Techno-Economic Feasibility Study of a DC Distribution Grid Supplying a Hydrogen Production Plant

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With the ever-growing threat of climate change and the urgent need for decarbonization as articulated in the Paris Agreement (2015), numerous sectors are facing unprecedented changes, starting with the power sector which needs to integrate the increasing number of electric vehicles, renewable energy sources and storage systems into the aging electrical grid. This paper describes the techno-economic feasibility of a DC distribution network replacing an existing AC grid which supplies a hydrogen production plant. A conclusive comparison between the two solutions is then demonstrated.

Keywords : DC, AC, distribution grid, hydrogen, feasibility, efficiency, power converter, electrolyzer, load flow, short circuit, ETAP

Avec la menace croissante du changement climatique et le besoin urgent de décarbonisation tel qu'articulé dans l'Accord de Paris (2015), de nombreux secteurs sont confrontés à des changements sans précédent, à commencer par le secteur de l'électricité qui doit intégrer le nombre croissant de véhicules électriques, de sources d'énergie renouvelables et de systèmes de stockage dans le réseau électrique vieillissant. Cet article décrit la faisabilité technico-économique d'un réseau de distribution à courant continu remplaçant un réseau à courant alternatif existant qui alimente une usine de production d'hydrogène. Une comparaison concluante entre les deux solutions est ensuite démontrée.

Mots-clefs : CC, CA, réseaux de distribution, hydrogène, faisabilité, rendement, électronique de puissance, électrolyseur, flux de charge, court-circuit, ETAP

1. Introduction

The current climate crisis forces the energy sector composed primarily of transport, heat, and electricity, to shift away from fossil fuels to renewable energy sources (RES) as well as other low carbon sources, creating thus the need for additional storage systems. On the other hand, the electrification of the transport and heat sectors will cause the surge of electric vehicles and heat pumps to the market. All these new sources and loads primarily of DC nature will need to be integrated into the electricity grid which still needs to provide reliable electric supply, stability, and resilience at all times. Today's grid however is incapable of doing so as some real life events such as in California (2022) have shown [1].

This article attempts to demonstrate the superior capability of a DC grid to fulfill this role over an AC network by selecting an existing case study from Tractebel Engie of a hydrogen production plant supplied by an AC distribution grid and developing an alternative improved grid solution employing DC technology.

1.1. Objectives

This paper aims at achieving the following main objective :

- To demonstrate the techno-economic feasibility of a DC grid supplying an existing hydrogen production plant.

The following steps are taken :

- Replacement of the current AC infrastructure by a more efficient distribution supply grid whilst incorporating DC technology.
- Estimation of the technical efficiency gained.
- Estimation of the economic CAPEX and OPEX costs of both systems.
- Conclusion about the most energy- and cost-efficient solution.

1.2. Scope of Study

- The paper focuses on the electrical aspects of the case study; non-electrical aspects of the plant such as the cooling system, water treatment, or production process of the hydrogen plant are not analyzed.
- The transmission section of the electrical grid is not included in the scope of study; sole the distribution part, hence medium and low voltage levels (MVAC-LVAC; MVDC-LVAC).
- The aim of this paper is not to replace the entire AC infrastructure of the case study by DC technology; the least amount of changes possible are applied in order to keep a similar grid design and reduce replacement costs.
- Aspects such as control, protection, grounding, harmonics, stability, arc flash, load shedding, or the working of electrolyzers are not included in the scope of study.

1.3. Assumptions

- No standards or norms yet exist for voltage levels in DC systems [2]; the voltage levels proposed are thus not nominal values.
- Power electronics shown in this paper are custom made, hence project based.
- The DC Distribution System is connected to the AC Utility Grid.
- The exact model of electrolyzers is irrelevant in this case study.
- The electrical distribution system is simulated for two operating modes :
    - Normal operating conditions for load flow analysis.
    - Exceptional operating conditions for short circuit analysis.

2. State-of-the-art

In this section, the state-of-the-art of DC distribution grids as described in the literature is overviewed by outlining existing standards, projects, key technologies, grid classification, and summarizing the potential future of DC grids.

2.1. Existing Standards

As of 2022, there are no international standards or consensus regarding voltage levels for DC systems [2], however the norm IEC 60038 mentions the most common sequences and recommends a range of voltage levels for DC distribution cases which are applicable to this report as shown below. A general rule of thumb widely employed states that voltage levels of MVDC distribution networks should match the power supply capacity of the corresponding AC distribution networks [3]; the selected voltage levels for LVDC should match the voltage levels of the DC loads [2]. Due to the lack of standardization, this paper considers the MVDC range from 1,5kV to ±50kV; the LVDC range for <1,5kV.

MVDC

- Recommended range : **100 kV (±50 kV) – 1,5 kV (±750 V).**
- Most commonly used sequence :

100 kV (±50kV) - 70 kV (±35 kV) - 40 kV (±20 kV) - 35 kV (±17,5 kV) - 20 kV (±10 kV) - 1.5 kV (±750V)

LVDC

- Recommended range : **1400 V (±700V) – 48 V.**
- Most commonly used sequence :

750 V (±375 V) - 700 V (±350 V) - 400 V - 375 V - 350 V - 300 V - 230 V - 120 V - 110 V - 60 V - 48 V

2.2. Existing and On-Going Projects

According to CIGRE [2] as of beginning 2022 : "*In spite of some existing projects of MVDC grids, the technologies for MVDC grids are project based and there are no unified, credible MVDC related standards as yet*". The same conclusion is drawn for LVDC projects.

However, numerous non-standardized LVCD and MVDC projects do exist from companies such as DC Systems B.V. [4], Siemens Energy [5], and ABB [6], as well as from the universities such as TU Delft [7] and RWTH Aachen [8].

Many of the completed DC distribution projects were classified at the time as HVDC by the manufacturing companies but can be classified today as MVDC systems when taking into account the voltage range as specified in point 2.1. MVDC and LVDC projects currently involve distribution grids, DC links, DC buildings, sustainable roads, street lighting, interconnection links between AC nodes, etc.

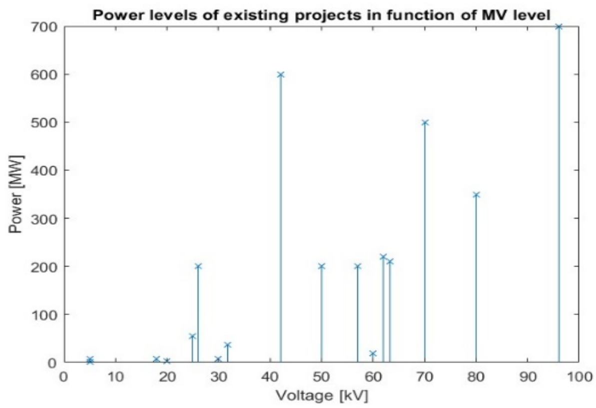

Figure 1 : Existing medium voltage projects classified with regards to power level.

