the Work Package 4.2. It is aimed to provide information about ground infrastructure and grids in ferry ports. It is more technically oriented and is based on the research results presented in delivery report for WP 4.1.

The evaluated technical solutions refer to the ports of Brestova (Istrian peninsula) and Porozina (island Cres) in Croatia, but the same methodology can be applied to any arbitrary ferry or passenger port and be used as a guide during the design of shore connection and battery charging systems.

Research conducted for the purposes of this report includes data collection and analysis of:

- Ferry power requirements for battery charging and cold Ironing (since the ship design activities are still ongoing, this study is based on one of the preliminary designs defined in the document "Preliminary Considerations on Machinery Configurations" and measurement results obtained on existing ferry between Brestova and Porozina);
- Possible hybrid all-electric power system topologies onboard ferry;
- Ferry operating profile;
- Power ratings of existing distribution grid components;
- Available power reserve on local MV supply lines;
- Distribution grid topology;
- Reliability indicators of distribution grid.

Main goal of this report is to evaluate the electrical parameters of the grid infrastructure and develop a methodology for the integration of ferry charging stations. For the ports where utility network must be upgraded, an optimal solution should be found with a goal of ensuring adequate supply and also keeping the connection and electricity costs to a minimum.

Future environmentally friendly hybrid and electrical ferries depend entirely on the ability to charge batteries while in port, so the reliability of the power supply will be a key factor when choosing the right charging system configuration. Distribution grids on islands and rural areas have mainly radial topology without possibility of redundant supply, so installing the energy storage system on shore side is the only solution for increasing reliability and enabling battery charging during power outages. In addition to that, it is necessary to evaluate if additional power system elements may be required (substations, distribution transformers, power converters, etc.).

Once implemented shore connection and battery charging systems must be safe both for people and interconnected equipment. In order to choose proper switching devices and determine required electrical protections and their settings, a load flow analysis needs to be performed together with short-circuit analysis, ground fault analysis, harmonic analysis, etc.

Since there are no reference ferry charging stations in Croatia and Italy, it is impossible to carry out any practical tests in line with the objectives of this work. For that reason, simulations will have an important role in evaluating the system behaviour. Although simulations cannot replace realistic measurements and tests, with well chosen and calculated electrical network parameters they can still provide satisfactory results for the evaluation of future solutions. In this report HOMER Pro and MATLAB software are used for simulation and system optimization when required.

The Report assumes working, management and technological presumptions of relevant and valid documents and recommendations of the International Electrotechnical Commision (IEC), International Organization of Standardization and other international expert bodies regulating electrical power system operational and safety procedures.

The Report is mostly based on the most recent data available, whenever possible or appropriate. Older sources are used in cases where there is  lack of data. When deciding between more reliable or more recent sources, as a rule, priority is given to sources with greater reliability.

The text of the Report is developed following the available scientific and expert knowledge of the electrical power system technology, i.e. in accordance with the accepted rules of science, profession and skill.

# 2 GROUND ELECTRICITY INFRASTRUCTURE

One important aspect of introducing hybrid or fully electrical shipboard power system is the analysis of the supporting land-based power infrastructure. The first information that needs to be identified is the installed power and capacity of battery banks on board. Since small ferries with capacity of approx. 100 cars and 400 passengers usually consume 1 MVA of electric power, it can be expected that batteries will be connected and charged via low voltage (LV) grid (in Croatia and Italy LV stands for 0.4 kV), according to the current low voltage shore connection (LVSC) standard, International Electrotechnical Commission (IEC)/IEEE 80005-3.

Usually the batteries will need to be recharged fast while the passengers and vehicles disembark. Fast recharging (for example, in 10 minutes) means that the power flow through the distribution network will be much higher and may cause overloading and undervoltage problems in the surrounding local grid. That leads to the next main problem, and that is to determine the available capacity of the nearby distribution network, owned and operated by the DSO (Distribution System Operator).

If the charging station is located near a densely populated area, then it can be expected that the distribution network is strong enough to deliver the required power, and possible upgrades will represent a minor investment for the DSO. However, if the charging station is located in a remote area, the proximity of an existing grid will represent a serious problem. If the existing medium voltage (MV) grid is far away and the existing infrastructure cannot match the required consumption, then either long MV cables must be laid down or an entirely new concept has to be defined.

The aforementioned concept involves installing a battery pack on land which will be slowly charged during the period of low consumption in the local grid (usually night time) and discharged during the day while the ferry is operational. This battery pack will be connected to the battery banks on board during the disembarkation of passengers and vehicles. This solution is feasible and saves a lot of costs associated with an unnecessary grid expansion, but since batteries degrade with time, their replacement costs must not be ignored and may affect the final decision.

There is one more problem that also needs to be solved, and it concerns the reliability of the distribution network. If the charging station is fed via a network consisting of long overhead lines with low reliability indices (SAIFI - System Average Interruption Frequency Index), then the cabling of the overhead lines and two-way supply must be considered in order to avoid possible network disturbances and long blackouts. In this way, network upgrades would ensure high reliability and enough capacity to directly feed the battery banks on board, thereby cancelling the need for land-based batteries.

In this report the analysis of ground infrastructure required for ferry shore connection and charging local will be done for ports Brestova and Porozina, but the same methodology can be applied for any arbitrary ferry port, especially on islands and smaller coastal places.

## 2.1 Basic features of MV and LV distribution grid in Croatia

Distribution grid is the final stage of electrical power transmission system and is used to distribute electrical energy to end users. Typical users connected to distribution grid are homes, industry, ports, city infrastructure, etc. In this chapter a brief overview of the structure and main characteristics of distribution grid in Croatia is given.

Distribution grid in Croatia is divided in two parts:

- Medium voltage (MV) distribution grid with rated voltages of 10/20/35kV
- Low voltage (LV) distribution grid with rated voltage of 0.4kV

Main components of distribution grids are:

- Overhead and cable transmission lines that carry electricity over distances that are far less than the transmission network (from a few tens of meters to a few tens of kilometres),
- Distribution transformers through which the electricity is transformed from MV to LV levels,
- Electrical consumers.

Consumer seen by the power grid represents each object that is connected to the grid and which takes real and reactive energy from it, but is also an integral part of the electrical grid which, depending on the operating characteristics, can be represented either as a fixed amount impedance independent of the node voltage, or variable impedance that depends on the actual node voltage.

Typical characteristics of distribution grids are:

- Lower voltage levels compared to the transmission grid ($U_{rated}$ <110 kV),
- Power transmission in the distribution network takes place over short distances,
- Motivated primarily by economic reasons, distribution grids usually have a radial structure which reduces operational safety,
- MV distribution grids in cities have ring topology, so in the case of failure of one line or transformer it is still possible to provide power from the other direction,
- LV grids and "rural" MV grids do not have possibility of two-way power supply,
- The main components of distribution grids are the same as in transmission networks, only designed for lower rated voltages, so performance is simpler.

The structure of MV distribution network can be:

- With two voltage levels (in the Republic of Croatia most often 35 - 10 kV), i.e. the distribution of electricity to low voltage is done through two transformations: first over 35 kV and then 10 kV networks. The 35 kV network is supplied from the transmission network transformers 110/35 kV.

- With one voltage level (in the Republic of Croatia 10kV or 20kV), in such a way that direct transformation110/10kV or 110/20 kV eliminates the need for a 35kV network.

Tendency of global distribution grid development is focused towards a reduction in the number of voltage levels. For that reason, single voltage level design (Figure 1) is the preferred construction design in the majority of new distribution substations and grids as well as those that are planned for replacement or retrofitting. There is also a strong trend to change the 10 kV voltage level to 20 kV wherever possible.

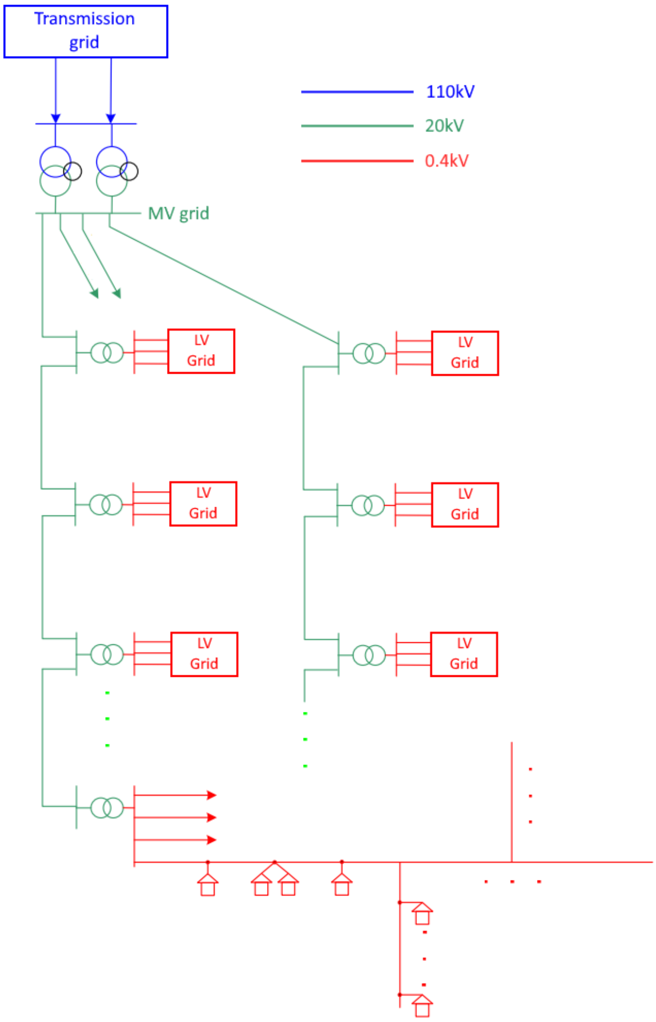



**Figure 1. Structure of distribution grid in Republic of Croatia**

The infrastructure of the ferry ports, which will also include future charging stations, is connected to the LV grid, so the main focus in this report will be on 0.4kV connection points. Circuit diagram of typical 10(20)/0.4kV TS with 0.4 kV bus bar is shown in Figure 2.

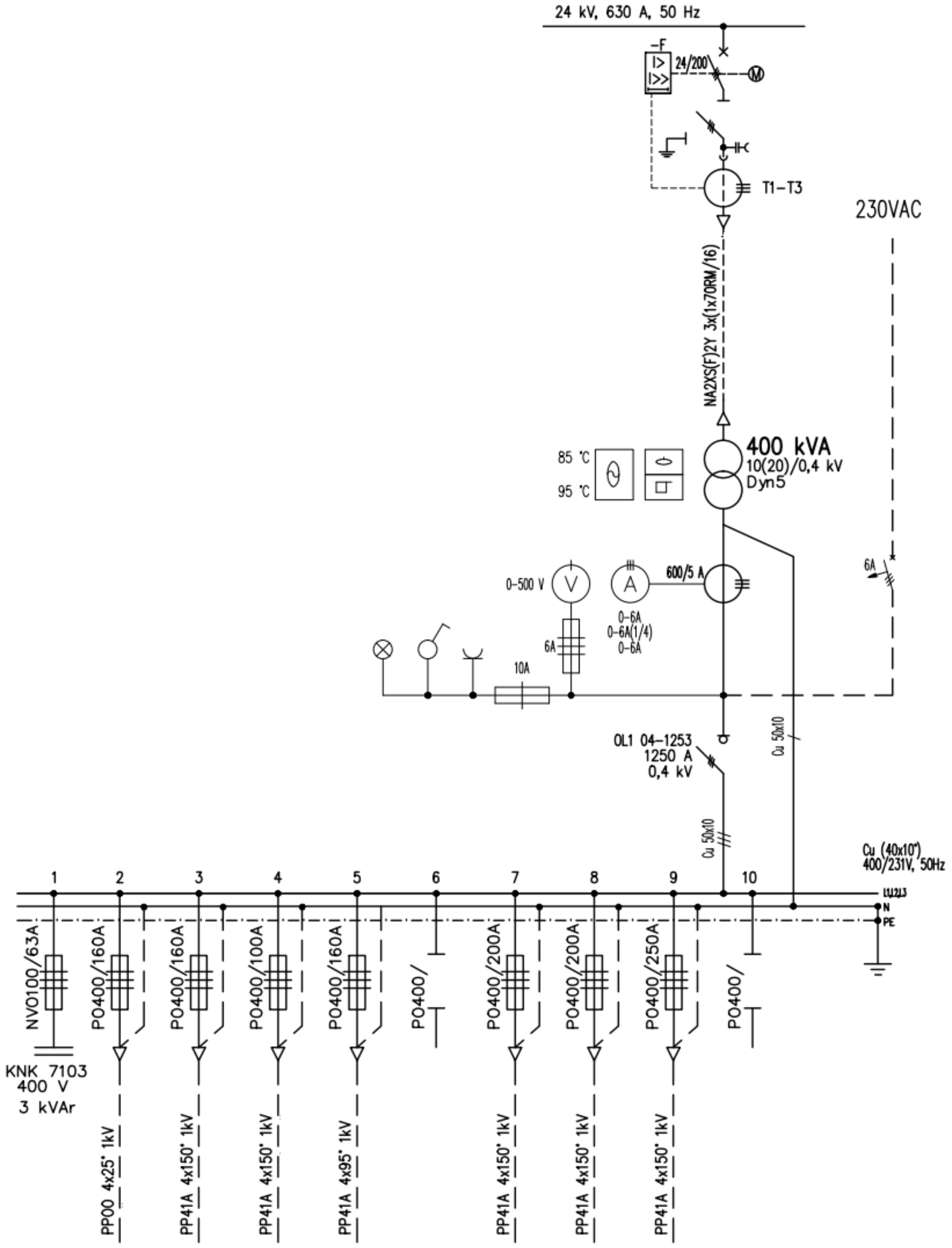



**Figure 2. Circuit diagram of typical public 10(20)/0.4kV TS**

LV grid is supplied from transformer substation (TS) 10(20)/0.4kV which commonly has one and rarely two transformers. The transformers are always directly earthed on LV side. Preferred earthing system is TN where all exposed and extraneous conductive-parts of the installation are connected directly to the earthed point of the power supply by protective conductors. Automatic circuit disconnection during fault in TN system is achieved by overcurrent protective devices (fuses, circuit breakers) or Residual Current Devices (RCD).

Standard power ratings of MV/LV transformers used in distribution grid are: 50, 100, 160, 250, 400, 630 and 1000 kVA. Various design solutions of MV/LV substations are possible, but in recent times a prefabricated substation is dominating. Typical KTS type TS for transformers up to 1000 kVA is shown in Figure 3.

**Figure 3. Standard 1000 kVA MV/LV transformer and typical KTS type TS**

After the power requirements from public or private users are determined, the design, installation and electrical protection of TS according to the requirements of reference standards and documentation is in the domain of the national DSO. Maximum rated power of MV/LV substation is 2000 kVA (two 1000 kVA transformers in same substation).

Since most of the public MV/LV substations are designed to meet the needs of households and civil infrastructure in the area where ferry port is located, it is unrealistic to expect that they will have a sufficient power reserve to meet the requirements of future shore connection/charging systems. Therefore, capacity of existing MV supply lines will play a key role in the possibility of increasing the power ratings of existing MV/LV TS, or installing new ones in the ports where this will be necessary. Again, it can be expected that in ports with limited power reserve the shore side energy storage systems will play important role in supporting the local grid.

## 2.2 Power supply reliability indicators in the distribution network

When it comes to connecting the user's equipment to the distribution grid, after defining its requirements, the user does not have too much influence on the realization of the LV or MV connection point. These aspects are in the domain of national DSO (Hrvatska Elektroprivreda - HEP in Croatia).

Therefore, while the user (electricity buyer) is responsible for all the equipment from the point of connection onwards, DSO must guarantee the quality, reliability and continuity of electricity supply in accordance with existing regulations. For specific consumers like considered ferry charging stations, it is crucial to have a continuous power supply, as any power outages would prevent battery charging while the ship is in port.

Power supply indicators (which are publicly available for the distribution grid in the Republic of Croatia) are calculated on the basis of data from electronic records, i.e. using the DISPO (Distribution Reliability) application, which has been in use at HEP since 2006. The application allows statistical processing of manually entered planned and unplanned network component downtimes with duration over three minutes.

To present the state of power reliability, the following indicators are most important:

- average number of long power outages of each network user (SAIFI),
- average duration of long power outages of each network user (SAIDI),
- average duration of long-term power outages per network user (CAIDI).

Figures 4, 5 and 6 below show the movement of SAIFI, SAIDI and CAIDI indicators for Croatian distribution grid during ten year period (2006 – 2016). From the perspective of ferry charging station, the most relevant indicator is SAIDI because it will directly affect the size of on shore ES in ports without possibility of redundant supply line.

It is important to emphasize that the stated permissible values at the level of the average per TS 10 (20) /0.4 kV are observed as average annual targets at the level of entire zones, i.e. groups of all TS 10 (20) /0.4 kV. Maximum allowable values (guaranteed level of power reliability) in the distribution grid are prescribed by the Croatian Energy Regulatory Agency (HERA).

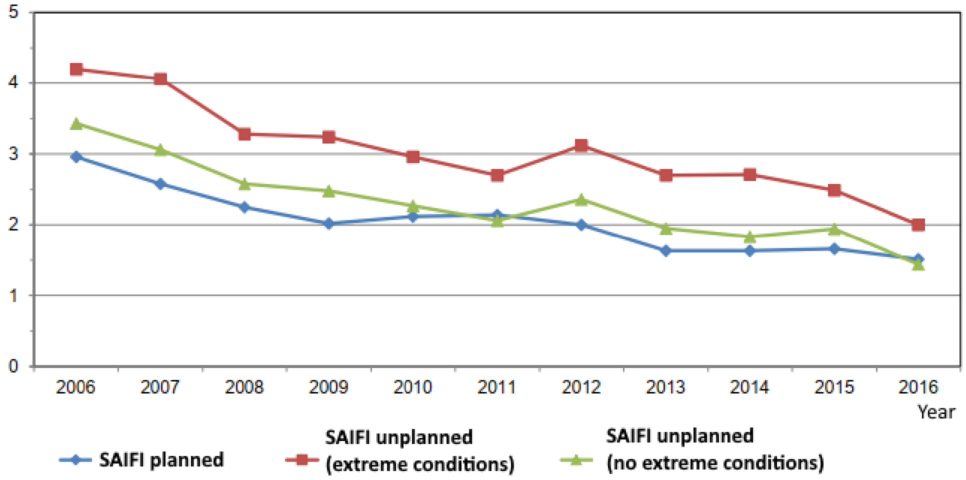



**Figure 4. Croatian distribution grid SAIFI indicators from 2007 to 2016**

If no actual values are available for the observed area or network element, power reliability analyses in the distribution network are carried out with the following experiential data:

- average time required to restore power to remotely controlled switching devices in distribution network: 10 min
- average time required to restore power in the case of manual switching control devices in the distribution network: 60 min
- time required to repair a fault on overhead lines: 300 min
- time required to repair cable faults: 960 min

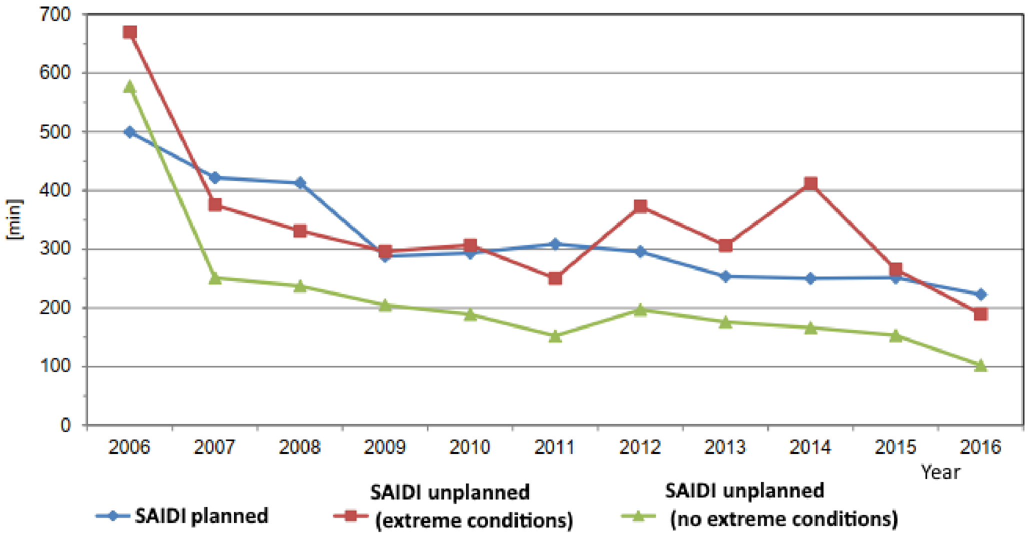



**Figure 5. Croatian distribution grid SAIDI indicators from 2007 to 2016**

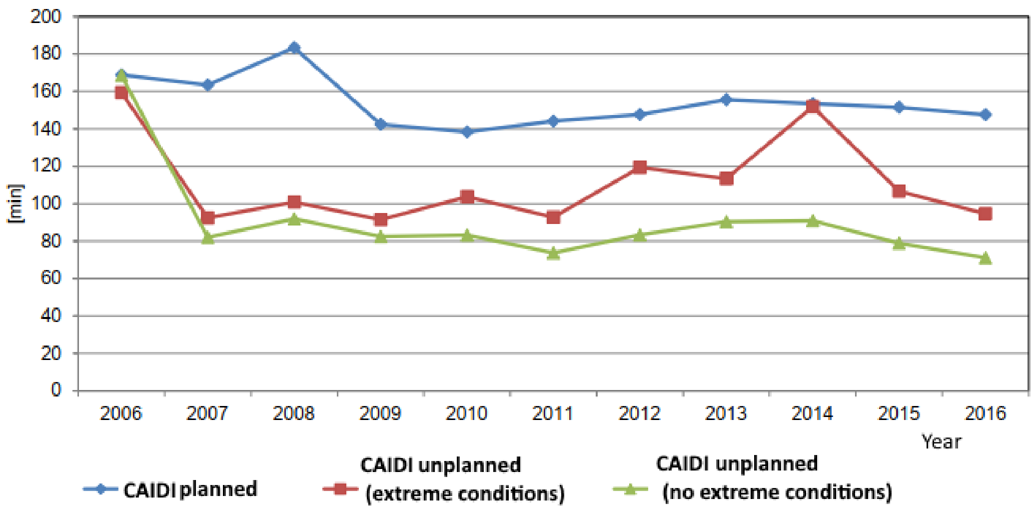



**Figure 6. Croatian distribution grid CAIDI indicators from 2007 to 2016**

## 2.3 Existing distribution grid in Brestova

Port of Brestova is dislocated from nearest populated places; 4.5km from Zagore (electrical power supply from TS Sisol) and 6.6km from Brseč (electrical power supply from TS Klančac). Existing 50kVA MV/LV transformer in Brestova is used only for supplying the port infrastructure. Transformer is placed in metal container which is located approximately 50 meters from the pier (Figure 7).

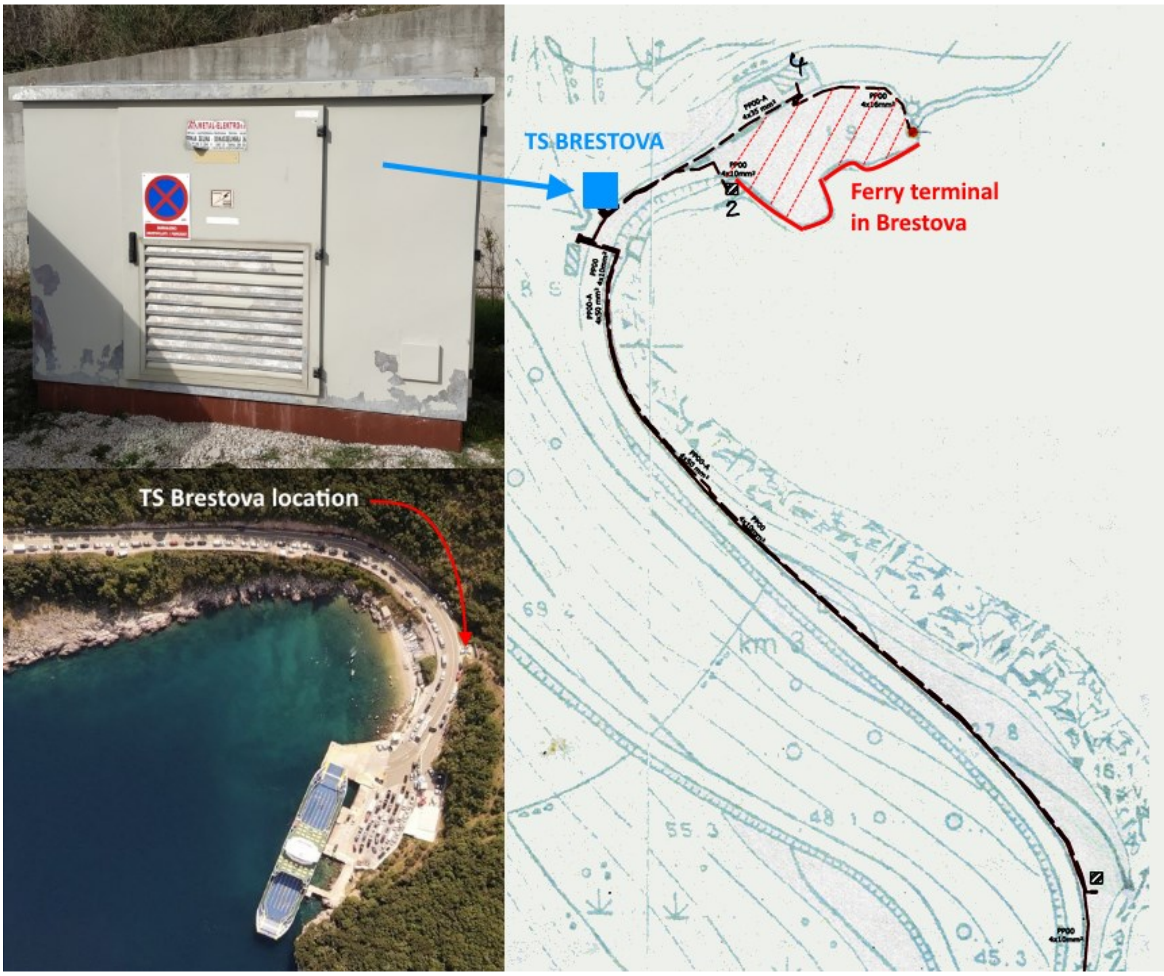



**Figure 7. Existing 50kVA TS (20/0.4kV) and its location in Brestova**

As there are no significant electrical consumers in port (restaurant, lighthouse, public lightning and ticket shop) measured average electrical consumption is low (Figure 8). As per current situation available power on LV side is between 40 and 45 kW.

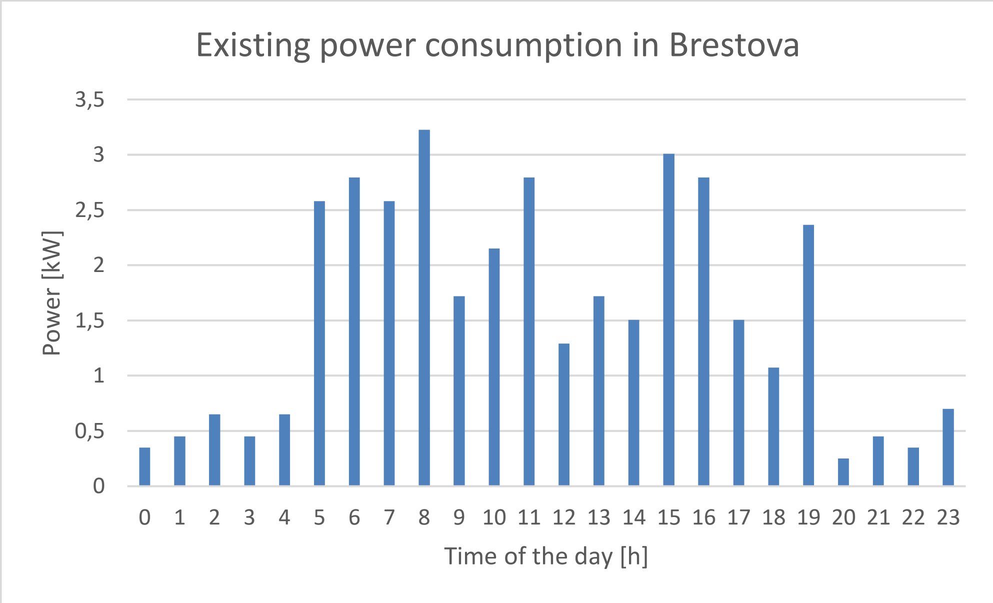



**Figure 8. Measured power consumption in Brestova during one day period**

Maximum transformer power rating that can be installed in existing container is 250 kVA. Installation of larger transformers (400 kVA to 1000 kVA) will require a new TS (preferably KTS type).

TS Brestova is connected to MV network with radial structure and there is no possibility of power supply from other direction, therefore it can be expected that long power outages may occur in case of power line faults or maintenance. Existing MV supply line has enough capacity for loads up to 2 MW.

## 2.4 Existing Distribution grid in Porozina

Unlike Brestova, port of Porozina is located in small populated area with 25-30 permanent residents, but with developed holiday neighbourhood, which is mostly populated during the summer tourist season. Existing MV/LV transformer is pole mounted, has a capacity of 250 kVA and is located 300 meters from the ferry pier (Figure 9). Total available power reserve during summer season at LV side does not exceed 50 kW.

According to the developing plan for the island of Cres, the construction of new 400 kVA TS is planned near the location of the existing one. Since the projected peak power of new TS is 315 kW the expected available power for battery charging will still be very low.

Existing MV power supply lines from 35/10 kV TS Cres can hold up to 4.5 MW of total power and current load is around 1MW. Same as in Brestova, it is connected to the radial MV network with no possibility of redundant power supply.


**Figure9. Existing 250kVA TS and its location in Porozina**

## 2.5 Brestova and Porozina – summary

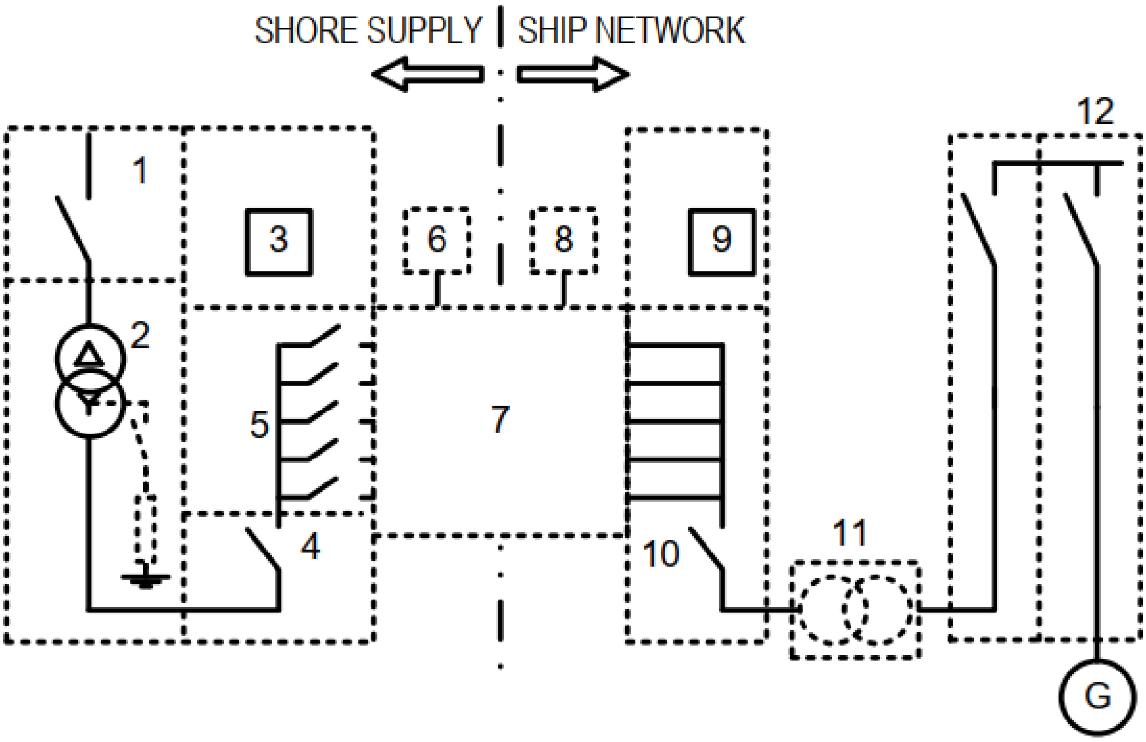
From the current state of distribution grid infrastructure in Brestova and Porozina, and future urban development plans for surrounding area, several conclusions can be drawn.

- In both ports, due to the radial network topology prolonged power outages may occur in case of system faults or environmentally caused effects (bad weather, lightning, etc.).
- Both ports will require on shore energy storage system to support distribution grid during battery charging and also to alow ferry charging during distribution grid power outages.
- Existing MV power lines in both ports will have enough capacity for shore connections up to 1MW even after planned upgrades will be completed.
- In port of Brestova same TS can be used for shore connection and public (port) infrastructure supply.

- Due to the low power reserve, even with the installation of the new TS and available energy capacity upgrade, port of Porozina will still require separate TS for shore connection system.
- Existing MV connection point for TS Porozina is placed about 300 meters from the port. If TS is to be located there (which is the most convenient solution) there may be a voltage drop problem on LV lines for shore connection supply.
- In both ports, any standard TS type up to 1000 kVA can be physically placed on existing locations if needed.

# 3 LV SHORE CONNECTION/CHARGING SYSTEM

The current trend of hybridization and electrification of coastal line ferries generates increasing demands on the construction of shore connection and battery charging systems. Block diagram of typical low voltage shore connection (LVSC) system according to IEC/IEEE CDV 80005-3 standard is shown in Figure 10. Requirements for distribution systems used on shore are given in IEC 60364, and ship distribution systems requirements are given in IEC 60092-101. In this report main focus will be on shore side infrastructure.




**KEYS**

1. SHORE SUPPLY SYSTEM
2. SHORE-SIDE TRANSFORMER AND NEUTRAL GROUNDING RESISTOR OR/AND IT POWER SYSTEM
3. SHORE-SIDE PROTECTION RELAYING NON INTEGRATED IN SHORE-SIDE CIRCUIT-BREAKER
4. SHORE-SIDE CIRCUIT-BREAKER
5. SHORE-SIDE FEEDERS CIRCUIT-BREAKERS
6. CONTROL SHORE
7. SHORE-TO-SHIP CONNECTION AND INTERFACE EQUIPMENT
8. CONTROL SHIP
9. SHIP PROTECTION RELAYING NON INTEGRATED IN ON-BOARD SHORE CONNECTION SWITCHBOARD
10. ON-BOARD SHORE CONNECTION SWITCHBOARD
11. ON – BOARD TRANSFORMER (WHERE APPLICABLE)
12. ON-BOARD RECEIVING SWITCHBOARD

**Figure 10. Typical low voltage shore connection/charging system**

Shore side infrastructure is supplied from local distribution grid and its main task is to transfer electrical energy to the vessel in a safe and efficient way. An equipotential bonding between the ship's hull and shore earthing electrode shall be established by the earth contacts of the plug, socket-outlet, ship connector and ship inlet. Construction of the LV equipment and operating safety procedures shall provide for the safety of personnel during the establishment of the connection of the ship supply, during all normal operations, in the event of a failure, during disconnection and when not in use.

The voltages and operating frequencies (Hz) of the ship and shore electrical systems shall match; otherwise, a frequency converter shall be utilized on shore. According to IEC/IEEE CDV 80005-3 where ships undertake a repeated itinerary at the same ports and their dedicated berths (which is the case for ferries), other IEC voltage nominal values may be considered.

For ferries, there are two options for realizing shore to ship connection and interface equipment (key 7 in Figure 5) for energy transfer from shore to ship: conventional plug in connections (Figure 11) and wireless inductive connections (figure 12).


**Figure 11. Example of plug in connection for ferries (source: www.siemens.com)**


**Figure 12. Example of wireless inductive connection for ferries (source: www.wartsila.com)**

The key factors that will dictate the configuration of shore side infrastructure for ferry shore connection and charging system are:

- available power from the existing distribution grid (as discussed in previous chapter),
- power system upgrade implementation possibility and costs,
- power converter requirement,
- type and location of charging station,
- system redundancy and fault tolerance
- possibility of using renewable power sources
- electrical power system topology on-board ferry (ship-side).

It is very difficult to reconcile the conflicting requirements for shore side charging power and the capacities of the existing ground infrastructure. This is especially the case in smaller island towns where the largest number of such ferries dock. There, the insufficient capacity of the electrical distribution grid often requires installation of additional energy storage (ES) system or renewable energy sources. Furthermore, the characteristics of battery storage modules on board ferries and associated charging systems are not unified, which poses a significant design problem for shore connection points, meaning that in most cases a suitable power converter will be required on shore.

## 3.1 Basic ferry power system topologies with battery ES

Although the focus of research in this report is placed on shore side infrastructure, it is necessary to briefly describe the possible configurations of ferry electrical power systems with battery ES.

Typical hybrid power system where batteries are used in combination with diesel electric propulsion is shown in Figure 13. Main advantage of this topology is that batteries can also be used as a stand-alone power source to provide power for propulsion motors, enabling zero emission operation when entering in port or emission free zones.

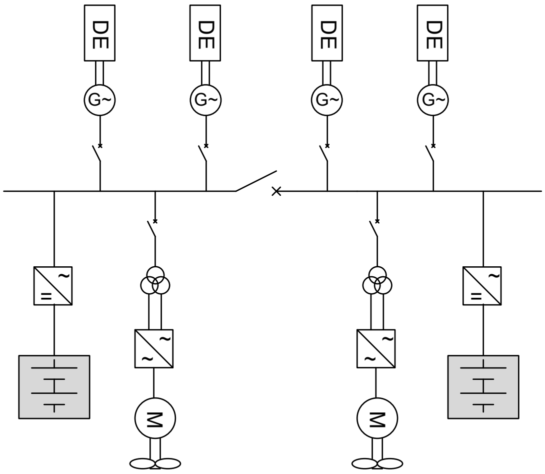



**Figure13. Hybrid propulsion with battery ES**

The most efficient power system topology for hybrid ferries in terms of emissions and fuel consumption is DC distribution shown in Figure 14.