2.3. Key Technologies

The list of technologies regrouped in table 1 mostly includes power electronics and protection equipment, vital for the technical feasibility of DC distribution grids [10].

Semi-conductors thus play a major role, especially in power conversion equipment. The current technology suffers from low-temperature ratings which may be resolved by the new generation of wide bandgap semiconductor devices in the near future [2].

Additionally, control algorithms for efficient power flow control are considered faster, more reliable and effective in DC than AC due to the lack of synchronization requirements as in AC but further research and development is required [9].

Table 1 : Key technologies for DC systems [9]

Key technology	Description
VSC (voltage source converter)	Key equipment utilizing IGBTs to realize energy exchange between AC and DC buses.
DC/DC Converters (= DC Transformer)	Equipment to assure control and conversion for reliable and stable voltage levels to critical loads. For MVDC, high-power converters are required.
DC Protection Technology	Key equipment for protection and safety, predominantly DC circuit breakers but also protection algorithms and power electronics.
DC Cable Technology	No standards yet for MVDC cable technology unlike HVDC. Some MVDC projects use AC cables running at peak voltage instead of RMS value.

2.4. Grid Classification

Electrical grids are classified with regards to different features, typically in terms of power control architecture, bus structure, and internal bus architecture.

Power Control Architecture

DC systems are controlled by centralized, decentralized, and distributed systems.

Centralized

Electrical production via a few large generation units such as coal, gas, or nuclear power plants results in an interconnected network with centralized control of energy generation. This type of power control design is the most simple and cost-efficient to implement, however with the increase of distributed energy resources (DER) and energy storage systems (ESS) the electrical grid is facing issues in terms of stability and flexibility when employing this type of centralized network topology [9].

Decentralized

As the name suggests, these networks no longer rely on a few centralized generation units as all nodes of the network possess individual autonomy resulting in higher efficient integration of DERs to the power grid [9]. Control networks of this kind can provide voltage supply at different levels to the several loads more easily than centralized control since the electricity generated via smaller power plants is utilized locally. However, the costs increase with the complexity of the design.

Distributed

This type of power control architecture is considered the most reliable in terms of control and integration of DERs as every node can be independent or interconnected to each other [9]. This type of topology is the most effective for the integration of renewable on-site sources and storage systems but also the most complex to control and protect which automatically translates to higher costs.

Table 2 : Characteristics of network topologies

Control Design	Centralized	Decentralized	Distributed
Reliability	Low	High	High
Complexity	Low	Intermediate	High
Costs	Low	Intermediate	High
N-1 redundancy	No	Yes	Yes
Bidirectional flow	No	Yes	Yes

Bus structure topologies

DC are either “point-to-point” structures based on current source converters (CSC) for long distance transmission, or “multi-terminal” structures based on voltage source converters (VSC) for distribution [2]. In this paper, DC distribution grids are studied thus the multi-terminal bus structures are analyzed. There are commonly four DC bus structures for a multi-terminal grid : radial, ring, ladder, and meshed.

Radial

This structure is the most employed for distribution as it is the simplest and most cost-efficient bus structure in terms of design and implementation, but the least reliable during fault occurrence. No loops are present in this structure as each feeder is fed from a single connection to the substations [9].

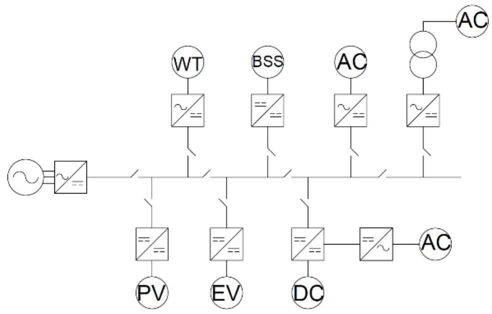

Figure 2 : Radial configuration example

Ring Bus Structure

This configuration connects the main sources to a collection of loads in a loop system, in other words a radial bus structure where each node is fed from two different paths. More components and complex protection equipment are needed which automatically translate to higher costs but also higher power reliability. A real life example of such a bus structure can be found on the DC grid project of the RWTH University in Aachen, Germany [9].

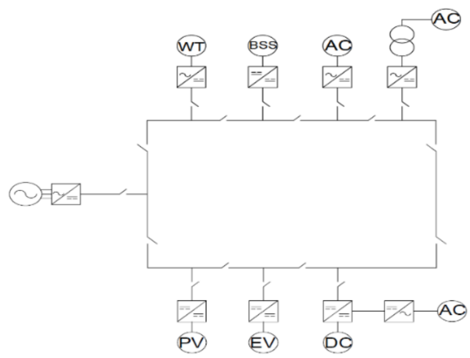

Figure 3 : Ring configuration example

Ladder Bus Structure
The combination of multiple ring bus structures connected in parallel as shown in figure 4 is called a ladder bus structure as all the sources and loads are connected to the rungs of a ladder-shaped power distribution structure [9]. This topology offers the most significant improvement in terms of reliability and protection but at higher costs.

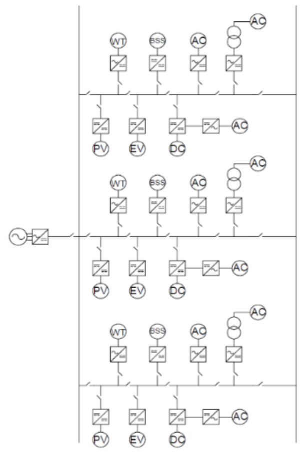

Figure 4 : Ladder configuration example

Meshed Bus Structure
Multiple ring bus structure joined internally together form the most efficient, reliable, and expensive type of configuration called a meshed structure. The degree of reliability offered is often required for critical systems such as datacenters or uninterruptable power supplies (UPS) [9].

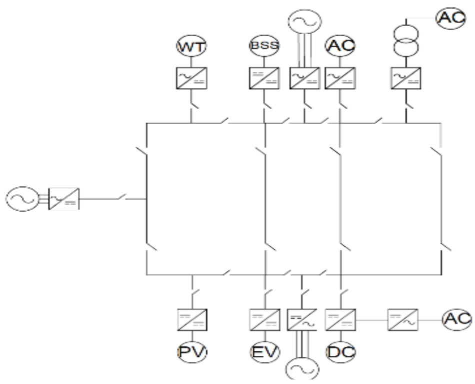

Figure 5 : Meshed configuration example

Table 3 : Summary of DC bus structure topologies

	Radial Bus	**Ring Bus**	**Ladder Bus**	**Meshed Bus**
Supply Reliability	Very Low	Moderate	High	Very High
Stability	Low	Moderate	High	Very High
N° of components	Low	Moderate	High	Very High
Capital cost	Very Low	Low	Moderate	Very High
Maintenance cost	High	Moderate	Moderate	High

Bus architecture
Medium and low voltage DC grids connect sources and loads to each other through power converters and DC links via two types of DC bus architecture : unipolar and bipolar schemes.