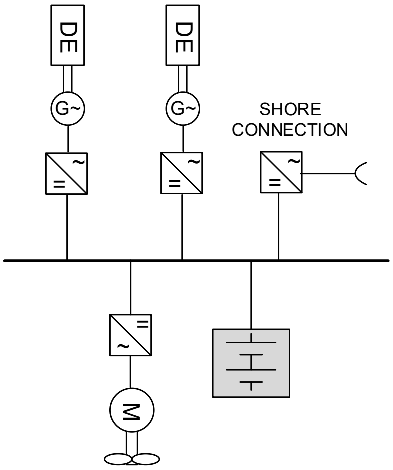



**Figure 14. Hybrid propulsion with DC distribution**

By using DC distribution further reduction of emissions can be achieved because the speed of main generators can be adjusted in dependence to load, which may significantly decrease SFC over a whole diesel engine power range. In addition to that, DC grid is taking far less space than traditional diesel-electric plant since there is no need for main switchboard and propulsion transformers.

Another hybrid solution that may be used on board ferries is to use power take off (PTO)/ power take in (PTI) hybrid electrical drive where mechanical and electrical propulsion is combined in kinematic drivetrain (Figure 15). In navigation, electrical drive is in PTO mode acting like a generator driven by main diesel engine. If main engine power is big enough to enable fast charging of battery storage during voyage, then inside harbour area electrical drive may be switched to PTI motor mode which may be powered by the batteries, auxiliary generators or combination of both. Batteries can also be used to provide additional shaft power when main engine and PTI motor runs in parallel.

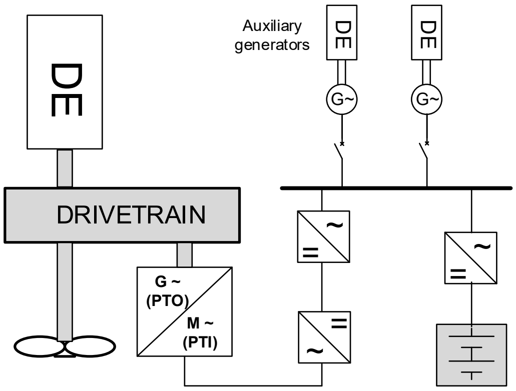



**Figure 15. Hybrid propulsion with DC distribution**

Finally, all electrical battery power system is shown in Fig. 16. It is the only solution that allows zero emission operation, but is completely dependent on shore side infrastructure required for battery charging.

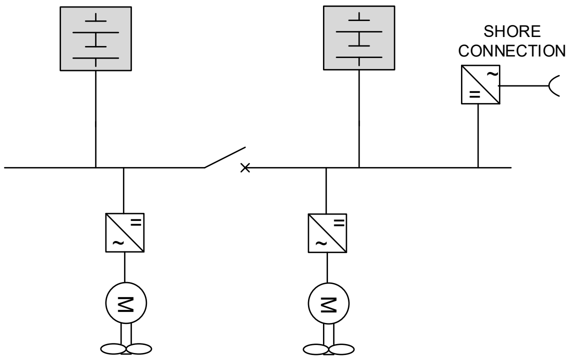



**Figure 16. All electric battery drive**

It can be seen that the method of charging battery ES on such ships will largely depend on the power system topology. For all electric ferries and ferries with DC distribution same connection point can be used for both battery charging and cold ironing, so it is logical to assume that power systems on new build vessels will be based on these topologies.

It can also be expected that a large number of existing ferries that are not yet at the end of their planned lifecycle will go through a kind of “hybridization” process in order to meet increasingly stringent environmental standards. Such ships will most likely require separate connections for cold ironing and charging. Therefore, it is very important that topology of ground infrastructure is flexible enough to meet different charging requirements, or it can be easily adapted to different requirements when needed.

## 3.2 Estimated power requirements and Proposed topology for ferry charging station in Bestova in Porozina

Based on inputs from WP3 (double-ended ferry design) and WP5 (route analysis) and power measurements on board ferry between Brestova and Porozina (Figure 17) following power requirements are estimated:

- Capacity of battery ES on board ferry: 500kWh
- Peak charging power: 500 kW
- Power required for cold ironing (ferry consumption while in port): 250 kW

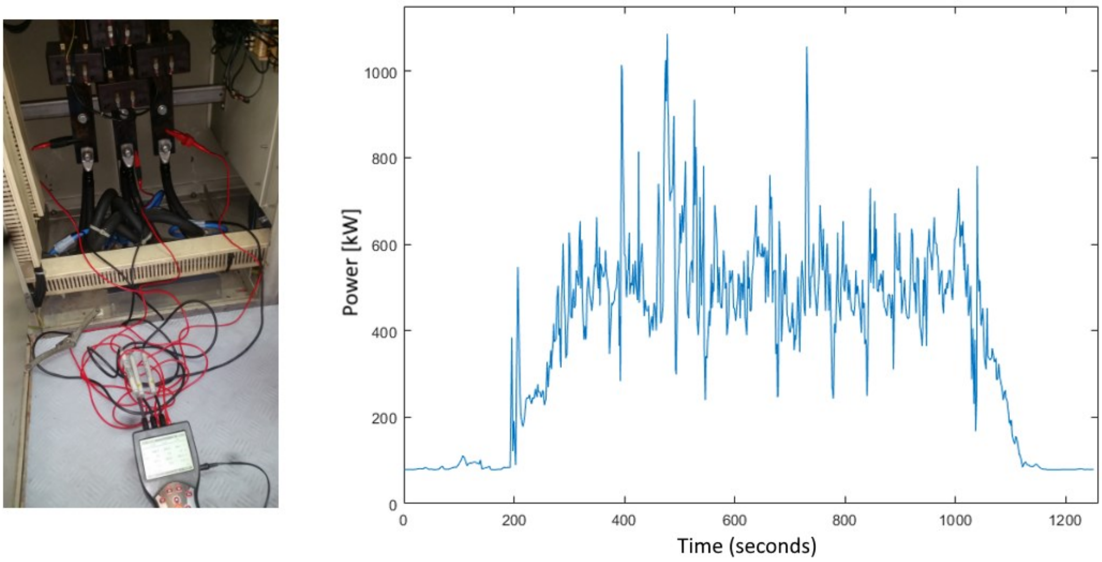



**Figure 17. Power measurement on board ferry during voyage between Brestova and Porozina**

Proposed hybrid double-ended ferry between Brestova and Porozina will use batteries as a primary power source during manoeuvring when entering/leaving port, and internal combustion engines during navigation.

Power system topology has not yet been determined but the proposed capacity of battery ES should be enough for planned exploitation profile. Ferry will be connected to shore side power during every stay in port. It is planned that equal charging stations will be placed in both ports.

The guiding thought during design of shore side charging infrastructure in Brestova and Porozina is to allow battery charging regardless of vessel power system topology and provide both AC and DC power when require.

Experience gained from exploitation of existing ferry charging stations, mostly in Norway and Sweden, has shown that on shore energy storage systems and renewable energy sources are key technologies for increasing energy efficiency and reliability of shore side power supply systems for ships. For this reason, it is also important to design shore side power infrastructure in such way to facilitate the easiest possible connection of such sources.

In order to meet the above conditions, a shore connection/charging system with a common DC bus is selected as a most suitable solution. (Figure 18).

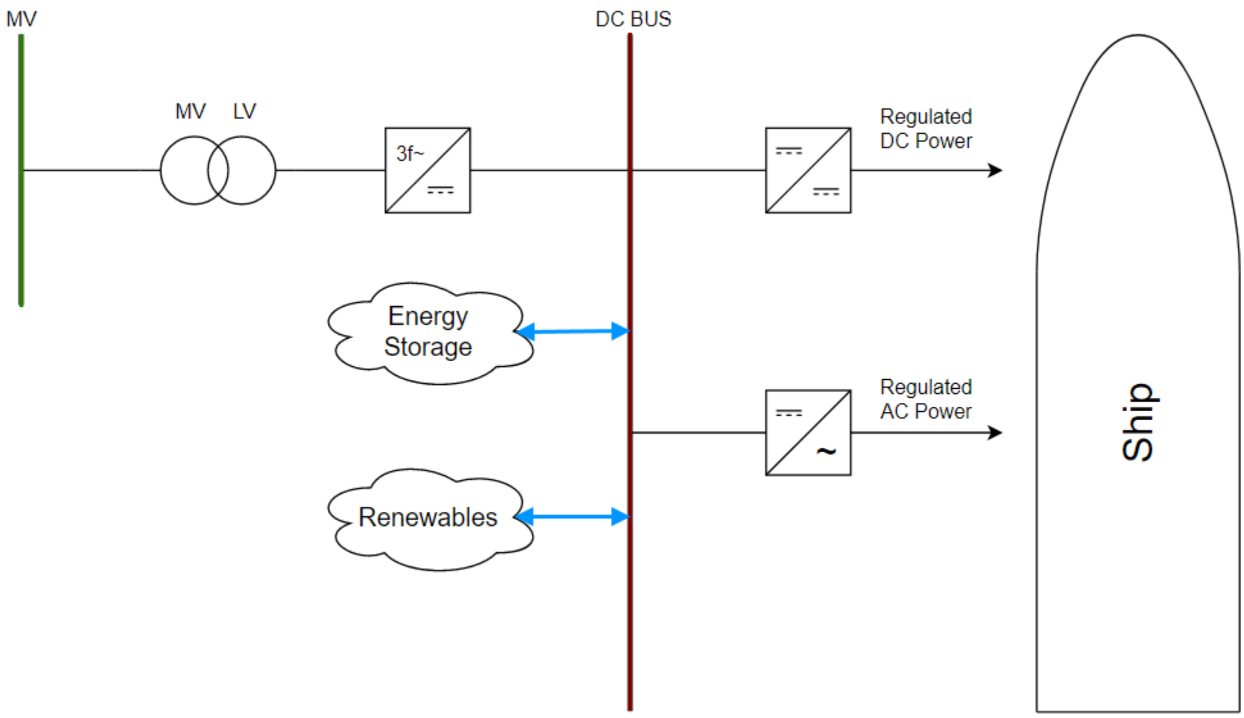



**Figure 17. Shore connection/charging system with a common DC bus**

There are many advantages of using the proposed topology of which the most significant are listed:

- Use of common DC bus can provide more efficient interconnection of system with different frequencies.
- When compared to AC bus, DC bus requires less power conversion stages for connections and interconnections of equipment.
- Parallel operation of multiple power sources is much easier on DC system because there is no need for synchronization.
- Rectifier can be placed in the same substation, together with MV/LV transformer, which reduce the length of 0.4 kV supply cables and consequently reduces possible voltage drop problems at high loads (this is especially applicable for port of Porozina).
- It is much easier to maintain required voltage level on DC system.
- There is no harmonic, reactive power and skin effect issues on DC bus.
- It is easier to design electrical protections because modern power electronic converters can almost instantaneously limit the current and power flow when required (e.g. system overload, short circuit, earth fault).
- By using higher DC bus voltage (750-1000 V) charging current, voltage drops and copper losses are reduced compared to 0.4 kV AC distribution.
- Battery storage system and renewable energy sources can be connected to DC bus via simple bi-directional DC-DC converters, which also facilitates power flow management.
- During power outages on supply distribution grid, important consumers within port facility can be supplied from battery energy storage.
- In future, with expected rapid grow of cars, trucks and busses, it will be much easier to realize charging stations for such vehicles and increase the port revenue by selling the energy from own micro grid.

# 4 OPTIMIZING THE SHORE SIDE POWER SYSTEM

The optimization of shore side power system is done with The HOMER Pro® microgrid software by HOMER Energy. This software is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected facilities like buildings, hospitals, schools, etc. It nests three powerful tools in one software product, so that engineering and economics work side by side: simulation, optimization and sensitivity analysis.

HOMER simulates the operation of a system by making energy balance calculations in each time step (interval) of the year. For each time step, HOMER compares the electric and thermal demand in that time step to the energy that the system can supply in that time step, and calculates the flow of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides in each time step how to operate the generators and whether to charge or discharge the batteries.

HOMER performs these energy balance calculations for each considered system configuration. It then determines whether a configuration is feasible, (i.e., whether it can meet the electric demand under the conditions that you specify), and estimates the cost of installing and operating the system over the lifetime of the project.

HOMER Pro has two optimization algorithms. The original grid search algorithm simulates all of the feasible system configurations and HOMER Optimizer® uses a proprietary derivative-free algorithm to search for the least-costly system.

## 4.1 Simulation model and parameters

The configuration of proposed charging station model realized in HOMER Pro® microgrid software is shown in Figure 19.

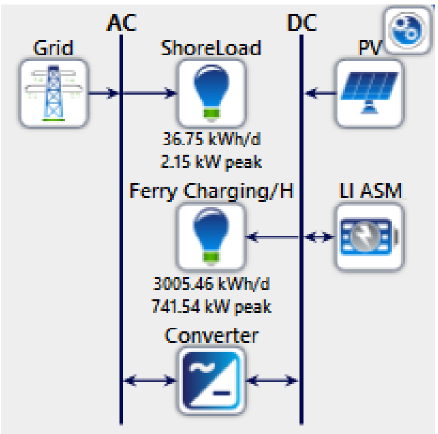



**Figure 19. Ferry charging station model realized in HOMER Pro® microgrid software**

The following initial parameters are used:

1. Grid parameters:
    - Grid sale capacity: 1000 kW.
    - Stand by charge (annual fee for connecting consumers to HEP's network- calculated from HEP's site for industrial consumers): $ 100 per year.
    - The purchasing price of electricity (including the price of labour and reactive power because industrial consumers pay both): $ 0.17 per kW
    - The selling price of electricity: $ 0.016 per kW

2. Grid reliability:
    - Number of power outages: 5 per year
    - Mean time to repair: 120 minutes

3. Power converter:
    - Installation costs: $ 400 per kW
    - Replacement costs: $ 300 per kW
    - Annual maintenance costs: $100 per year
    - Estimated life cycle: 15 years

4. On shore battery ES (Corvus Orca Energy is used in model):
    - Capacity of one battery bank: 125 kWh
    - DC voltage (min/rated/max): 800V/980V/1100V
    - Initial state of charge (SOC): 100%
    - Minimal allowed SOC: 20%
    - Degradation limit: 30% of full capacity (the influence of temperature on battery aging was taken into account (Figure 20))

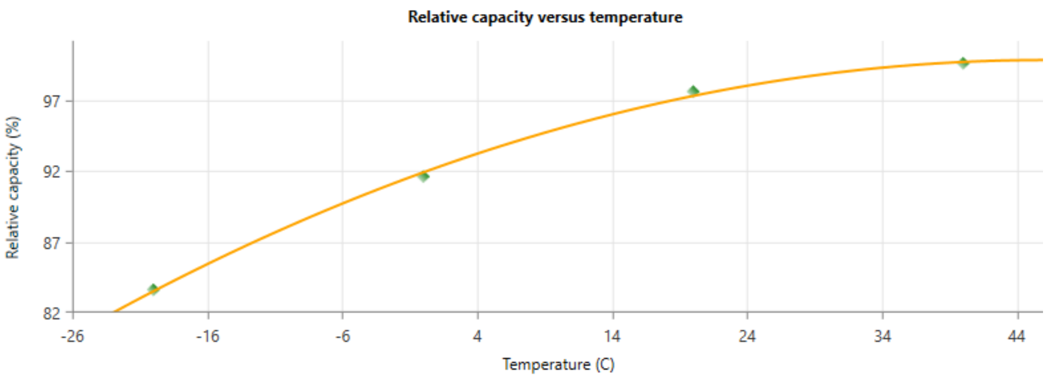



**Figure 20. Battery ES relative capacity vs temperature**

5. Photovoltaics (PV):
    - A generic flat panel without curvature or active sun tracking was modelled
    - Price: $2500 per kW
    - Global horizontal irradiance (GHI) data for Brestova-Porozina area (Figure 21) is taken from NASA database (part of HOMER software)
    - Estimated PV generated power during one year is shown in Figure 22.

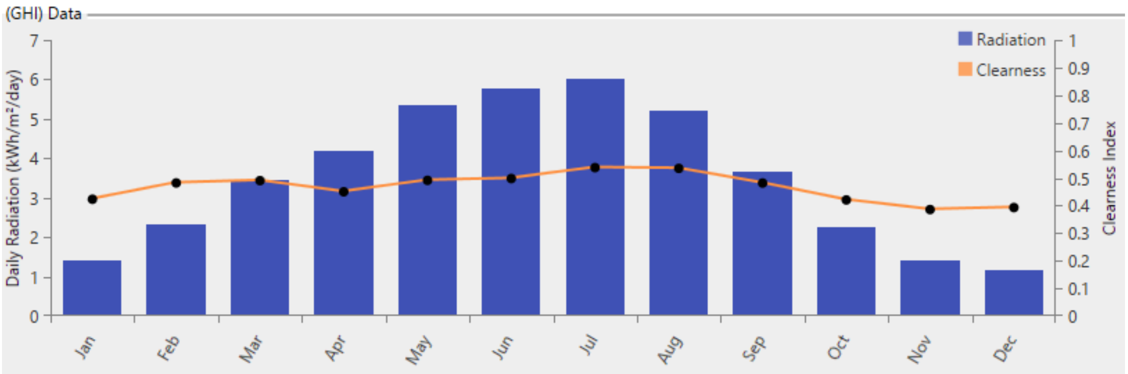



**Figure 21. GHI for Brestova-Porozina area**

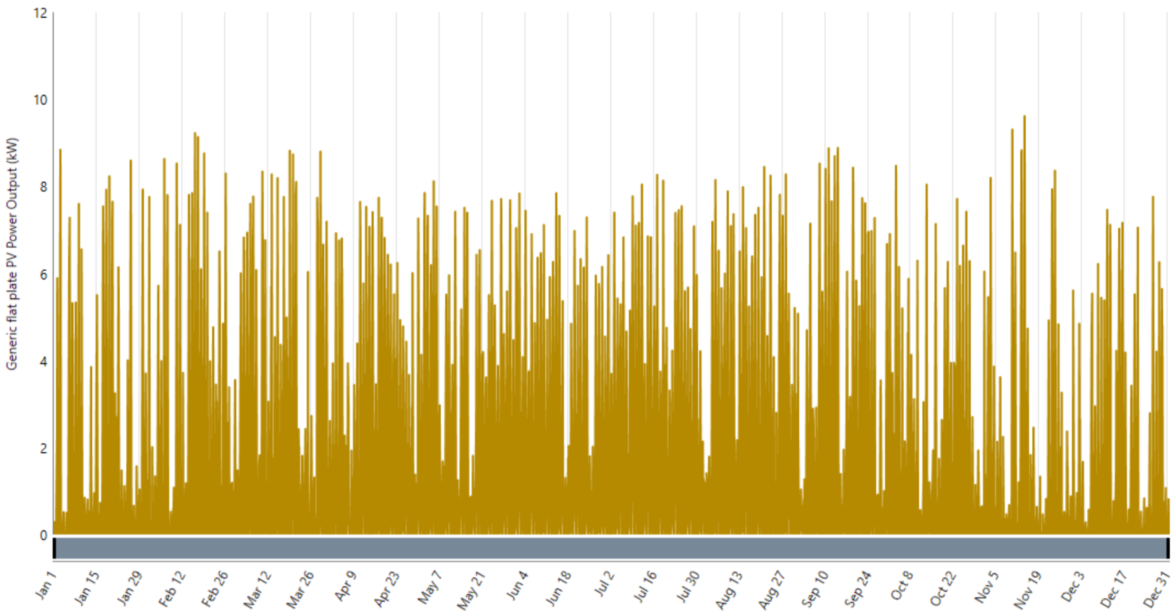



**Figure 22. Estimated PV generated power during one year**

6. Shore side load:
   - According to data from HEP, a generalized model was developed. The port infrastructure consumed power, both in Brestova and Porozina are extremely small to have an impact on the Ferry load.

7. Ferry charging and hotel load:
   - As mentioned in previous chapter, estimated power of the ferry hotel load is 250 kW and charging power is 500 kW. The schedule of arrivals and departures of the ferry was taken from the Jadrolinija and based on it a generalized charging schedule was made (Figure 23).

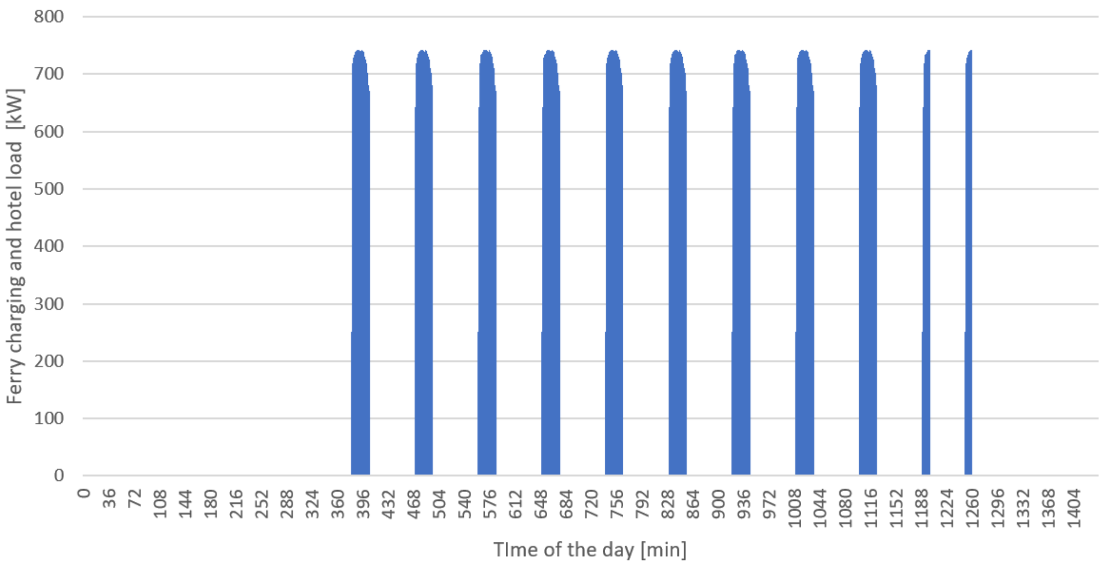



**Figure 23. Generalized charging schedule**

## 4.2 Simulation results

Simulation results based on previously defined parameters show two possible solutions for charging stations in Brestova and Porozina which are briefly summarized in Table 1.

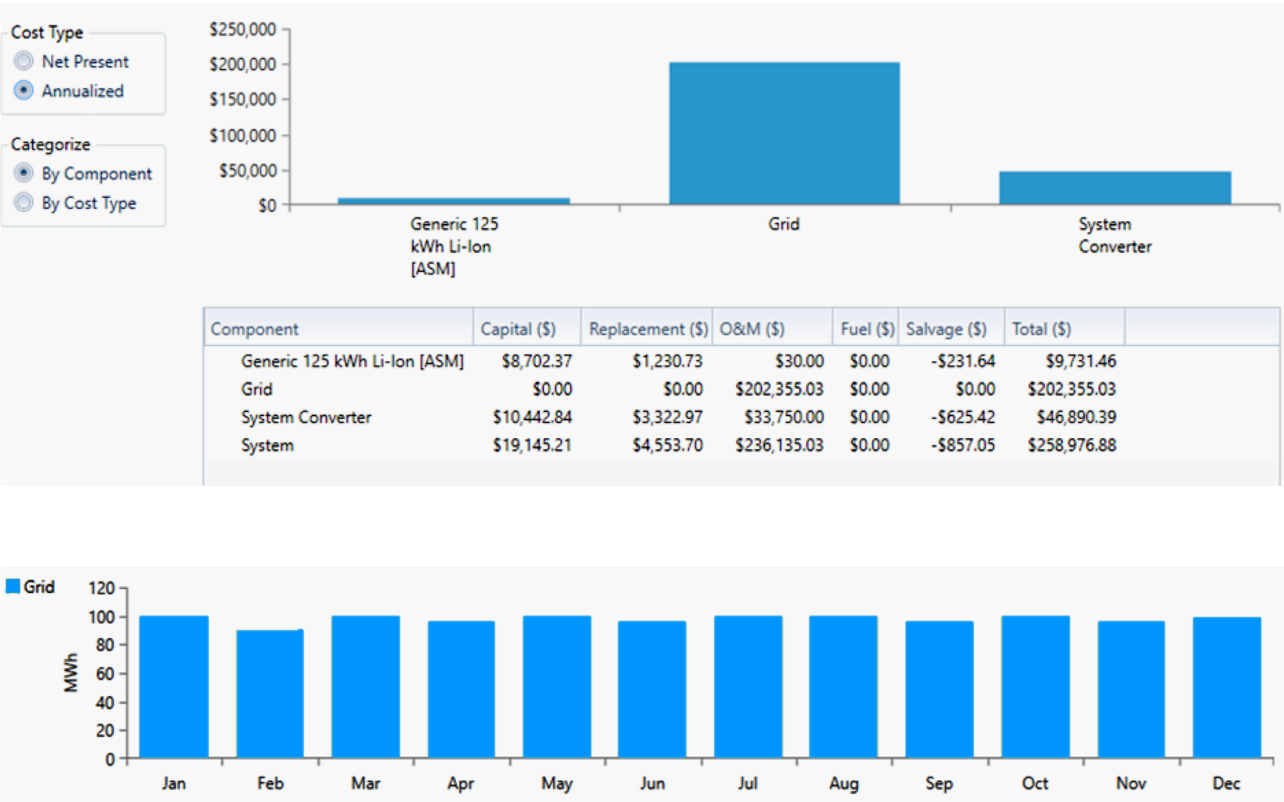
First solution includes PV panels but the battery is consumed almost to the end and is constantly at the lower SOC limit. In this configuration, reducing the size of the converter is supported because the batteries are partly charged from the solar panels. This reduces the cost of the system but also reduces reliability.

Second solution is far better in terms of reliability. The converter is larger so it maintain battery SOC status above minimum level. In addition, it is possible to put 5 to 10 kW of PV, but according to Homer, it is suboptimal from a financial point of view.

**Table 1. Summary of two possible solutions for ferry charging stations in Brestova and Porozina**

| | Solution 1 | Solution 2 |
|---|---|---|
| PV power | 9.36 kW | No PV installed |
| Battery ES power | 3 x 125 kW | 3 x 125 kW |
| Required converter power | 207 kW | 338 kW |
| Autonomy on battery ES only | 2,08 hours | 2,08 hours |
| Estimated initial costs | $ 220000 | $ 250000 |

The choice of solution will ultimately depend on the investor, but given that in such systems, reliability is in the first place, option number 2 is taken as the best solution. Also, if required it is very easy to add additional PV modules once the price and efficiency will be more favourable. Estimated annual cost by component for solution 2 and electrical energy demand from the grid can be seen in Figure 24.




| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Generic 125 kWh Li-Ion [ASM] | $8,702.37 | $1,230.73 | $30.00 | $0.00 | -$231.64 | $9,731.46 |
| Grid | $0.00 | $0.00 | $202,355.03 | $0.00 | $0.00 | $202,355.03 |
| System Converter | $10,442.84 | $3,322.97 | $33,750.00 | $0.00 | -$625.42 | $46,890.39 |
| System | $19,145.21 | $4,553.70 | $236,135.03 | $0.00 | -$857.05 | $258,976.88 |

**Figure 24. Estimated annual cost by component for chosen solution and electrical energy demand from the grid**

It is interesting to see how the system behaves during power outages on supply distribution grid. Battery SOC status during normal condition and during power outage of maximum estimates duration of 120 minutes is showed in Figure 25. It can be seen that chosen shore side battery ES can hold its SOC above 20% and charge the on board batteries during fault. Unmet load is marked with red line.

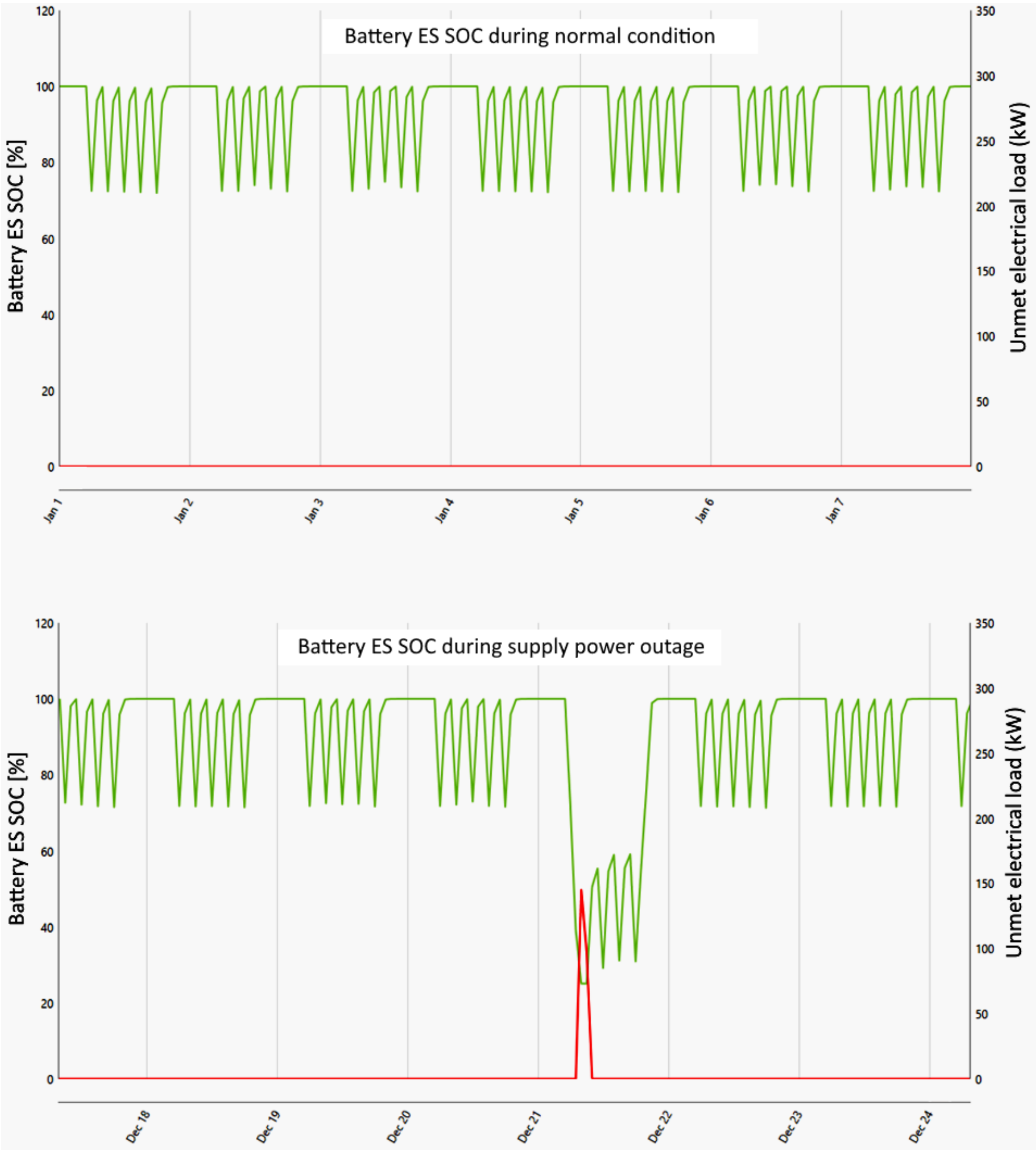



**Figure 25. Estimated annual demand for electrical energy from the distribution network**

Finally, rectifier output power is shown in Figure 26 and degradation of battery with time expressed in percentage of total capacity in figure 27. According to simulation results maximum expected life time of on shore Li-Ion battery ES is around 15 years, but it is more realistic to expect life time of 10-12 years.

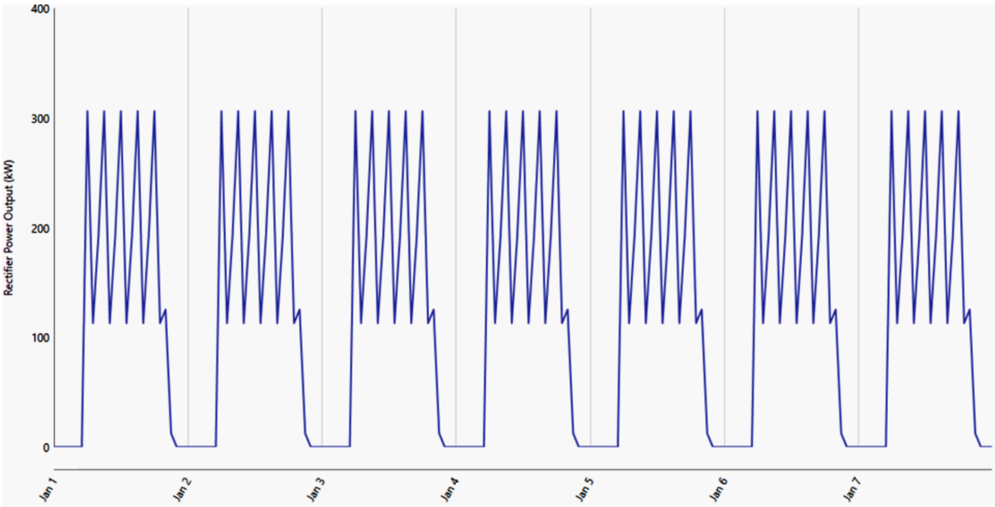



**Figure 25. Rectifier output power**

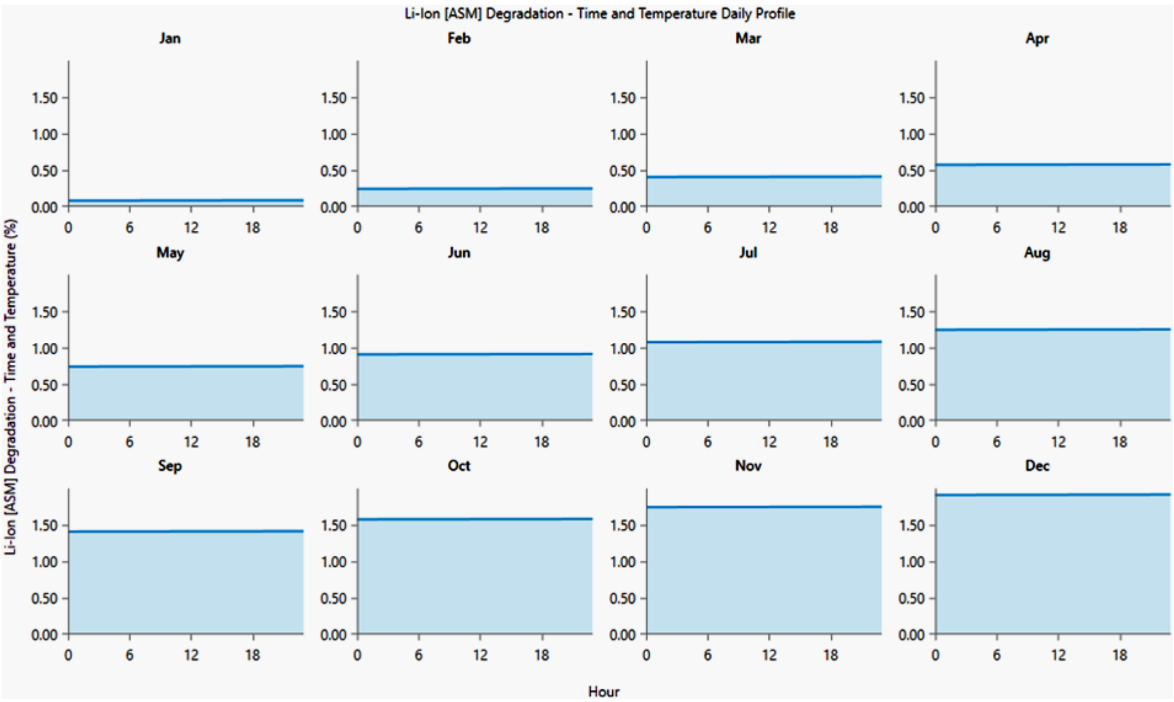



**Figure 25. Estimated annual demand for electrical energy from the distribution network**

# 5 POWER REQUIREMENTS FROM LV DISTRIBUTION GRID AND ELECTRICAL PROTECTIONS FOR CHARGING STATIONS IN BRESTOVA AND POROZINA

From simulation results in previous chapter, it can be seen that maximum rectifier load does not exceed 300 kVA, but in this calculation estimated maximum power of 340 kW will be used. Considering the fact that all modern AC/DC power converters have power factor between 0.95 and 1, the value of 0.95 is used as a worst case scenario. In this chapter basic electrical parameters required for choosing the power and size of MV/LV TS are calculated.

## 5.1 Calculating the peak current of LV supply line

The peak current load of the LV shore connection supply line $I_{pk}$ is approximately (with neglected grid losses and voltage drops):

$$|I_{pk}| = \frac{\sqrt{P_{pk}^2 + Q_{pk}^2}}{\sqrt{3} \cdot U_n}$$

$P_{pk}$ is peak active power load (340 kW in this case)

$Q_{pk}$ is peak reactive power load

$U_r$ is rated line to line voltage (0.4 kV).

$$Q_{pk} = P_{pk} \frac{\sqrt{1 - cos^2\varphi}}{cos\varphi} = 340 \frac{\sqrt{1 - 0.95^2}}{0.95} = 111.75\ kVAr$$

The approximate peak load current is:

$$|I_{pk}| = \frac{\sqrt{P_{pk}^2 + Q_{pk}^2}}{\sqrt{3} \cdot U_n} = \frac{\sqrt{340^2 + 111.75^2}}{\sqrt{3} \cdot 0.4} = 516.58\ A$$

## 5.2 Choosing the MV/LV transformer size

The selection of the minimum required transformer rated power $S_r$ in TS 10(20)/0.4 kV is calculated on the basis of the peak load, reserve factor $F_r$ and allowed transformer overload factor$F_{ol}$. Allowable loads of cables and transformers in the process of planning the distribution network development are given in table 2.

**Table 2. Allowable loads of cables and transformers**

| Grid element | Permanently permissible load (normal conditions) | Allowable load during the duration of an unplanned event |
|---|---|---|
| Overhead line | 100% $I_{pk}$ | 120% $I_{pk}$ (winter); 110% $I_{pk}$ (summer) |
| Cable | 100% $I_{pk}$ | |
| Transformer | 100% | 120% (winter) ; 110% (summer) |

The values of $F_r$ =0.2 and $F_{ol}$=1.1 are used.