Unipolar
A DC bus possessing unipolar features contains only positive (+) and negative (-) poles as shown in figure 6. This classic configuration is the cheapest option for installation; however, the lack of redundancy makes it less reliable than the bipolar structure. Furthermore, one single voltage level can be supplied to the different loads, only the polarity may change.

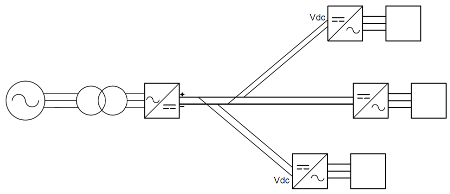

Figure 6 : Example of unipolar bus structure [9]

Bipolar
A DC bus possessing bipolar features contains positive (+), negative (-), and neutral wires as shown in figure 7, hence there are three ways for load connection : positive and neutral (V_{DC}); negative and neutral (-V_{DC}); positive and negative ($2V_{DC}$). The voltage rating of a bipolar DC line is expressed in the following way : $\pm X\ V$. The redundant features assure power reliability and availability during fault conditions by continuously supplying the loads via one of the poles, but which translate to higher installation costs. However, since the converters possess smaller voltage ratings than their unipolar counterparts, lower costs may apply to the bipolar structure on top of lower maintenance. Bipolar buses are considered most suitable for high-load applications and preferred over unipolar design as two different voltage levels enable easier connections between the DC bus and the distributed loads.

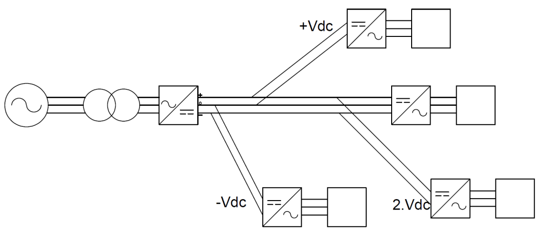

Figure 7 : Example of bipolar bus structure [9]

2.5. Future Developments

Even though DC grids present major advantages over the current AC grid such as easier integration of DERs, less conversion steps, higher power capacity, absence of synchronization requirements and reduction of converter size, challenges and barriers which hinder their adoption exist. The lack of standardization, experience and qualified workers, the AC market inertia, low technological readiness level for power control and protection do not permit a replacement of the current aging electrical grid which remains the most cost-competitive option.

The replacement of existing AC grids by pure DC grids does not make sense on a techno-economic level today, however some studies reveal the potential of evolving towards hybrid AC/DC grids to not disrupt the existing infrastructure and save up on installation costs [9].

Hybrid AC/DC grids enable a smooth transition from centralized to decentralized network topology. Pure DC grids would appear at new construction sites incorporating storage systems, renewables, and DC loads.

In any case, the outdated and unreliable grid used today cannot sustain the exponentially growing demand for electricity. Modernizing the power grid is an obligation, and DC grids represent a promising technology to achieve this goal.

3. Case Study

The case study represents a hydrogen production plant whose overall working is non-relevant, merely the electrical supply configuration is analyzed (figure 8).

In short, the hydrogen used for the generation of e-fuels is produced via electrolyzers supplied by the power grid. This paper focuses exclusively on the electrical distribution system, thus the 33kV switchgears which are fed from the 400kV substation and supply 362MW lines of ring main units (RMU), a balance of plant of 10MVA and a 58MVA process. The maintenance supply is excluded from the area of study. The overall design of the electrical supply of this study is shown in figure 9.

It should be emphasized that each electrolyzer module presented in this case study includes an internal rectifier unit for DC operation and is therefore intrinsically presented as a DC load. Given the total number of such loads in this project, the interest of creating a direct current distribution network to effectively supply the electrolyzers that no longer need an internal rectification step becomes obvious.