Several approaches are possible for calculating required transformer power, but the most common method is:

$$S_r > \frac{P_{pk}}{F_{ol} \cdot (1 - F_r) \cdot cos\varphi} = \frac{340}{1.1 \cdot (1 - 0.2) \cdot 0.95} = 406{,}7\ kVA$$

Standard distribution transformer with rated power of 630 kVA satisfies the set requirements and is selected as solution for supplying shore connection infrastructure in Brestova and Porozina. Such transformer can be placed in standard concrete housing (KTS type). Depending on the manufacturer, the approximate average dimensions of such TS are: length 4 m, width 2 m and height 2, 8 m, so it can be easily placed at existing location in both ports.

### 5.2.1 Cable cross section and voltage drop

Power line sizing is the determination of the minimum standard conductor cross section that guarantees:

- that the voltage drop at the final consumer will not exceed the maximum allowed (less than 8% according to IEC60364-5-52 (Table 4))
- that the maximum current of the section under greatest load will be lower than the permanently allowed current of the selected cable

To accurately determine the minimum cross section of the LV cable, it is necessary to know the physical and electrical characteristics of the cable, the method of cable laying and temperature correction factors. Since the selection of cable and its laying design is in the domain of DSO, and most of required parameters cannot be directly obtained by measurement, a detailed calculation is out of scope of this report. However, to obtain a sufficiently accurate approximation minimum cross-sectional size for three phase power outlet can be determined from rated current:

$$I_r \geq \frac{I_{pk}}{CF}$$

$I_r$ is rated current

$CF$ is correction factor

Since it is not possible to predict correct value, it is assumed that LV cables will be laid according to manufacturer's recommendations, and that the ground temperature at the depth of one meter does not exceed 35°C. Using standard correction factor tables, selected CF value of 0.95 gives maximum rated current of LV supply cables of 544 A. Current carrying capacity of standard LV copper cables are given in Table 3.

**Table 3. Current carrying capacity of standard LV power cables**

| Conductor cross-sectional area | 2 cables, single-phase a.c. or d.c. | 3 or 4 cables, three-phase a.c. | 2 cables, single-phase a.c. or d.c. | 3 or 4 cables, three-phase a.c. | 2 cables, single-phase a.c. or d.c. flat and touching | 3 or 4 cables, three-phase a.c. flat and touching or trefoil | 2 cables, single-phase a.c. or d.c. flat | 3 cables, three-phase a.c. flat | 3 cables, three-phase a.c. trefoil | 2 cables, single-phase a.c. or d.c. or 3 cables three-phase a.c. flat | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Horizontal | Vertical |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| ($mm^2$) | (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) |
| 1 | 14 | 13 | 17 | 15 | 19 | 17.5 | – | – | – | – | – |
| 1.5 | 19 | 17 | 23 | 20 | 25 | 23 | – | – | – | – | – |
| 2.5 | 26 | 23 | 31 | 28 | 34 | 31 | – | – | – | – | – |
| 4 | 35 | 31 | 42 | 37 | 46 | 41 | – | – | – | – | – |
| 6 | 45 | 40 | 54 | 48 | 59 | 54 | – | – | – | – | – |
| 10 | 61 | 54 | 75 | 66 | 81 | 74 | – | – | – | – | – |
| 16 | 81 | 73 | 100 | 88 | 109 | 99 | – | – | – | – | – |
| 25 | 106 | 95 | 133 | 117 | 143 | 130 | 161 | 141 | 135 | 182 | 161 |
| 35 | 131 | 117 | 164 | 144 | 176 | 161 | 200 | 176 | 169 | 226 | 201 |
| 50 | 158 | 141 | 198 | 175 | 228 | 209 | 242 | 216 | 207 | 275 | 246 |
| 70 | 200 | 179 | 253 | 222 | 293 | 268 | 310 | 279 | 268 | 353 | 318 |
| 95 | 241 | 216 | 306 | 269 | 355 | 326 | 377 | 342 | 328 | 430 | 389 |
| 120 | 278 | 249 | 354 | 312 | 413 | 379 | 437 | 400 | 383 | 500 | 454 |
| 150 | 318 | 285 | 393 | 342 | 476 | 4036 | 504 | 464 | 444 | 577 | 527 |
| 185 | 362 | 324 | 449 | 384 | 545 | 500 | 575 | 533 | 510 | 661 | 605 |
| 240 | 424 | 380 | 528 | 450 | 644 | 590 | 679 | 634 | 607 | 781 | 719 |
| 300 | 486 | 435 | 603 | 514 | 743 | 681 | 783 | 736 | 703 | 902 | 833 |
| 400 | – | – | 683 | 584 | 868 | 793 | 940 | 868 | 823 | 1,085 | 1,008 |
| 500 | – | – | 783 | 666 | 990 | 904 | 1,083 | 998 | 946 | 1,253 | 1,169 |
| 630 | – | – | 900 | 764 | 1,130 | 1,033 | 1,254 | 1,151 | 1,088 | 1,454 | 1,362 |
| 800 | – | – | – | – | 1,288 | 1,179 | 1,358 | 1,275 | 1,214 | 1,581 | 1,485 |
| 1,000 | – | – | – | – | 1,443 | 1,323 | 1,520 | 1,436 | 1,349 | 1,775 | 1,671 |

It can be concluded that three 3x400mm² underground cables between LV distribution grid bus bars and on shore power converter will satisfy the requirements for this particular case.

**Table 4. Maximum allowed voltage drop according to IEC60364-5-52**

| Type of installations | Lighting circuits | Other uses (heating and power) |
|---|---|---|
| Low voltage installations supplied directly from a public low voltage distribution system | 3% | 5% |
| Low voltage installation supplied from private LV supply | 6% | 8% |

For a three-phase circuit, the voltage drop can be approximated using following formula:

$$\Delta v\% = \frac{100}{v_r^2} \cdot \left(r \cdot P_{pk} \cdot l + x \cdot Q_{pk} \cdot l\right)$$

Where $r$ is the cable resistance per unit length, $x$ is cable reactance per unit length, $l$ is length of cable and $v_r$ is rated line voltage. Electrical characteristics of typical LV cables at 70°C are given in table 5:

**Table 5. Electrical characteristics of typical LV power cables**

| Size mm² | AC resistance (ohm/km) | | Reactance (ohm/km) | | Impedance (ohm/km) | |
|---|---|---|---|---|---|---|
| | 50Hz | 60Hz | 50Hz | 60Hz | 50Hz | 60Hz |
| 1.5 | 15.4 | 15.4 | 0.141 | 0.169 | 15.4 | 15.4 |
| 2.5 | 9.45 | 9.45 | 0.130 | 0.156 | 9.45 | 9.45 |
| 4 | 5.88 | 5.88 | 0.120 | 0.144 | 5.88 | 5.88 |
| 6 | 3.93 | 3.93 | 0.113 | 0.135 | 3.93 | 3.93 |
| 10 | 2.33 | 2.33 | 0.107 | 0.128 | 2.33 | 2.33 |
| 16 | 1.47 | 1.47 | 0.0993 | 0.119 | 1.47 | 1.47 |
| 25 | 0.927 | 0.927 | 0.0955 | 0.115 | 0.932 | 0.934 |
| 35 | 0.668 | 0.669 | 0.0911 | 0.109 | 0.674 | 0.678 |
| 50 | 0.494 | 0.494 | 0.0883 | 0.106 | 0.502 | 0.505 |
| 70 | 0.342 | 0.343 | 0.0858 | 0.103 | 0.353 | 0.358 |
| 95 | 0.247 | 0.247 | 0.0833 | 0.0999 | 0.261 | 0.266 |
| 120 | 0.196 | 0.197 | 0.0817 | 0.0980 | 0.212 | 0.220 |
| 150 | 0.159 | 0.160 | 0.0814 | 0.0976 | 0.179 | 0.187 |
| 185 | 0.128 | 0.129 | 0.0807 | 0.0969 | 0.151 | 0.161 |
| 240 | 0.0983 | 0.0992 | 0.0792 | 0.0950 | 0.126 | 0.137 |
| 300 | 0.0793 | 0.0805 | 0.0782 | 0.0939 | 0.111 | 0.124 |
| 400 | 0.0634 | 0.0648 | 0.0776 | 0.0931 | 0.100 | 0.113 |
| 500 | 0.0510 | 0.0528 | 0.0770 | 0.0924 | 0.0924 | 0.106 |
| 630 | 0.0417 | 0.0438 | 0.0751 | 0.0901 | 0.0859 | 0.100 |
| 800 | 0.0350 | 0.0373 | 0.0741 | 0.0890 | 0.0820 | 0.0965 |
| 1000 | 0.0304 | 0.0328 | 0.0735 | 0.0882 | 0.0795 | 0.0941 |

Voltage drop calculation is done for the case where rectifiers are located on the terminal itself. Cable length for this scenario is approximated to be:

- 50 meters for the port of Brestova
- 300 meters for port of Porozina.

Calculated values are:

- $\Delta v\% = 0.94\%$ for port of Brestova
- $\Delta v\% = 1{,}63\%$ for port of Brestova

It can be seen that the selected cables satisfy installation requirements in both ports.

## 5.3 Short circuit current calculation

With reference to the diagram in Figure 26, a short-circuit is assumed on the load terminals (in this case power converter) terminal. The network can be studied and represented by using the resistances and reactances of each electrical component. The resistance and reactance values must be all related to the same voltage value assumed as reference value for the calculation of the short-circuit current (400 V in this case).

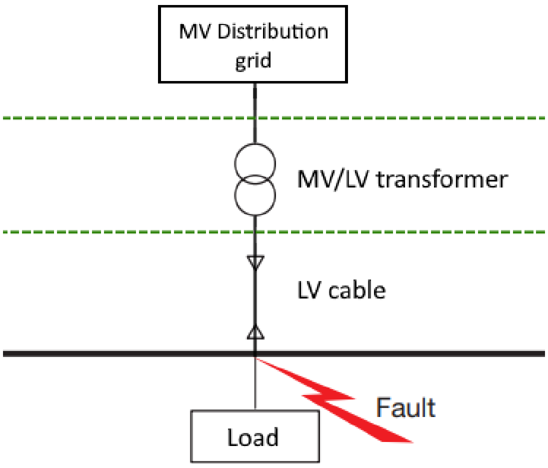



**Figure 26. Electrical network presentation for calculation of short circuit current at load terminals**

For the purpose of this preliminary research a power method for calculating three phase short circuit current is used. This method allows a quick but approximate evaluation of the three-phase short-circuit current in a network.

Since the fault is on the LV side, all the parameters determined for the MV section (20 kV) of the network shall be related to the secondary rated voltage (0.4 kV) by applying the following coefficient:

$$K = \frac{20}{0.4} = 50$$

The structure of the electrical network taken into consideration can be represented through system component resistances and reactances in series (figure 27) which allows equivalent impedance to be calculated as seen from the fault point.

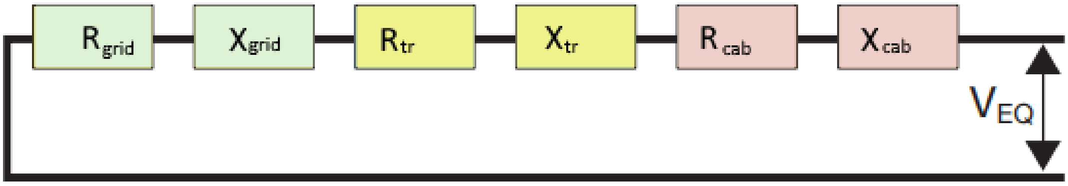



**Figure 27. Electrical network represented through system component resistances and reactances in series**

Equivalent voltage source at short circuit point is:

$$V_{eq} = \frac{c \cdot v_r}{\sqrt{3}}$$

The voltage factor *c* is used to simulate the effect of some phenomena which are not explicitly considered in the calculation, such as the voltage changes in time, the changes of transformer taps, the sub transient phenomena of the rotary machines (generators and motors), etc. In this calculation it will be assumed that c=1.1.

The impedance which represents MV distribution grid $Z_{grid}$ can be determined from its short-circuit apparent power $S_{kgrid}$ through the following relationship:

$$Z_{grid} = \frac{c^2 v_{grid}^2}{S_{kgrid}}$$

Short-circuit power values according to IEC 60076-5 Standard for different MV grid voltage values are given in Table 6.

**Table 6. Short-circuit power values according to IEC 60076-5 Standard for different MV grid voltage values**

| Distribution network voltage practice [kV] | Short-circuit apparent power Current European practice [MVA] | Short-circuit apparent power Current North-American [MVA] |
|---|---|---|
| 7.2–12–17.5-24 | 500 | 500 |
| 36 | 1000 | 1500 |
| 52–72.5 | 3000 | 5000 |

In this case $S_{kgrid}$=500 MVA will be used which gives:

$$Z_{grid} = \frac{1.1^2 \cdot 20000^2}{500 \cdot 10^6} = 968\ m\Omega$$

MV grid resistance and reactance can be calculated from $Z_{grid}$ by using following relationships:

$$X_{grid} = 0.995 \cdot Z_{grid} = 963.16\ m\Omega$$
$$R_{grid} = 0.1 \cdot X_{grid} = 96.316\ m\Omega$$

Short circuit current is calculated on the LV side, so all the parameters determined for the MV part of the grid must be related to the LV side by using the coefficient K:

$$Z_{grid\ LV} = \frac{Z_{grid}}{K^2} = \frac{0.968}{50^2} = 0.3872\ m\Omega$$

$$R_{grid\ LV} = \frac{X_{grid}}{K^2} = \frac{963.16}{50^2} = 0.3852\ m\Omega$$

$$X_{grid\ LV} = \frac{R_{grid}}{K^2} = \frac{96.316}{50^2} = 0.03872\ m\Omega$$

The impedance of the transformer can be calculated from the transformer nominal parameters: rated voltage on secondary winding $V_{2r}$, apparent power $S_{rTR}$ and short circuit voltage in percent $v_{k\%}$,

The values of short-circuit voltage $v_{k\%}$ in relation to the rated power of the transformers for typical distribution transformer are given in Table 7 (reference Standard IEC 60076-5). For selected 630 kVA transformer $v_{k\%}$=4 is used.

Table 7. The values of short-circuit voltage $v_{k\%}$ in relation to the rated power

| Rated apparent power $S_n$ [kVA] | Short-circuit voltage $v_{k\%}$ |
|---|---|
| ≤ 630 | 4 |
| 630 < $S_n$ ≤ 1250 | 5 |
| 1250 < $S_n$ ≤ 2500 | 6 |
| 2500 < $S_n$ ≤ 6300 | 7 |
| 6300 < $S_n$ ≤ 25000 | 8 |

Transformer impedance can be calculated by using the following formula:

$$Z_{tr} = \frac{V_{2r}^2 \cdot v_{k\%}}{100 \cdot S_{rTR}} = \frac{400^2 \cdot 4}{100 \cdot 630 \cdot 10^3} = 10.16\ m\Omega$$

Transformer resistive and reactive components can be obtained from the transformer total losses $P_{Ltr}$ and secondary winding rated current. According to data sheets of major transformer manufacturers (Siemens, ABB, and Legrand), maximum total power losses for 630 kVA dry type transformers varies between 10 kW and 12 kW. The value of 11 kW is used in calculation.

$$I_{2r} = \frac{S_{rTR}}{\sqrt{3} \cdot V_{2r}} = \frac{630 \cdot 10^3}{\sqrt{3} \cdot 400} = 909{,}32\ A$$

$$R_{tr} = \frac{P_{Ltr}}{3 \cdot I_{2r}^2} = \frac{11 \cdot 10^3}{\sqrt{3} \cdot 909.32^2} = 7.68\ m\Omega$$

$$X_{tr} = \sqrt{(Z_{tr}^2 - X_{tr}^2)} = \sqrt{(10.16^2 - 7.68^2)} = 6.65\ m\Omega$$

For calculation of LV cable resistance and reactance a data from table 5 is used. The calculation is done for cable length of 50 meters, so the values are:

$$R_{cab} = 3.965\ m\Omega$$

$$X_{cab} = 3.91\ m\Omega$$

The total short circuit impedance $Z_{Tk}$ is:

$$Z_{Tk} = \sqrt{\left(R_{grid} + R_{tr} + R_{cab}\right)^2 + \left(X_{grid} + X_{tr} + X_{cab}\right)^2}$$

$$= \sqrt{(0.3852 + 7.68 + 3.965)^2 + (0.03872 + 6.65 + 3.91)^2} = 16.03\ m\Omega$$

Finally, estimated three-phase short-circuit current on load terminals is:

$$I_{k3f} = \frac{c \cdot V_{2n}}{\sqrt{3} \cdot Z_{Tk}} = \frac{1.1 \cdot 400}{\sqrt{3} \cdot 16.03 \cdot 10^{-3}} = 15.85\ kA$$

Calculated short circuit current is below the range of maximum design values of short circuit currents for private and industrial LV connections points in Croatian distribution grid (Table 8).

**Table 8. Common design short-circuit current values for different connection voltage levels in Croatia**

| Rated voltage at connection point | Short circuit current (kA) |
|---|---|
| LV 0.4 kV (households) | 9 |
| LV 0.4 kV (industry/private) | 37 |
| MV 10 kV | 12.5 |
| MV 10 kV | 12.5 |
| MV 35 kV | 12.5 |

## 5.4 Choice of electrical protection devices

### 5.4.1 Protections against over current and short circuit

The scheme of proposed installation from utility grid to the LV load terminals for analysed solution is shown in Figure 28. Circuit breaker CB1 and associated protections is set by DSO.

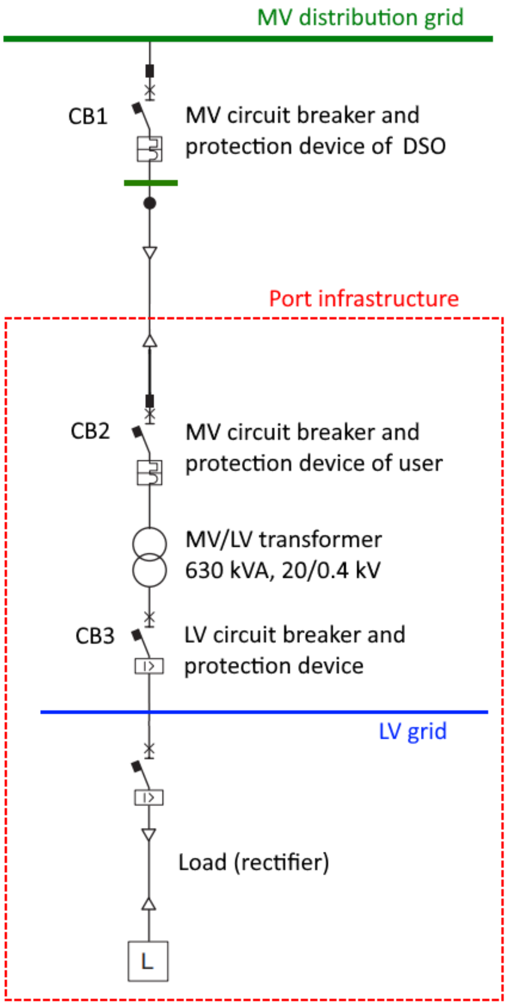



**Figure 28. Scheme of proposed installation from utility grid to the LV load terminals for analysed solution**

MV distribution grid (20kV) owned by the DSO company (HEP in Croatia) having its own MV protection device (CB1) usually characterized by independent maximum over current time tripping curves with two steps:

- First threshold with fault elimination time $< 0.5$ seconds (AC inverse time over current)

- Second threshold with fault elimination time $< 0.25$ seconds (Instantaneous over current)

Current settings depends on network characteristics, but average values that can be found in literature are about 70 A for first and 400 A for second threshold. In order to enable the selectivity of protection, it is necessary to determine the characteristics of CB2 and CB3 protection devices.

MV/LV 630 kVA transformer has secondary (0.4 kV side) rated current of 909.32 A (calculated in previous chapter). The primary rated current (20 kV side) is

$$I_{1r} = \frac{S_{rTR}}{\sqrt{3} \cdot V_{1r}} = \frac{630 \cdot 10^3}{\sqrt{3} \cdot 20 \cdot 10^3} = 18.2\ A$$

By using proven practical formulas to calculate currents that are really present in the installation, three phase short circuit current at the LV bus bar (secondary side of transformer) can be calculated as:

$$I_{2k} = \frac{S_{rTR}}{\sqrt{3} \cdot V_{2r} \cdot v_{k\%}} \cdot 100 = \frac{630 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 4} \cdot 100 = 22.733\ kA$$

Three-phase short-circuit current related to the MV side because of a fault on the LV side is

$$I_{1k} = \frac{S_{rTR}}{\sqrt{3} \cdot V_{1r} \cdot v_{k\%}} \cdot 100 = \frac{630 \cdot 10^3}{\sqrt{3} \cdot 20 \cdot 10^3 \cdot 4} \cdot 100 = 454.6\ A$$

or valuated by different relation

$$I_{1k} = \frac{I_{2k}}{V_{1r}} \cdot V_{2r} = \frac{22733}{20000} \cdot 400 = 454.66\ A$$

Load rated current is 517 A (calculated in previous chapter).

Based on the calculated values and practical recommendations for MV/LV transformer protection circuit, following settings are recommended:

1. **CB 2**

The overcurrent protection on the MV side of the user has usually two tripping thresholds;

- overload protection, also indicated with I>
- short-circuit protection, also indicated with I>>.

The setting values of currents and times for each threshold shall be set, whenever possible, at a level lower than the protections of the DSO (CB1). In addition to the two thresholds previously identified for the CB2 protection settings the following protection functions can be assigned:

- protection against the transformer overload, not strictly necessary if already provided by the circuit-breaker on the LV side or by any other dedicated devices, such as for an example thermometric equipment which controls the temperature inside the machine through thermal probes,
- protection against short-circuits on the secondary of the transformer; on the supply side of the LV circuit breaker,

Recommended settings for CB2 are:

- Over current protection I>:  60 A, 0.4 s, related to 20 kV. That corresponds to 60x20000/400=3 kA threshold for I>>.

- Short circuit protection I>>: 350 A. 0.2 s, related to 20 kV. That corresponds with 360x20000/400= 17.5 kA

For the calculated current values, a standard MV vacuum or gas (SF6) circuit breaker shown on Figure 30 can satisfy the set requirements for CB2.

2. **CB 3**

In general LV breaker on CB3 position shall have:

- a breaking capacity related to the voltage on the LV side, greater than the r.m.s. short-circuit current value on the LV bus bar (22.72 kA),

- a making capacity higher than the peak value of the short-circuit current on the LV bus bar (between 40A and 45A, depending on transformer characteristics and short circuit power factor),
- a rated uninterrupted current, suitable for the maximum current of the installation, coinciding with the rated current of the transformer secondary winding,
- a size which, through proper settings, guarantees selectivity with the MV protection device upstream and with the circuit-breakers provided for the loads downstream

For the calculated current values a standard moulded case circuit breaker (MCCB) shown on Figure 30 can satisfy the set requirements for CB3.

**3. CB 4**

In general LV breaker on CB 4 position shall have:

- a breaking capacity greater than the r.m.s. short-circuit current value on the load installation point (15.85 kA),
- a rated uninterrupted current, suitable for the maximum current of the installation,
- a size which, through proper settings, allows cable protection against overload and against short-circuit.

For the calculated current values a standard moulded case circuit breaker (MCCB) can satisfy the set requirements for CB3.


**Figure 29. MV vacuum circuit breaker suitable for CB 2 position (source: ABB)**

**Figure 30. LV Moulded Case Circuit Breaker (MCCB) circuit breaker suitable for CB 3 and CB 4 position (source: ABB)**

Proposed selectivity charts for considered supply network is shown in figure 31.

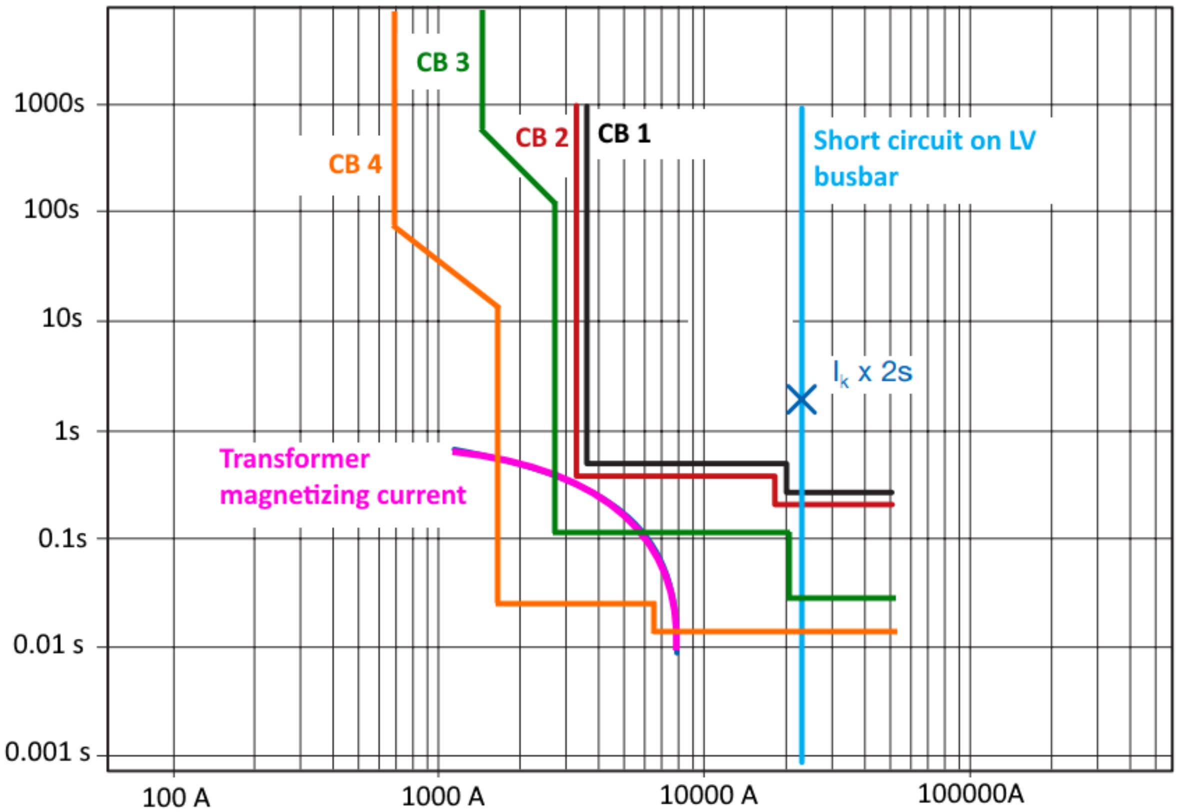



**Figure 31. Proposed overcurrent/short circuit selectivity chart for considered supply network**

### 5.4.2 Protection against earth fault

As it is mentioned before all MV/LV distribution transformers are in Δ/Y connection with earthed star point on LV side (TN system). In such system a phase to-earth fault occurring on the LV side downstream the CB 3 causes on the MV primary side a current which results to be $\sqrt{3}$ times lower than the value calculated for the three-phase fault on the LV bus bar. On the other hand, if the fault is assumed to be between transformer LV terminals and CB 3 the setting of the current threshold of the protection release should have an adequate value so that the protection of CB 2 trips due to such a fault.

Knowing the LV side short circuit current (22.73 kA), the fault (phase to earth) current, related to the LV side, affecting the circuit-breaker on the MV side can be calculated:

$$I_{2kEF} = \frac{I_{2k}}{\sqrt{3}} = \frac{22.72 \cdot 10^3}{\sqrt{3}} = 13.1\ kA$$

As the first over current threshold on CB 2 is set to 3 kA (related to 0.4 KV), the protection is able to trip due to a phase-to-earth fault on the LV side.

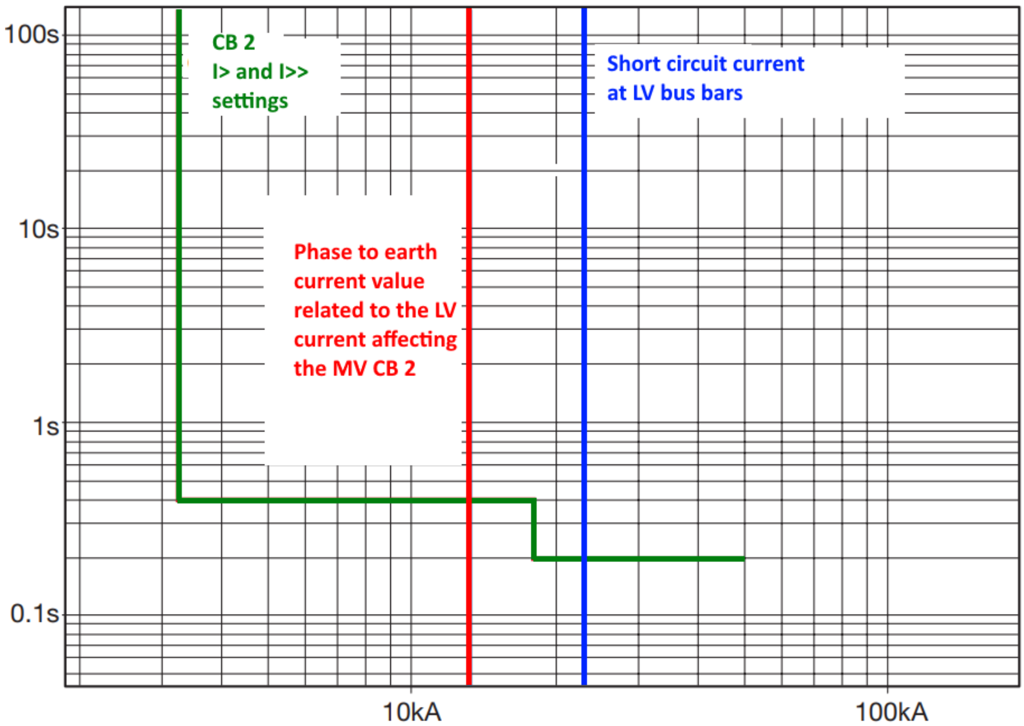



**Figure 31. Proposed earth fault selectivity chart for considered supply network**

Using transformation ratio K=50, corresponding fault current on MV side is

$$I_{1kEF} = \frac{I_{2k}}{K} = \frac{13.1}{50} = 262\ A$$

Which compared to MV breaker CB 2 first overcurrent protection threshold set on 60 A guarantees that CB 2 will trip during phase to earth fault. Corresponding selectivity chart is shown in Figure 32.

If the zero sequence protection is used (earth fault detection detected through the phase voltage transformer with open delta-connected secondary windings or through a toroidal current transformer measuring the sum of the three phase currents), its tripping threshold shall be lower than the neutral time overcurrent protection (51N) threshold defined by DSO. However, this type of protections are set in insulated neutral networks (IT system) and will be not discussed here.

## 5.5 Proposed system for common DC bus protections

The interconnection of AC/DC power converter and common DC bus do LV distribution grid can only be implemented when the safe network operation is guaranteed by the use of suitable electrical protection system. The protection of distribution supply line is explained in previous chapter and this system is well covered with existing standards and regulations.

While the existing ISO standards for LV and HV shore connections define requirements and protections of standard plug in connections required for cold ironing, the standards for battery charging equipment and its integration still do not officially exist.

In order to provide safe operation of suggested charging station with common DC bus, a protection system configuration shown in Figure 32 is proposed. In case of power supply loss from distribution grid, the reconnection of DC supply must be enabled by means of auxiliary under voltage relay U<. The protective functions may be also built in AC/DC power converter control system. DC bus connection to 0.4 kV distribution system should be done through visible lockable switch disconnector (repair and maintenance).

To ensure the safety of common DC bus, a two way transfer tripping communication line between 0.4 kV AC and DC bus interconnection protection systems must be used. Protection of DC bus consists of voltage surge arrestor and DC circuit breaker which are both included in interconnection protection system.

There should be a single earthing protection system in common DC bus which connects exposed conductive parts at 0.4 kV AC electrical equipment and DC bus equipment. Protection against electric shock on DC side is provided by means of transfer tripping from the insulation monitoring device on all the DC bus interconnection systems.

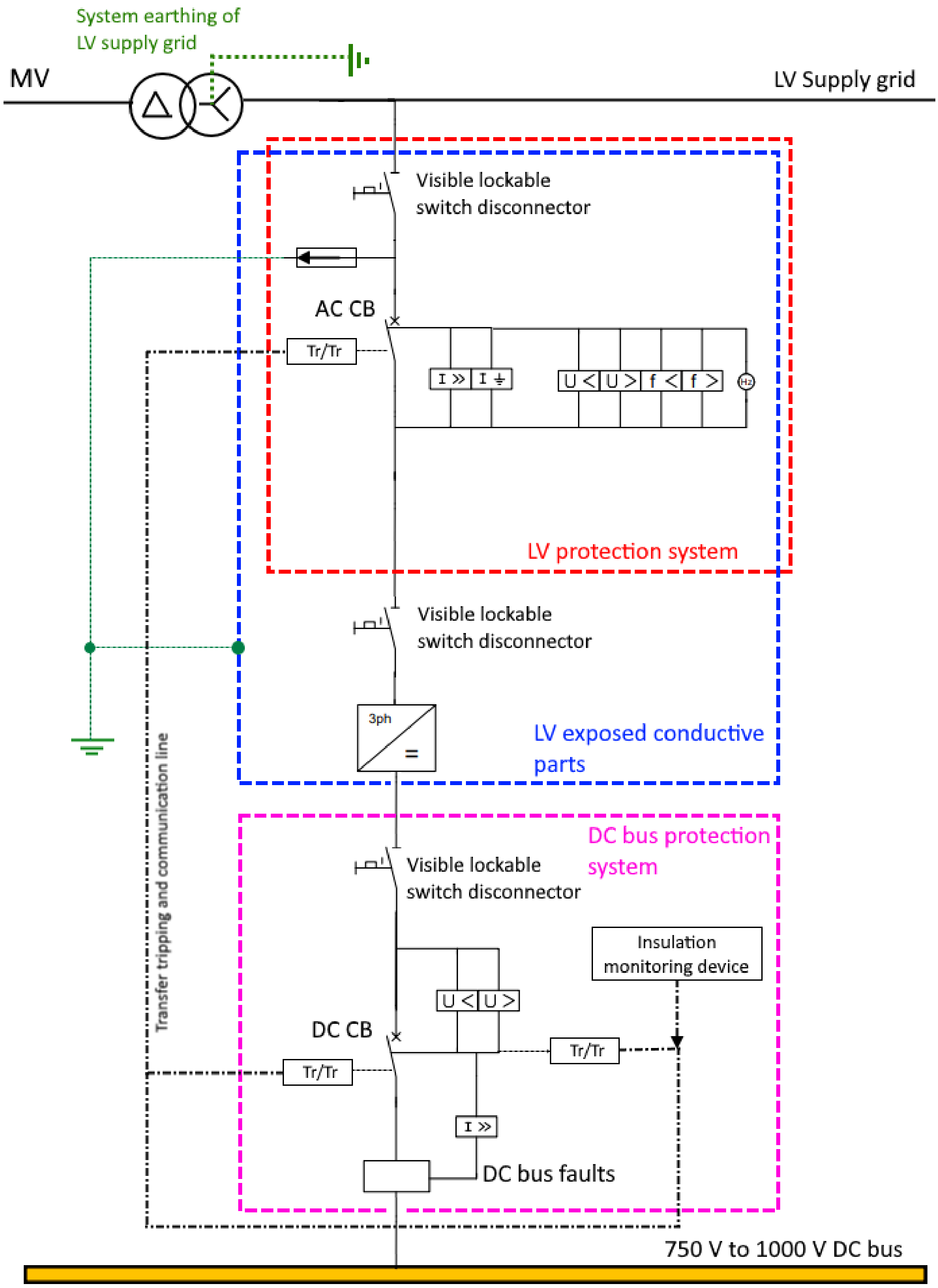



**Figure 31. Proposed electrical protection system for common DC bus**

## 5.6 Power quality issues on supply grid due to presence of non linear load

Use of non-linear loads such as rectifiers and frequency converters may adversely affect supply distribution grid power quality, especially on the LV side due to harmonic distorsion. Harmonically distorted current (which deviates from the pure sinusoid) is created by nonlinear consumers that act as current sources of higher harmonics. Simply put, a power electronics converter takes energy from the power grid on the fundamental harmonic to spend most of it on the electric load, and to a lesser extent converts it into harmonic currents which are sent back into the network and behave as a harmonic current source. This harmonic current branches through the network up to the smallest consumers inversely proportional to their impedances (lower impedance - higher current).

At distribution transformer reactance, the harmonic current creates a voltage drop that is proportional to the magnitude of the harmonic current and the initial reactance of the transformer. That harmonic voltage drop across the transformer reactance is at the same time the voltage of the harmonics on the grid from which the total harmonic distorsion (THDu) can be determined by using following formula:

$$THDv = \frac{\sqrt{\sum_{h=2}^{n} V_{(h)}^{2}}}{V_1} \cdot 100\ \%$$

Problems that arise in the power system due to the presence of higher harmonics are numerous and affect additional costs due to:

- declining energy efficiency of installations (energy losses)
- necessity for equipment oversizing
- productivity losses (accelerated aging of equipment, unwanted shutdowns)

The consequences can be divided into short-term, medium and long-term, and in order to study them and reduce their effect, numerous parameters need to measured and analysed. Some of the most important short-term consequences of harmonic disturbances in networks are:

- Destruction of capacitors in consumer installations because of increase in current due to resonance. This effect was especially noticed in industrial installations having static converters, in fluorescent lighting instalations containing power factor capacitors and in areas that are significantly congested with computers.
- Unnecessary activation of protective devices. Harmonics have a detrimental effect mostly on thermal protection devices.

- Interference affecting low current systems (remote control, telecommunications, hi-fi systems, computer screens, TV).

Higher harmonics are responsible for current overloads that cause overheating and premature aging of equipment, which creates long-term problems such as:

- Overheating of transformers and neutral conductors caused by higher currents harmonics, especially third-order harmonics.
- Neutral conductors in electrical installations and power supply systems have the same cross section as well as phase conductors. In newer installations, use of neutral conductors with larger cross section due to increased third harmonic currents is already being used.
- Retrofitting such larger neutral conductors into existing networks could cause significant costs, including a increasing in demand for copper and aluminum.
- Poor power factors associated with nonlinear loads are responsible for significantly increasing current levels in power systems and consumer installations, hence by increasing the cost of losses.
- Destruction of equipment (capacitors, switches, etc.)