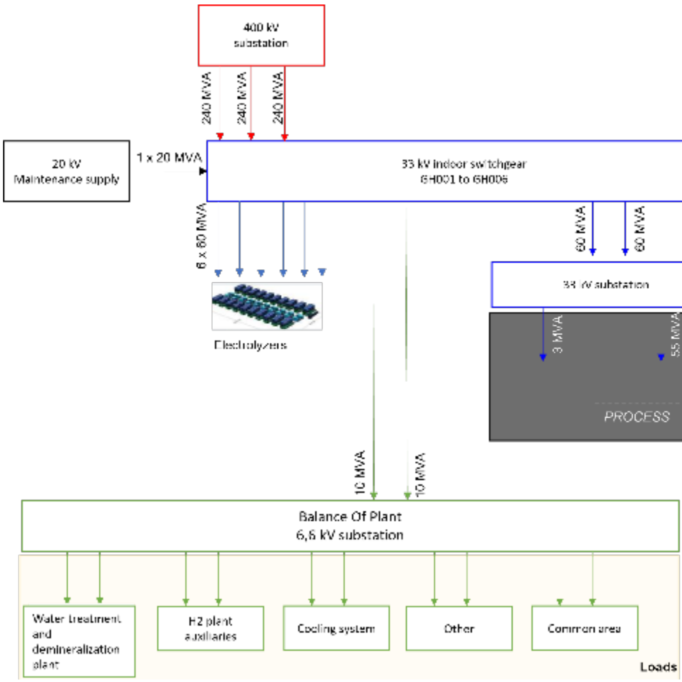

Figure 8 : Electrical supply configuration of case study

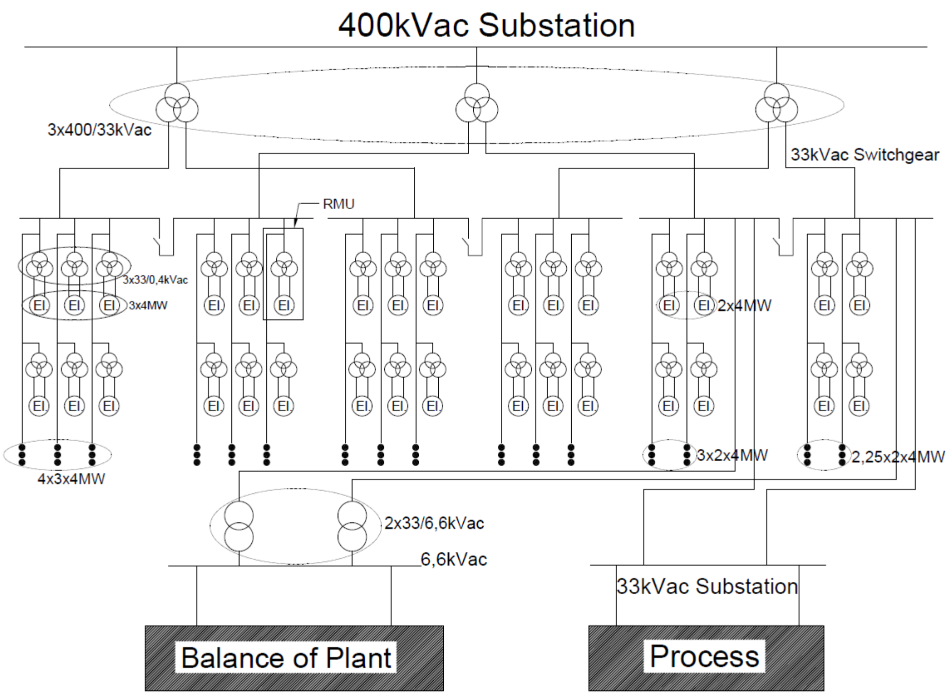

Figure 9 : Configuration of case study

To fulfil the N-1 criteria, three triple-winding 400/33kV transformers of 2x120MVA supply the six branches of the 33kV switchgears. The grid topology is thus radial with a triple feeder and a redundant MV bus.

In case of power loss of one secondary winding, the third one ensures the supply to a limited extent.

Each 33kV line supplies at most 24MW worth of RMUs whose typical configuration is shown in figure 10. Each RMU contains up to four electrolyzers of 1MW supplied by a triple-winding 33/0,4kV transformer of 2x2,1MVA via copper bus bars.

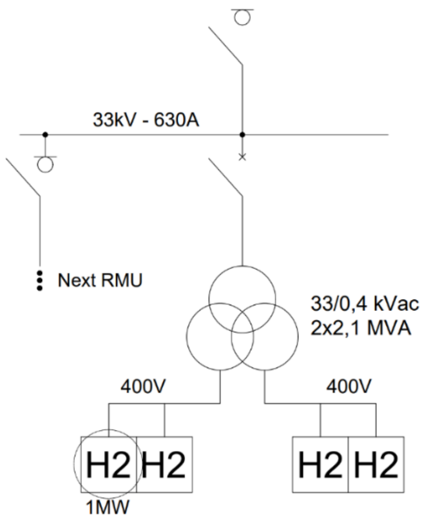

Figure 10 : Internal configuration of RMU

4. Technical feasibility

This chapter aims at finding an alternative configuration to the original case study by employing DC technology and simultaneously obtaining a more efficient result. The alternative configuration is adapted throughout this paper with regards to its technical feasibility and verified by means of simulations with ETAP.

4.1. Alternative DC Solution

As mentioned in the scope of study, replacing the entire existing infrastructure does not make sense, instead the goal is to replace as little as necessary while changing the nature of the grid to obtain a technical feasible and more efficient solution. Furthermore, N-1 redundancy characteristics need to be guaranteed. A hybrid AC/DC grid therefore is more practical than a pure DC network, which is why the 400kVac substation (figure 9) is left untouched. The next question to ask is thus “Where should the rectification step (AC to DC) take place?”.

Rectification scenarios

A few scenarios are possible :

1. Rectification after the 400kVac substation (before 400/33 kV transformers).
2. Rectification after the triple-winding 400/33kV transformers.
3. Rectification after the 33kVac switchgears (each branch).
4. Rectification at the input of each RMU (before 33/0,4 kV transformer).

Two scenarios are to be excluded directly : scenarios 1 and 4.

Scenario 1 would require converting 400kVac into the equivalent DC voltage! At such high voltage levels, the conversion step would result in astronomical investment and maintenance costs. Furthermore, N-1 redundancy characteristics offered by the three HV/MV transformers are no longer present and the entire infrastructure would need to be re-designed and replaced which should be avoided as previously stated.

Scenario 4 is significantly more feasible than scenario 1 since rectification occurs at a lower voltage level, however when applying this logic it becomes clear that the change made to the original configuration is minimal with no gain in efficiency. In fact, each MV/LV transformer of the RMUs is replaced by a rectifier put in series with a DC/DC transformer to obtain 400V at the input of every electrolyzer which results in an increase of conversion steps instead of a decrease.

The remaining scenarios appear to be preferable options than the previous two. Scenario 2 avoids rectifying at high voltage as in scenario 1 and additionally keeps the redundancy characteristics with the presence of the three HV/MV transformers. However, the process and the balance of plant still require an AC supply, meaning that an additional inverter step (DC to AC) is necessary for the 33kV branches supplying these two loads which results in a loss of efficiency.

Furthermore, AC switchgears cannot be retrofitted into DC but need to be entirely replaced by more expensive equivalent DC switchgears. There are little to no real-life examples of such DC switchgears at medium voltage levels, although the literature reassures its feasibility [2].

Final rectification scenario

Scenario 3 thus remains and seems to represent the most attractive solution : to maintain the 33kV switchgears in AC to effectively supply the AC loads, avoid expensive replacement costs of the AC bus bars and apply rectification at the input of every line of RMUs. This is illustrated in figure 11.

Rectifying 33kVac to the equivalent DC voltage means achieving between 33 and 46,67kVdc, hence a higher voltage level achieved as well as higher power transfer capability and fewer line losses compared to the AC case study. Moreover, due to the smaller power rating achieved when comparing scenario 3 to scenarios 1 and 2, the required rectifier modules also result in smaller size and investment costs ensuing a more techno-economic feasible solution.

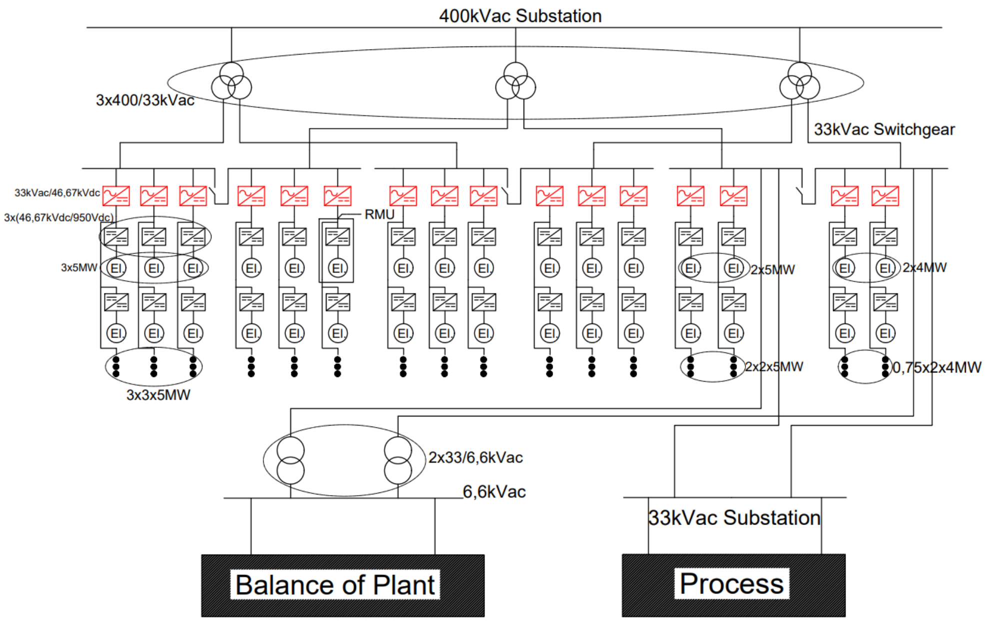

Figure 11 : Alternative configuration to case study

Since the RMUs are supplied in direct current, the internal MV/LV transformers present in the original case are replaced by DC/DC converters to step down the voltage from 46,67-33kV to a low voltage level. At their rated power, these converters are regarded as more efficient than AC transformers for the same power rating and may even provide more power at same voltage ranges. Thus, instead of carrying on with up to 4 electrolyzer units per RMU, each module may contain up to 5 units at 950Vdc therefore reducing the number of RMUs in series from 6 to 5. Figure 12 illustrates the design of this newly formed RMU.

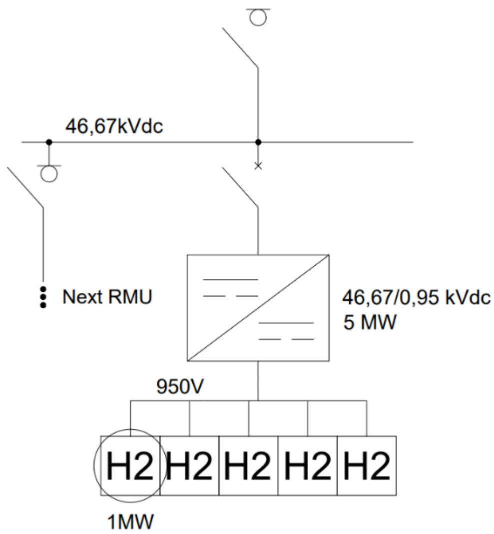

Figure 12 : Alternative RMU design

One downside with this scenario is the need to replace the AC bus bars of the RMU by equivalent DC bus bars, however there are many examples of such products on the market, guaranteeing its technical feasibility.

To summarize, the third scenario is chosen as it sustains the same design and redundancy features as the original system, carries on with supplying the AC loads and prevents replacement of the 33kV switchgears.

In addition, scenario 3 possesses a simpler and symmetric design compared to scenario 2, and the addition of rectifiers at the input of each RMU line allows the use of smaller rectifier modules : 25MW to be transmitted per rectifier instead of 75MW.

Finally, the literature specifies that previous three-phase AC cables can simply be retrofitted in DC [9] as shown in figure 13, thus the cables previously used to connect the lines of RMUs to the 33kV switchgears are utilized to connect the lines of RMUs to their respective rectifier module with direct current.

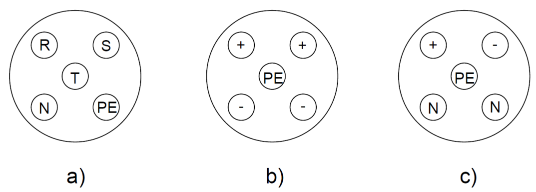

Figure 13 : Cable set-up for ac (a), 1st case DC (b) and 2nd case DC (c) [9]

Elements to replace :
- AC bus bars of the RMUs by equivalent DC bus bars.
- MV/LV transformer of the RMUs by a MV/LV DC/DC converter.

Elements to add :
- 33kV rectifier.
- Up to 1 additional electrolyzer unit per RMU.

4.2. Simulation Results on ETAP (Demo Version)

Since the configuration for the hybrid AC/DC grid is selected, the next step aims at obtaining simulation results for load flow and short circuit analysis via ETAP.

The voltage and current ratings portrayed in every simulation include the nominal values from the original AC grid for the AC part and the calculated non-nominal values for the DC part (e.g. rectifying from 33kVac to 46,67kVdc).

The already-known characteristics for the DC part of the grid are summarized here :
- Maximum power to be transferred per line of RMUs : 25MW.
- Rectifier : 33kVac ⟶ 46,67kVdc; 25MW maximum per unit.
- DC/DC converter : 46,67kVdc ⟶ 950Vdc; 5MW maximum per unit.
- DC copper bus bar : 46,67kVdc or 950Vdc; Current to be calculated.

The calculated values for the DC part of the grid are listed here :

- Line current on 46,67kVdc bus bar : $I = \frac{P}{U} = \frac{25MW}{46{,}67kVdc} = 535{,}67A$.
- Line current on 950Vdc bus bar : $I = \frac{P}{U} = \frac{5MW}{950Vdc} = 5{,}263kA$ (1,053kA/electrolyzer unit).
- Input current of DC/DC converter : $I = \frac{5MW}{46{,}67kVdc} = 107{,}13A$.

Load flow analysis

The demo version of ETAP unfortunately heavily limits its range of use as it does not permit simultaneous AC/DC load flow analysis for the proposed hybrid scenario (same limitation for the short circuit analysis).

Furthermore, the number of DC buses is limited to 10 units meaning that only a single line of 5 RMUs is analyzable instead of the complete system, thus the following results must be examined with precaution.

AC part

The order of magnitude of the obtained load flow analysis results for the AC part of the alternative grid seems to be in accordance with the original case study results. A slight voltage drop is observed downstream of the 240/33kV transformer, but its value remains within the admissible limits of ± 5%. The second branch of the transformer however must be fully modelled to obtain the correct voltage.

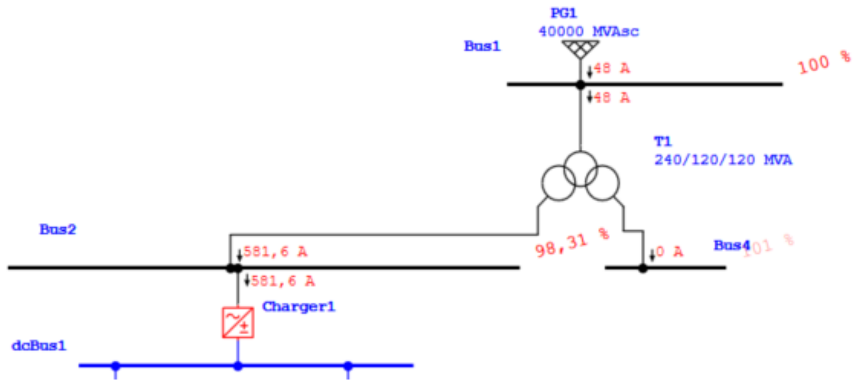

Figure 14 : Load flow analysis of AC part of the grid

DC Part

The power rating values attributed to the converters and DC cables of the load flow analysis were calculated previously and represent the minimum power rating they must possess to supply the number of loads downstream. In practice, a higher nominal power rating of the converter would be selected, or less loads supplied to obtain a certain safety margin.