Maximum alowable voltage harmonic distorsion THDv in public distribution systems is defined in EN 50160 standard (Table 9).

**Table 9. Values of individual harmonic voltages at the supply terminals for orders up to 25, given in percent of rated voltage defined in EN 50160 standard**

| Odd harmonics | | | | Even harmonics | |
|---|---|---|---|---|---|
| Not multiples of 3 | | Multiples of 3 | | | |
| Order *h* | Relative voltage (%) | Order *h* | Relative voltage (%) | Order *h* | Relative voltage (%) |
| 5 | 6 | 3 | 5 | 2 | 2 |
| 7 | 5 | 9 | 1.5 | 4 | 1 |
| 11 | 3.5 | 15 | 0.5 | 6 .... 24 | 0.5 |
| 13 | 3 | 21 | 0.5 | | |
| 17 | 2 | | | | |
| 19 | 1.5 | | | | |
| 23 | 1.5 | | | | |
| 25 | 1.5 | | | | |

As it is systematically analyzed and explained within WP 4.1 deliverable report (Deliverable WP 4.1, Section 5) the harmonic spectrum of the current drawn from the grid by a nonlinear consumer depends to a large extent on the front end topology.

In proposed charging system for Brestova and Porozina, there is no need to return energy to the grid due to the unprofitability of installing renewable energy sources, therefore the cheapest and most simple solution is to use three phase diode bridge rectifier in combination with boost DC-DC converter for DC bus voltage regulation. The comparison of three common front end topologies for rectifier systems is given in table 10.

**Table 10. Comparison of of three most common front end topologies for rectifier systems**

| | Active front end (AFE) | Thyristor rectifier | Diode rectifier |
|---|---|---|---|
| Power factor | ≈ 1, controlable | Varies with load (>0.94) | >0.96 |
| THDi | < 2% | up to 12% | up to 10% |
| Bidirectional power flow | Yes | Yes | No |
| Weight and volume | 80% | 100% | 100% |
| Maintenance | Complex | Less complex than AFE | Simple |
| DC voltage control | Controlable around rectifying voltage | Controlable from 0 to full rectyfing voltage | Can be controlled by DC-DC converter |
| Cost | High | Medium | Low |

Although the active rectifier gives the best results in terms of harmonic distortion, it also has a number of disadvantages, primarily high installation and maintenance costs and complex design. In addition to that, for specific application the problem may be the narrow range of voltage regulation around the mean value of the rectified network voltage.

Tyristor rectifier has the ability to regulate the voltage by simply changing the firing angle of the thyristor but is much less efficient than the combination of a diode rectifier and a DC-DC converter, especially under lower load. Also, the voltage control is possible only from 0 to maximum value of rectified voltage.

Having disadvantage only in term of higher harmonic currents, the combination of front end full bridge diode rectifier (6 or 12 pulse) and DC-DC converter (Figure 32) imposes itself as the best power supply solutions for common DC bus. If required DC-DC converter can have insulated topology, but in most practical applications conventional buck-boost topology is used in DC/DC stage (WP 4.1 deliverable report, page 31).

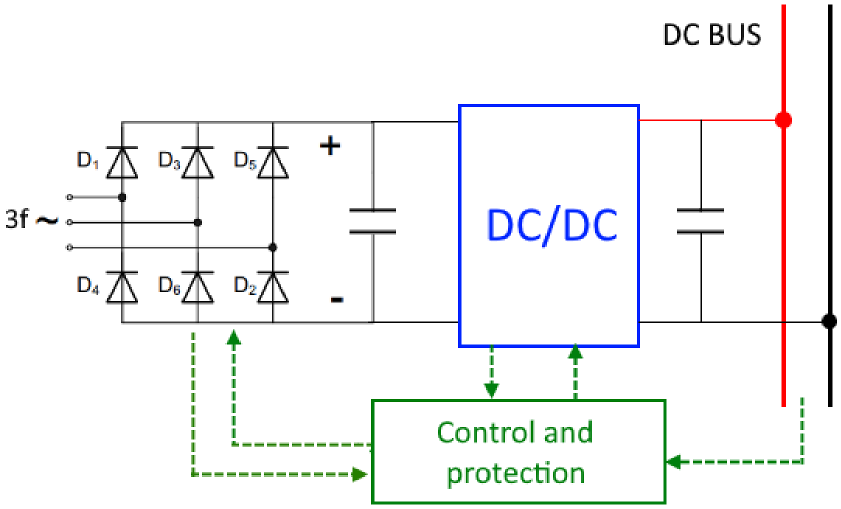



**Figure 32. DC bus power supply with diode rectifier and DC/DC converter**

To see if the proposed model meets the requirements defined in EN 50160 standard, a simulation of the influence of rectifier front end on LV busbar harmonic distortions was performed in MATLAB®/Simulink for 6 and 12 pulse rectifier topologies (Figure 33).

Distribution transformer is modeled with following parameters:

- Winding 1 connection; D11
- Winding 1 parameters; RMS line voltage (20 kV/50 Hz), Resistance 0.003 p.u., Inductance 0.08 p.u.
- Winding 2 connection; Yg
- Winding 3 parameters; RMS line voltage (0.4 kV/50Hz), Resistance 0.002 p.u., Inductance 0.08 p.u.
- Core type; three limb
- Nominal power; 630 kW

Parameters of 20 kV network and LV cable are set acording to values calculated in Section 5.

Simulation is performed for load conditions that represent 50% and 95% of rectifier rated power. Rectifier input line currents and LV bus bars line voltages are analysed. Harmonic content of LV bus bar voltage is obtained by performing FFT analysis. Simulation results are shown in Figures 34 to 37.

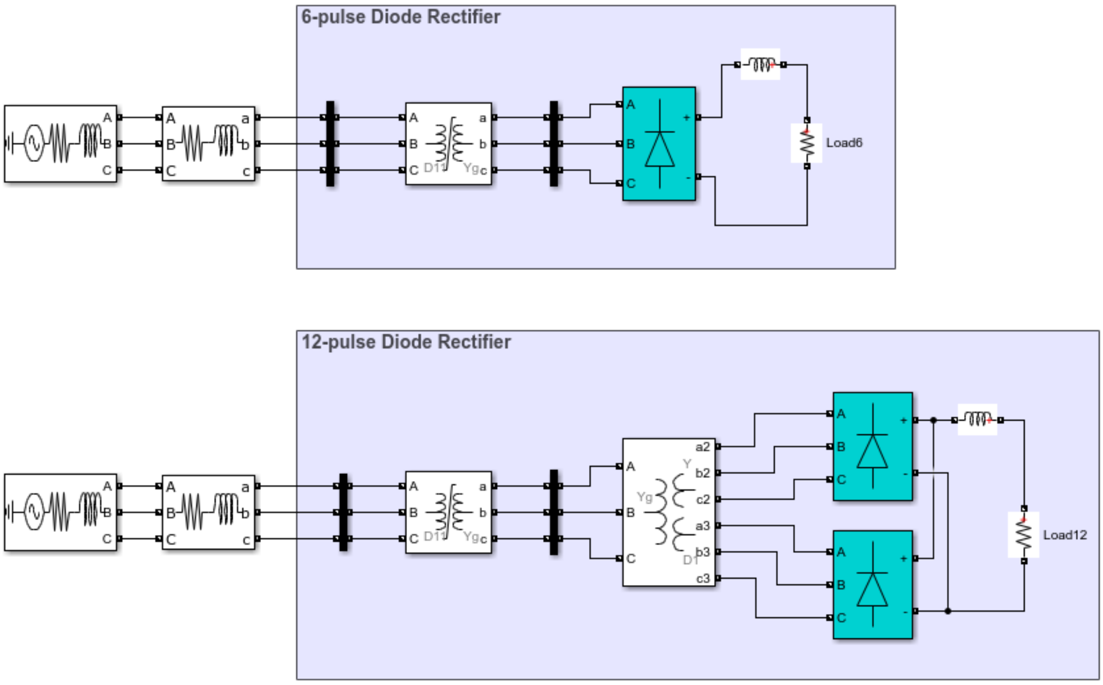



**Figure 33. Simulink model of 6 and 12 pulse diode rectifier connected on LV distribution grid**

From the simulation results, it can be seen that the LV busbar power quality is more than satisfatory within the whole load range, while the level of 5$^{th}$ harmonics exceeds the EN 50160 standard limit when the 6-pulse bridge is used at almost full load. This may probably be solved by increasing the serial reactance of the supply line or by using the distribution transformer with higher $v_k$ (higher impedance).

It can be concluded that prefered rectifier front end topology for the proposed shore connection/charging stations in Brestova and Porozina will be 12-pulse diode bridge. In addition to the obvious advantages in terms of power quality that can be seen from the simulation results, this configuration also has advantages with respect to reliability and availability.

Namely, since the 12-pulse configuration consists of two 6-pulse bridges, in this case connected in parallel, in the event of a fault on one of them, half the power is still available to supply the DC link and charge the onshore ES. By selecting converter bridges of slightly higher power then required, almost 100 percent redundancy can be obtained. With one 6 pulse bridge, operating at about 75% of maximum required power will not seriously compromise the power quality as can be seen from simulation results.

12-pulse configuration, however requires a three winding three phase transformer which should be considered when designing a new transformer substation.