The simulated results obtained show the power equally distributed to each RMU, but this outcome should be interpreted with caution as the entire single line diagram could not be simulated. No voltage drop is shown on either the DC buses or cable. At such high voltage levels, the voltage drop is particularly negligible for the DC buses. Same can be shown with the DC cable connecting the five separate 47kVdc bus bars to each other.

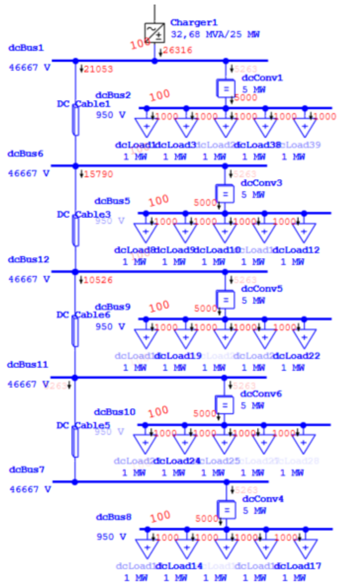

Figure 15 : Load flow analysis of DC part of the grid

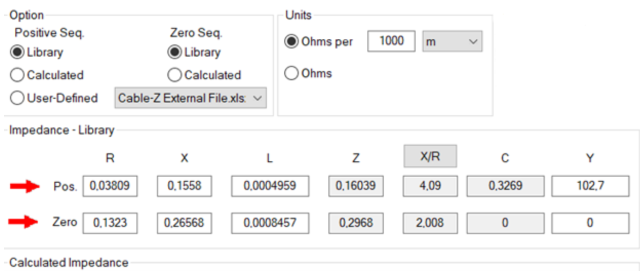

Figure 16 : Cable rating of 47kVdc connector

Figure 16 indicates the impedance values of the DC cable in this simulation. It is worth noting that the positive line is four times more reactive than resistive.

$$Voltage\ drop\ \Delta U = R * I = 0{,}03809 * 536 = 20{,}42V$$

$$Voltage\ drop\ (\%) = \frac{\Delta U}{U} * 100 = \frac{20{,}42}{46667} * 100 = 0{,}0437\%$$

Such low voltage drop percentages are negligible and not shown in this simulation. Power losses for the same voltage level are typically higher in AC, as both AC and DC current do incur resistive voltage drop (2%), but direct current does not incur inductive reactance voltage drop (3 to 5%) unlike alternative current. Therefore, inductive reactance is negligible for steady DC current and since there are no reactive components, AC-related losses like capacitive, inductive and skin effect losses are nonexistent.

Short circuit analysis

As for the previous simulation, this analysis is restricted by the ETAP Demo version.

AC part

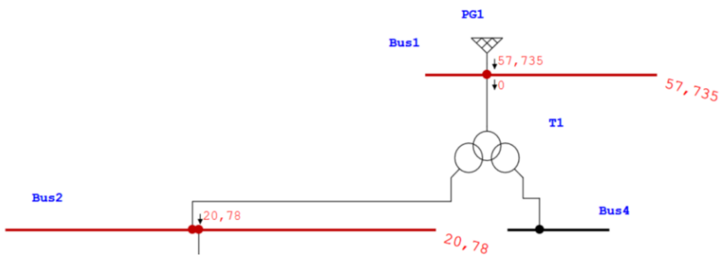

Figure 17 : Short circuit analysis of the AC part of the grid

The results obtained for the short circuit analysis in AC picture no anomalies and are consistent with the data of the original case study. For example, the short circuit current value obtained for the 33kV bus bar (called *Bus2* in figure 17) is equal to 20,78kA in the simulation which is close to the nominal short-circuit value of the bar rated at 25kA.

DC part

Even though some DC buses of this part of the grid were considered faulty by ETAP, the short circuit results obtained for the DC bus bars located downstream of the first DC/DC converter are nonetheless the same for every 950Vdc bus. The order of magnitude of the short circuit results are theoretically realistic since the simulation reveals a short circuit current value of less than 1kA for the 46kVdc bus, and about 7,9kA for the 950Vdc bus bar. For this simulation in ETAP, it is assumed that the contribution of short circuits by the rectifiers and DC/DC converters is equal to 150% of the rated equipment current.

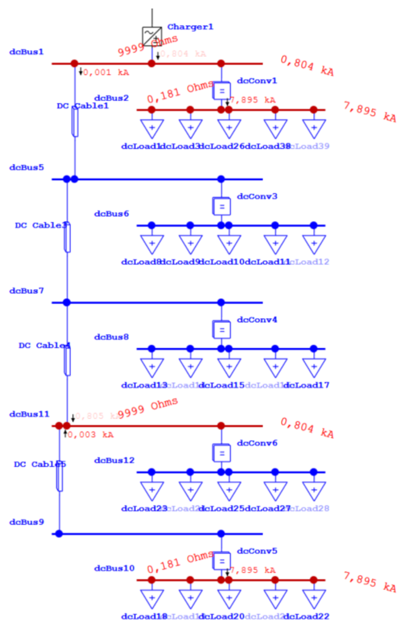

Figure 18 : Short circuit analysis of the DC part of the grid

The simulation of the entire single line diagram would provide more accurate results, but the ones obtained here do provide a realistic view and the <u>proof that this configuration is technically feasible</u> when considering the load flow and short circuit analysis of the system. Since this configuration is a hybrid AC/DC structure, AC and DC faults will practically interact with each other.

4.3. Efficiency analysis

The efficiency gain of one system over another can be determined by comparing the efficiency value of each configuration. The system's yield can basically be measured with the following ratio : $\frac{P_{output}}{P_{input}} = \frac{Pel - P_{losses}}{Pel} = \frac{P_{loads}}{P_{el}}$.

The higher the efficiency, the lesser the system's losses. Several losses occur in an electrical network, and the main losses are regrouped in the two following categories : **line** (or transmission) losses and **converter** (transformers, power electronics, drives, etc.) losses.

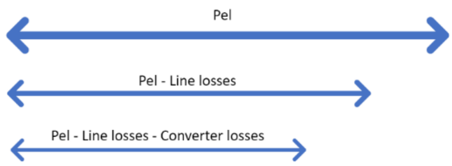

Figure 19 : Power balance of electrical network

The main argument for adopting hybrid AC/DC grids is the observed increase in efficiency due to the effective power transmission capacity of DC and the decreased number of conversion steps for systems employing sources and loads of DC nature. The comparison of the total number of conversion steps between this newly hybrid AC/DC grid and the original case study is shown in the table 4 :

Table 4 : Total number of converters per configuration

Original case study	Proposed alternative
3x400/33kV – 2x120MVA transformer	**3**x400/33kV – 2x120MVA transformer
2x33/6,6kV – 2x10MVA transformer	**2**x33/6,6kV – 2x10MVA transformer
91x33/0,4kV – 2x2,1MVA transformer	**60**x23,335/0,95kV – 5MW DC/DC converter **14**x46,67/0,95kV – 5MW DC/DC converter
362x0,4kVac/0,4kVdc – 1MW rectifier	**16**x33kVac/46,67kVdc – 25MW rectifier
Total: 458 converters	**Total: 95 converters**

As depicted in this table, the conversion steps are nearly reduced by a factor of five which signifies less converter losses. This is largely due to the elimination of internal rectifiers located in each of the 362 electrolyzer modules. However, the power ratings have changed between the two different scenarios.

Line losses are significantly reduced due to higher voltage capacity after rectification (up to 46,67kV instead of 33kV). Furthermore, the power-transfer capability for the same cable section of DC versus AC is theoretically increased by minimum **41%** (=$\sqrt{2} = \frac{Upeak}{Urms}$) thanks to higher RMS voltage values of DC and less conductor losses such as skin effect, power factor, proximity effect, reactive losses, etc. Finally, the existing three-phase AC cables of this study are retrofitted into a bipolar DC configuration which can theoretically transmit almost double the power to the load when utilizing the correct configuration.

4.4. Conclusion

After achieving a feasible DC alternative solution to the AC case study, the newly formed hybrid grid was verified through a load flow and short circuit analysis with nominal and non-nominal values via ETAP, despite the limited simulations of the demo version. Simulating the entire single line diagram is recommended to reach a more accurate conclusion.

For this reason, the exact numerical efficiency gain could not be determined in this study, although it is estimated that the efficiency of the new grid variant to the original case-study is higher as a consequence of lower conversion steps and line losses.

However, the gain factor of the newly formed system is not immensely significant as high transmission losses do occur in the HVAC part of the grid and no DERs such as solar panels or batteries are coupled with the DC loads, reducing thus the incentive to invest in a DC distribution system.

If the case study had been a multi-terminal grid incorporating several renewable sources and storage systems, then the overall significant increase in grid efficiency from AC to DC would be observed more distinctly.

5. Economic Feasibility

This chapter attempts to assess the economic feasibility of the newly formed DC alternative found in chapter 4 by analyzing the capital expenditures (CAPEX) and operational expenditures (OPEX) costs of both AC and DC systems to establish a final cost-benefit analysis between the two. The CAPEX and OPEX expenses are already determined for the original case study, and since changes to the original grid are exclusively pursued at downstream of the 33kV switchgears, the majority of costs related to the equipment are the same for the high voltage part of both grids. As a reminder, this paper does not consider protection aspects.

5.1. CAPEX

The CAPEX expenses in this paper include the main manufacturing and engineering service costs although they are difficult to estimate for DC due to the lack of qualified workers and standards on the market. Since the key technologies mentioned in chapter 2 are not largely available on the market, some costs such as the power electronics required for the DC system are roughly estimated on the basis of their technological readiness level (TRL) and costs associated with previous existing projects.

Main manufacturing costs

These expenses are determined for the AC grid and include costs related to raw materials, direct labor, overhead (variable + fixed), and contingencies. The manufacturing assets are mostly identical to both cases, except for the DC part of the grid where the costs for the different assets and expenses such as labor need to be estimated.

The main manufacturing costs are composed of the :

- 400kV transmission system.
- 33kV transmission lines.
- 400kV gas insulated substation.
- 6,6kV switchgear.
- 33kV switchgears.

Changes from the original to the substitute system are summarized here :

- Replacement of 33/0,4kV transformers by 46,67/0,95kV DC/DC converters.
- 74 RMUs (max 5MW each) in total instead of 91 RMUs (max 4MW each).
- Internal changes of RMU : 33kV-630A AC switchgear by 46,67kV-535,67A DC switchgear (nominal values to be determined); 400V AC copper bus bars replaced by 950V DC copper bus bars.
- Addition of rectifier units at the input of every line of RMUs; total = 16.
- Electrolyzer units no longer require internal rectification; 362 less rectifiers.
- Total cable length reduction of roughly 16%; cable units retrofitted from AC to DC.

The identical costs between the two systems are summarized in table 5 :

Table 5 : Identical cost values for AC and AC/DC grid

400kV Transmission System	1.496.000	€
400kV Gas Insulated Substation	49.130.000	€
6,6kV Switchgear	2.570.000	€
Subtotal	**53.196.000**	€

The cost values of the 33kV transmission lines and switchgears for the DC part are listed in table 6, ‘X’ being the unknown cost value of the new RMUs and project-based converters whose nominal power ratings still need to be determined :

Table 6 : Different cost values for AC and AC/DC grid

	Original grid	Alternative grid	
33kV Transmission System	11.301.043	10.780.000	€
33kV Switchgears	24.330.000	4.500.000 + X	€
Subtotal	**35.631.043**	**15.280.000 + X**	€

Service engineering costs
Further CAPEX expenses (drawings, tests, site arrangement, service engineering costs) are roughly estimated by adding 20% to manufacturing costs of the DC section of the grid (transmission, switchgear, etc.). Contingencies are estimated at 10%.

5.2. OPEX

The OPEX expenses in this paper include the non-tangible maintenance and operational costs and therefore more challenging to estimate than the CAPEX expenses.

Maintenance costs
Maintenance procedures aim at ensuring the reliability, maintainability, availability, and safety of the grid by applying corrective, preventive, predictive, and proactive measures. Generally, the maintenance budget for AC grids are estimated at **20%** of the total CAPEX value. Since DC grids currently possess low TRL equipment and standards, it is expected that DC systems are overall costlier to maintain until the maturing of the technology. Maintenance costs for DC are estimated at **25%** of the CAPEX. This value increases if protection aspects are considered.

Operational costs
Operational costs are directly related to the overall grid's efficiency as it involves the electric costs of supplying the loads, in this case the electrolyzers. By considering the average cost of electricity and the system's efficiency, the operational costs are deduced by first establishing the value of true power which is equal to the power required to supply the loads divided by the efficiency value ($P_{el} = \frac{P_{load}}{\eta}$) and multiplying the result by the average electricity price ($Operat.costs = P_{el} * Cost_{elec}$). In this paper, the exact numerical efficiency value is not established for either system, notably due to the absence of nominal values and catalogue components.