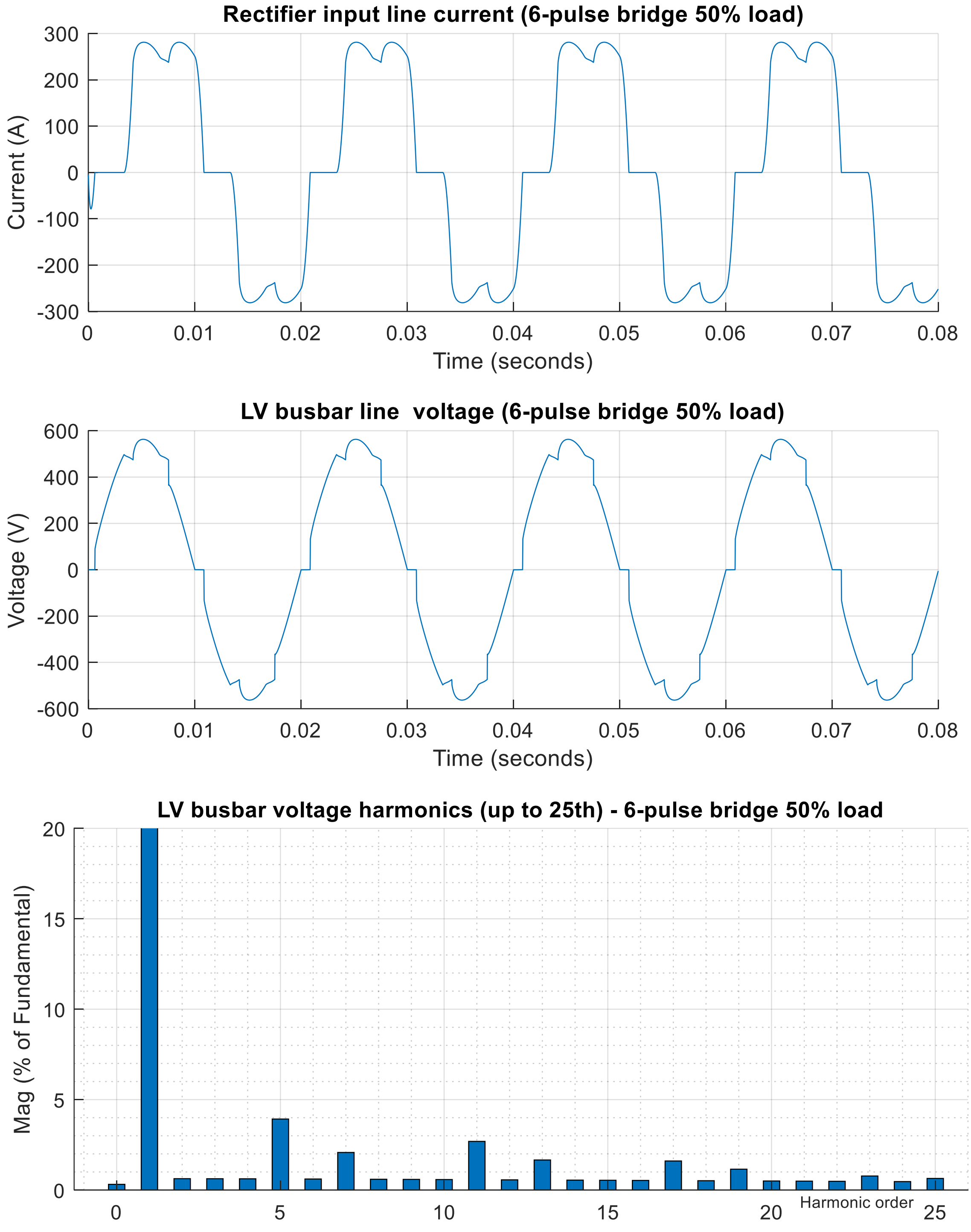



**Figure 34. Simulation results for 6-pulse diode rectifier fornt end at 50% load**

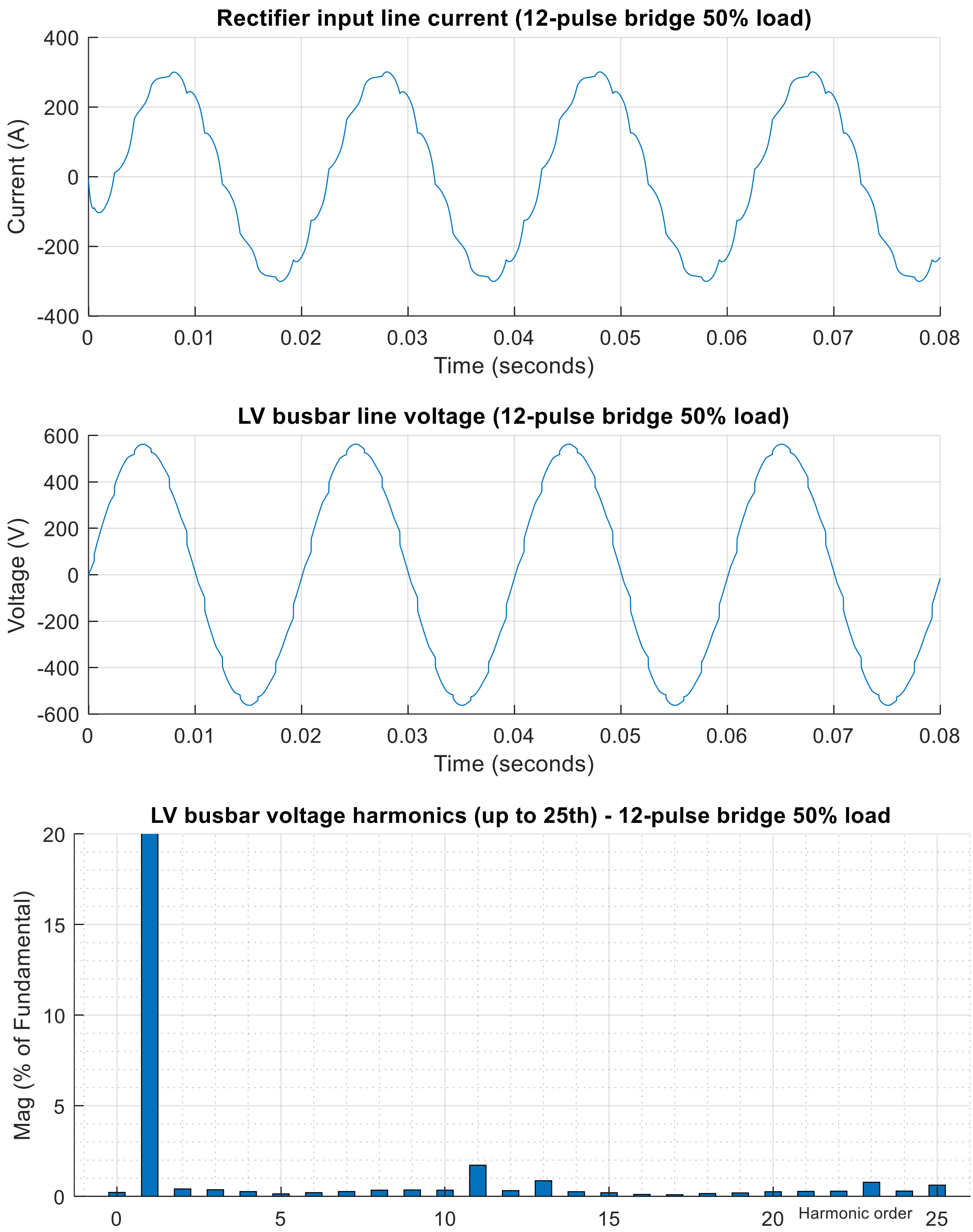



**Figure 35. Simulation results for 12-pulse diode rectifier fornt end at 50% load**

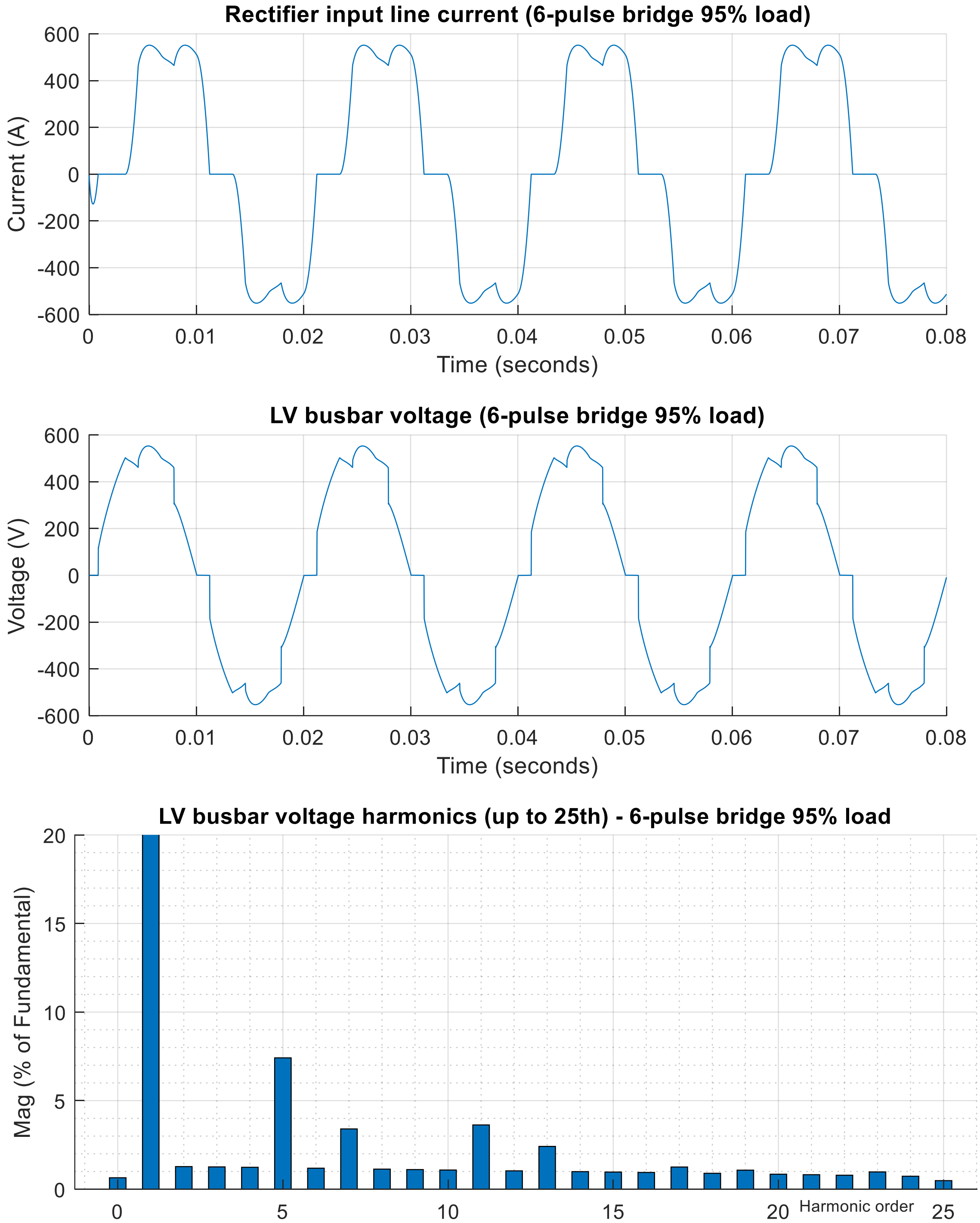



**Figure 36. Simulation results for 6-pulse diode rectifier fornt end at 95% load**

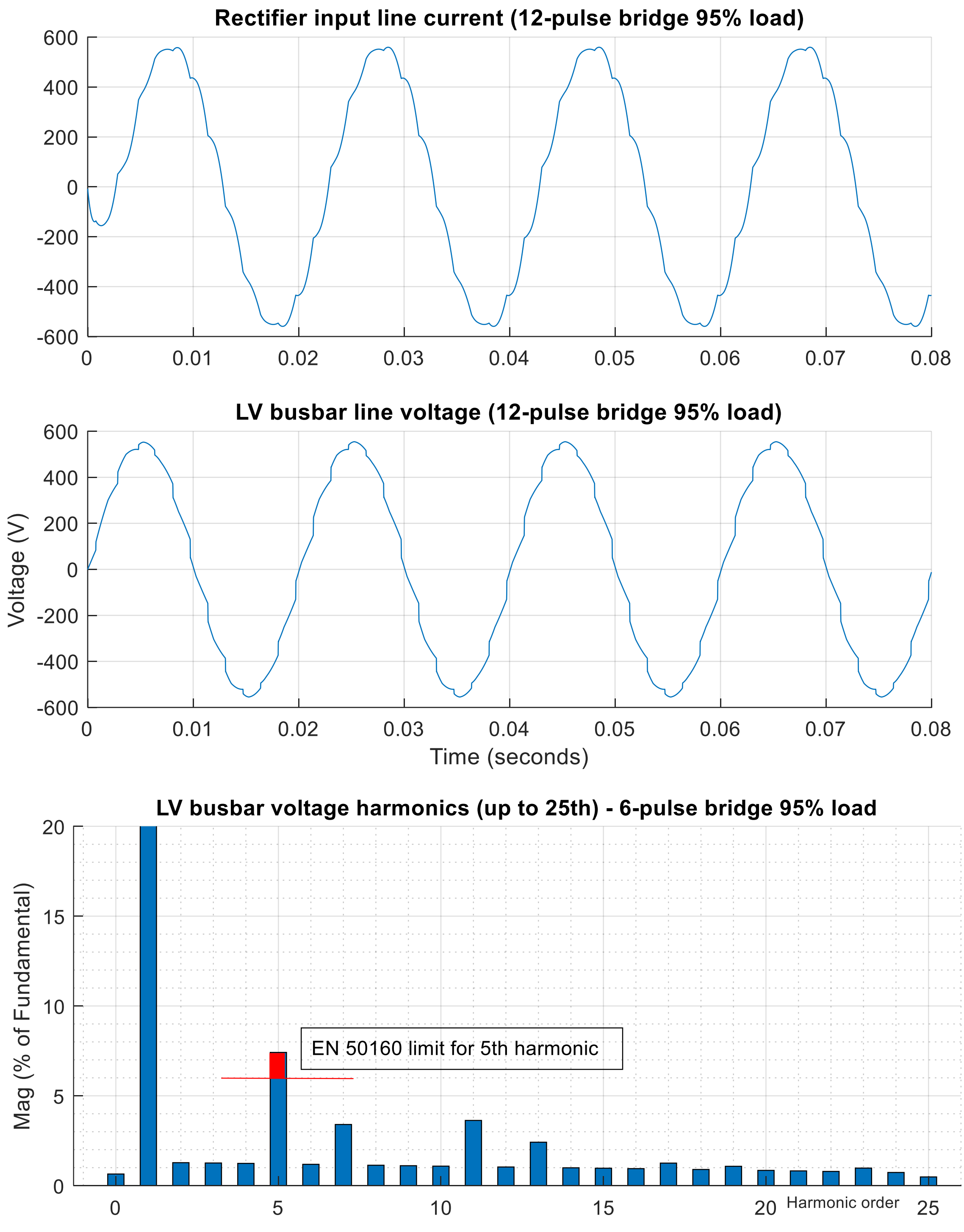
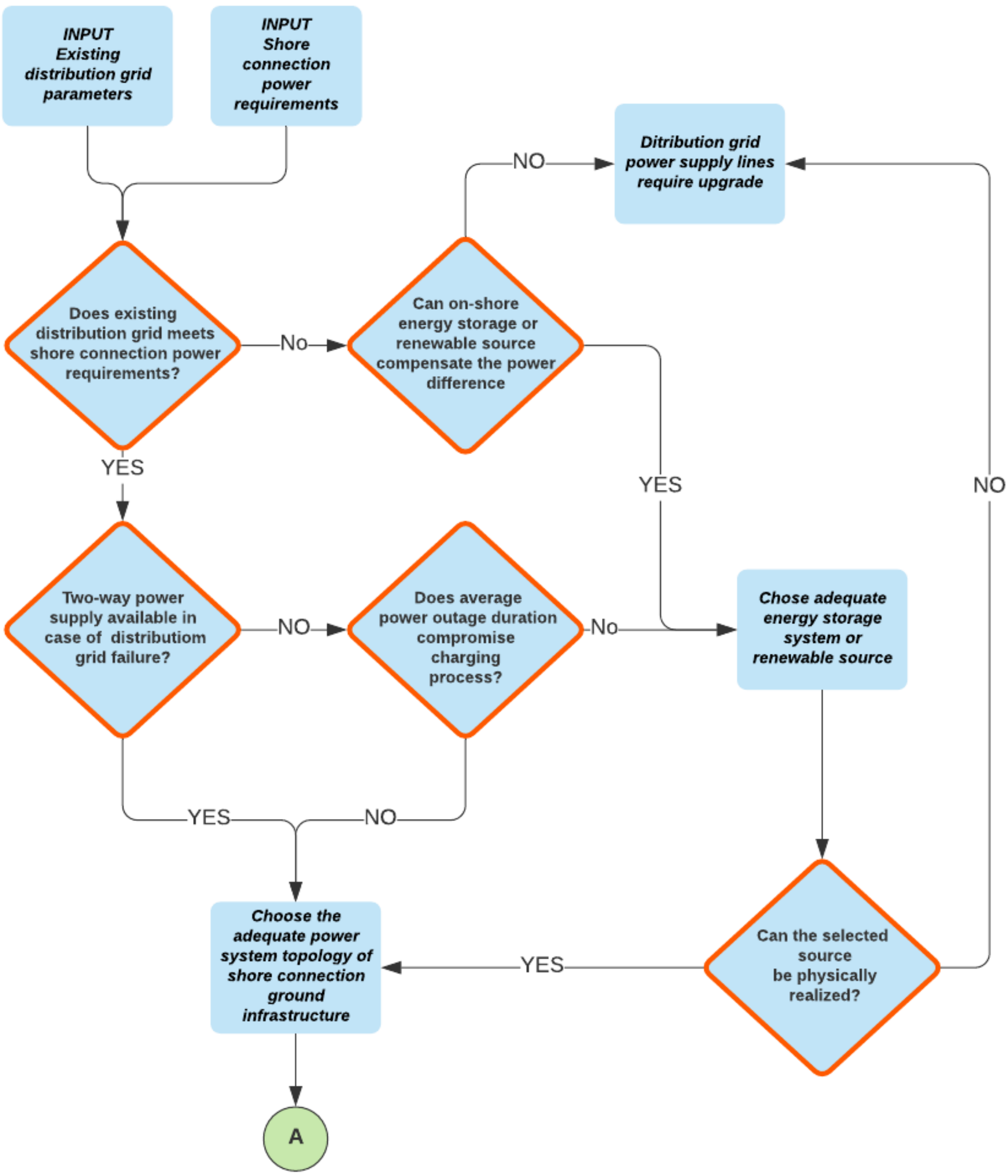
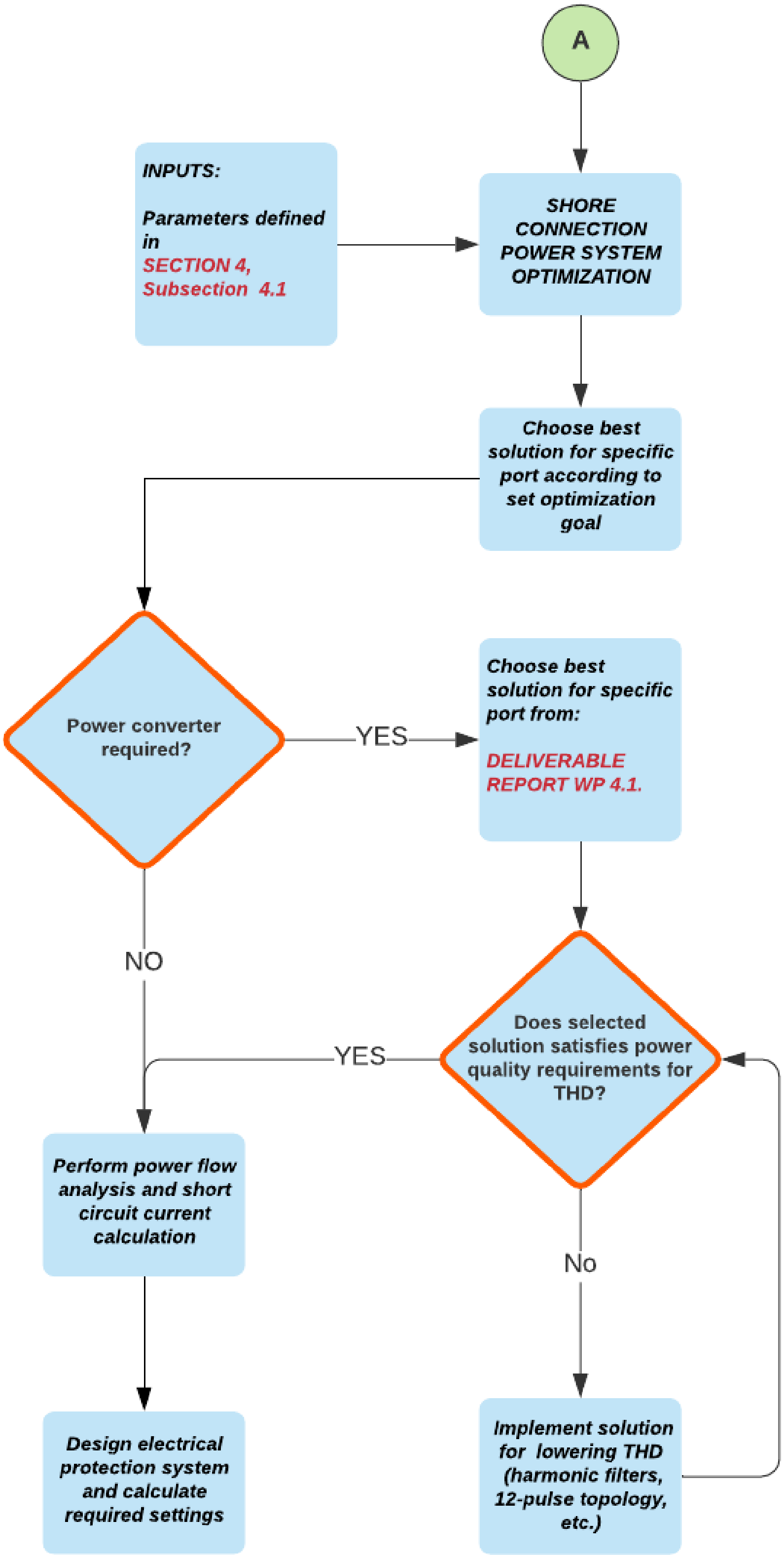



**Figure 37. Simulation results for 12-pulse diode rectifier fornt end at 95% load**

# 6 METODOLOGY FOR EVALUATING AND OPTIMIZING GROUND ELECTRICITY INFRASTRUCTURE AND GRIDS IN FERRY PORTS




A
INPUTS:
Parameters defined in
SECTION 4, Subsection 4.1
SHORE CONNECTION POWER SYSTEM OPTIMIZATION
Choose best solution for specific port according to set optimization goal
Power converter required?
YES
Choose best solution for specific port from:
DELIVERABLE REPORT WP 4.1.
NO
Does selected solution satisfies power quality requirements for THD?
YES
No
Perform power flow analysis and short circuit current calculation
Design electrical protection system and calculate required settings
Implement solution for lowering THD (harmonic filters, 12-pulse topology, etc.)

# 7 CONCLUSIONS

The focus of this report was on evaluating the electrical parameters of the grid infrastructure and developing a methodology for the integration of ferry charging stations. The research was focused to the ports of Brestova and Porozina, since they are the subject of interest in activities within work package 4.

The main conclusions of this report are:

**GROUND ELECTRICITY INFRASTRUSTURE**

1) Fast recharging (for example, in 10 minutes) means that the power flows through the distribution grid will be much higher and may cause overloading and undervoltage problems in the surrounding local grid.
2) Distribution grids on island and rural areas (where majority of ferry ports are located) have radial topology in most cases, which makes them more susceptible to failures and power outages that impose use of energy storage system on shore side.
3) Since small ferries with capacity of approx. 100 cars and 400 passengers usually consume up to 1 MVA of electric power, so the batteries will be connected and charged via low voltage (LV) grid.
4) Tendency of distribution grid development in the world goes towards a reduced number of voltage levels, so the one voltage level design (20 kV/0.4 kV in Croatia) is preferred at construction of most new and replacement of existing distribution substations and grids.
5) Available power ratings of MV/LV transformers used in distribution grid are between 50 kVA and 1000 kVA.
6) Capacity of existing MV supply lines will play a key role in the possibility of increasing the power ratings of existing MV/LV TS, or installing new ones in the ports where this will be necessary.
7) TS Brestova is connected to MV network with radial structure and there is no possibility of power supply from other direction. Loads up to 2 MW can be supplied via existing MV supply line.
8) Existing MV power supply lines in port of Porozina can hold up to 4.5 MW of total power and current load is around 1MW. Same as in Brestova, it is connected to the radial MV network with no possibility of redundant power supply.
9) In both ports, due to the radial network topology prolonged power outages may occur in case of system faults of environmentally caused effects (bad weather, lightning, etc.).
10) In port of Brestova same TS can be used for shore connection and public (port) infrastructure supply.
11) Due to the low power reserve, even when the new TS will be installed, port of Porozina will require separate TS for shore connection system.
12) Existing MV connection point for TS is dislocated from the port (about 300 meters). If TS will be located there (which is most convenient solution) there may be a voltage drop problem on LV lines for shore connection supply so the cable cross section must be carefully chosen.

13) In both ports, any standard TS type up to 1000 kVA can be physically placed on existing locations if needed.

**LV SHORE CONNECTION/CHARGING SYSTEM**

14) Required shore power for Brestova and Porozina are 500 kW for battery charging and 250 kW for cold ironing while the ferry is in port.

15) An equipotential bonding between the ship's hull and shore earthing electrode shall be established by the earth contacts of the plug, socket-outlet, ship connector and ship inlet.

16) Construction of the LV equipment and operating safety procedures shall provide for the safety of personnel during the establishment of the connection of the ship supply, during all normal operations, in the event of a failure, during disconnection and when not in use.

17) Ports with insufficient capacity of the electrical distribution grid often requires installation of additional energy storage (ES) system or renewable energy sources.

18) Characteristics of battery storage modules onboard ferries and associated charging systems are not unified, which poses a significant design problem for shore connection points, meaning that in most cases a suitable power converter will be required on shore.

19) In order to facilitate the easiest possible connection of such sources and provide both AC and DC power for battery charging and cold ironing, an onshore charging system with a common DC bus is selected as a best solution for Brestova and Porozina.

20) Use of common DC bus can provide more efficient interconnection of system with different frequencies.

21) When compared to AC bus, DC bus requires less power conversion stages for connections and interconnections of equipment.

22) With common DC bus it is easier to design electrical protections because modern power electronic converters can almost instantaneously limit the current and power flow when required (e.g. system overload, short circuit, earth fault).

23) During power outages on supply distribution grid, important consumers within port facility can be supplied from battery energy storage.

24) In future, with expected rapid grow of cars, trucks and busses, it will be much easier to realize charging stations for such vehicles and increase the port revenue by selling the energy from own micro grid by using suggested topology.

25) The optimization of shore side power system is done with The HOMER Pro® microgrid software by HOMER Energy. Estimated initial costs for optimal configuration are $250 000 per port.

**POWER REQUIREMENTS, ELECTRICAL PROTECTIONS AND POWER QUALITY**

26) Standard distribution transformer with rated power of 630 kVA satisfies the set requirements and is selected as solution for supplying shore connection infrastructure in Brestova and Porozina.

27) 3x400mm$^2$ underground cables between LV distribution grid bus bars and on shore power converter will satisfy the requirements for this particular case.

28) Calculated short circuit current is below range of maximum design values of short circuit currents for private and industrial LV connections points in Croatian distribution grid.

29) For the calculated current values, a standard MV vacuum or gas (SF6) circuit breaker shown on can satisfy the set requirements for MV breaker on user (port) side.

30) Standard moulded case circuit breaker (MCCB) shown on can satisfy the set requirements for supplying busbar and electrical load on LV side.

31) To ensure the safety of common DC bus a two-way transfer tripping communication line between 0.4 kV AC and DC bus interconnection protection systems should be used.

32) There should be a single earthing protection system in common DC bus which connects exposed conductive parts at 0.4 kV AC electrical equipment and DC bus equipment. Protection against electric shock on DC side is provided by means of transfer tripping from the insulation monitoring device on all the DC bus interconnection systems.

33) Using of nonlinear load such as rectifiers and frequency converters may affect power quality of supply distribution grid, especial on LV side due to harmonic distortion.

34) In proposed charging system for Brestova and Porozina, there is no need to return energy to the grid due to the unprofitability of installing renewable energy sources, therefore the cheapest and most simple solution is to use three phase diode bridge rectifiers in combination with boost DC-DC converter for DC bus voltage regulation.

35) Prefered rectifier front end topology for the proposed shore connection/charging stations in Brestova and Porozina will be 12-pulse diode bridge. In addition to the obvious advantages in terms of electricity quality that can be seen from the simulation result, this configuration also has also advantages from the reliability point of view.

In general, the results of the study show how, in practical terms, an inclusive approach promoted in WP 4.1 deliverable report can be used to successfully design shore connection and charging system according to specific requirements and available ground infrastructure in ferry port.

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