It can be assumed that the efficiency of both systems lie in a similar range as minimal changes were carried out for the alternative configuration. Due to the effectiveness of DC technology, higher converter efficiency, lower number of conversion steps and transmission losses, it can be safely assumed that the hybrid AC/DC grid of this study presents a higher operational system efficiency than the original AC grid.

5.3. Cost-Benefit Analysis

Both configurations are compared with regards to the CAPEX and OPEX expenses; some values like the numerical efficiency values are therefore estimated. Due to the several assumptions established in this cost-benefit analysis, a sensitivity analysis is recommended to obtain a wider range of results. In the next presented tables, the original AC grid is called system A and the alternative solution is called system B.

CAPEX comparison

Manufacturing and service costs are assumed to be higher for the new configuration since the unit costs of DC power converters, RMUs and DC bus bars are significantly higher than for the matured AC technology. This is represented in table 7 :

Table 7 : Comparison of manufacturing and service costs

Total manufacturing costs system A	**88.827.043**	EURO
Total manufacturing costs system B	**96.206.000**	EURO

OPEX comparison

As a reminder, the maintenance costs are calculated with the following formulas :

$$0{,}2{*}CAPEX_{System_A} \text{ and } 0{,}25{*}CAPEX_{System_B}$$

The results are shown in table 8 :

Table 8 : Comparison of maintenance costs

Total maintenance costs system A	17.765.409	EURO/YEAR
Total maintenance costs system B	24.051.500	EURO/YEAR

To evaluate the operational costs, the global numerical efficiency value of the system which includes transmission and component losses is estimated for both systems. Since system B is considered more efficient than system A, the following values of efficiency are given : $\eta_A = 0{,}85;\ \eta_B = 9$.

The operational costs are calculated with the following formula and results shown in table 9 :

$$\frac{0{,}2€}{kWh} * \frac{8760h}{year} * \frac{430000kW}{\eta}$$

Table 9 : Comparison of operational costs

Total operational costs system A	886.305.882	EURO/YEAR
Total operational costs system B	837.066.667	EURO/YEAR

The OPEX expenses spent per year can thus be found with the following formula and results shown in table 10 :

$$OPEX_{System} = (Maitenance_{costs} + Operational_{Costs}) * time$$

Table 10 : Comparison of OPEX costs

Total OPEX costs system A	904.071.291	EURO/YEAR
Total OPEX costs system B	861.118.167	EURO/YEAR

Total costs
CAPEX expenses are thus higher for system B than system A as DC grids require more expensive equipment and the use of skilled workers, which are currently scarce; OPEX expenses on the other hand are lower for system B than system A since the assumed higher efficiency of system B yields to lower operational spendings per year.

The total costs are estimated via the following formula :

$$Total\ costs\ = Manufacturing_{costs} + (Maitenance_{costs} + Operating_{Costs}) * time$$

By inserting the values obtained above, the total costs are equal for system :

- A : $88.827.043 + (904.071.291) * t$
- B : $96.206.000 + (861.118.167) * t$

By equalizing both equations, a return on investment (ROI) is deduced to predict the time it takes for system B to become more profitable than system A :

$$88.827.043 + (904.071.291) * t = 96.206.000 + (861.118.167) * t$$

⇔ $t = 0{,}172$ years = 63 days.

The obtained result is very optimistic, mostly due to the numerous assumptions formulated in this study. This result would change dramatically when taking into account other important aspects such as protection and obtaining nominal power rating values for the electrical equipment and lines. Furthermore, the CAPEX and OPEX costs are grossly estimated on the basis of the known figures from the original case study and are subject to significant fluctuations in practice.

A sensitivity analysis may be applied on several values, most importantly on the efficiency gain of system B as the operating costs cause the biggest impact on the economic feasibility.

6. Conclusion

Chapter 2 provides the state-of-the-art of DC grids and answers the question : "*What does the ideal DC system look like and what is required?*"
This depends on the type of application for which the electrical grid is needed; a pure DC distribution grid technically makes sense for standalone grids incorporating renewable energy systems, storage systems and DC loads. However, replacing the existing AC infrastructure would be a massive undertaking requiring significant investment which is why constructing hybrid AC/DC grids enables a smooth transition from centralized AC systems to decentralized meshed DC grids in the future.

Chapter 3 provides a brief description of the original case study as well as an overview of the scope of study.

Chapter 4 provides an alternative DC solution to the original case and a technical feasibility analysis. It therefore answers the question "*How can the case-study be configured with a DC distribution system, and which configuration is the most energy-efficient?*". The existing design undergoes the least number of changes to become a more efficient hybrid AC/DC grid to effectively supply AC and DC loads. The rectification step takes place at medium voltage level permitting efficient power transfer and few conversion steps. The technical feasibility is partially verified via limited simulations using ETAP for load flow and short circuit analysis, and the efficiency gain is estimated based on several assumptions which should be subject to a sensitivity analysis.

Chapter 5 provides an economic feasibility analysis to the proposed AC/DC solution by determining the CAPEX and OPEX costs of both grid scenarios before conducting a cost-benefit analysis. It therefore answers the question "*Which configuration is the most cost-efficient?*". The original AC grid possesses lower CAPEX costs compared to the alternative grid proposed in chapter 4, however the OPEX costs are higher due to an overall lower efficiency driving the operational costs up every year. The cost-benefit analysis therefore suggests that the hybrid AC/DC scenario is more cost-efficient after only 63 days, but further research is required to accurately estimate these three costs: manufacturing, maintenance and operating costs. This can be achieved with a detailed report cataloguing the necessary equipment in DC with its attributed price as well as the numerical efficiency value of both systems. Finally, considering the protection and safety aspects which are problematic with current technology may result in a totally different conclusion regarding feasibility.

7. Future Work

Chapters 4 and 5 require a thorough revision with data from DC equipment manufacturers to obtain nominal power rating values of the grid as well as a numerical efficiency estimation for both case studies.

A functional version of ETAP or other software should provide an accurate assessment of the efficiency gain as well as validate the technical efficiency by providing a full load flow and short circuit analysis of the newly proposed hybrid grid.

Future work should incorporate other important aspects left out in this paper, notably protection, control, and grounding as these are key for the adoption of DC grids.

Furthermore, a compatibility analysis is recommended between the DC loads, power converters, DC buses and other equipment.

Finally, the economic feasibility should be revised with more accurate data and less assumptions. An environmental and social impact may be of importance once the techno-economic feasibility of DC grids is entirely achieved.

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