Multi-arrays H2 electrolysis unit
Electrical architecture

Paper No. PCIC energy EUR24_26

Cécile Gaudeaux
Air Liquide Engineering
Olof Palme strasse 35,
Frankfurt
Germany

Tripti Mishra
Air Liquide Engineering
Olof Palme strasse 35,
Frankfurt
Germany

Abstract - Hydrogen is currently enjoying a renewed and widespread momentum in many national and international climate strategies. Many governments and companies are putting significant resources on the development of hydrogen technologies. A low-carbon hydrogen economy offers promising opportunities not only to fight climate change, but also to enhance energy security and develop local industries in many countries.
Air Liquide started working on H2 Electrolysis a few years ago and can claim to operate the largest PEM plant in the world (20MW PEM in Canada).
This paper will present the steps to follow to design the electrical installation when going to a multi-array H2 electrolysis plant.
We will go through the parameters to be considered, the ones coming from regulation and local standards as well as the ones dictated by the operation and maintenance teams.
By increasing the size of the plant, we are reaching the capacity of the equipment available on the market and some of the principles could have to be challenged.

Index Terms — PCIC energy Paper Format, Writing instructions, Style requirements.

I. INTRODUCTION

Building the electrical architecture of a new plant is always to follow the same mindset and procedure. Each technology has its own specificities to be considered. While the ASU plants require a strong knowledge in large motors design, the Electrolyser (ELY) plants oblige us to develop awareness of dealing with harmonics and reactive power compensation.

The ELY journey in Air Liquide has started with small units (less than 2,5 MW) integrated in an industrial plant, the next step is now dealing with multi-arrays plants connected to the HV grid.

In this article we will describe the typical architecture of the electrolyser plant and highlight the differences when compared to other traditional ASU or petrochemical plants in terms of design, load type, control philosophy and maintenance as well as reliability. Also, some experiences from Air Liquide on going project in the basin of port Jerome is shared where relevant

II. Presentation of ELY multi array plant

Electrolysis technology has existed for decades. However, it is only in the last 10 years that we have seen a significant increase in global interest for water electrolysis, with the adoption of ambitious national climate protection programs. Water electrolysis is regarded as the central element for sector coupling and is expected to make an important contribution to reducing greenhouse gas (GHG) emissions close to net-zero by 2050.

While the Electrolysis equipment was running by batches for various processes such as Chloride, the business case has changed and the target is to run the plant continuously to provide green H2 to industrial units. Air Liquide is owning its H2 pipeline and the plant is designed to continuously feed the network.

The plant is designed based on multiple modules (called array). The combination of individual cells is referred to as a stack. These stacks are then grouped process wise and connected to electrical systems which usually consist of power converters and transformers. The complete system with stacks and power electronics is referred to in the Normand'hy project as 1 array. In this project, 12 arrays are planned for installation.

The type of units represents a huge investment where the electrical equipment is key but not representing the highest percentage in the EPC breakdown price.

Item	% overall price
Electrolyzers (incl transformer and rectifiers)	28%
BoP : Rotating (LP H2 and HP H2 compressors) + Package Units (H2 purification, cooling water system, ...)+ Pressure vessels	11%
Electrical equipment (harmonic filter, switchgears....)	9%
Bulk	6%
Construction	28%
Services	10%
Risks	8%

Table 1: Multi array plant - Basis of estimation (Europe based).

It is evident from Table 1 that for Electrolyser plant electrical scope is quite big and in comparison to the traditional technologies such as ASU the design considerations and challenges are different. Here below are listed the criteria considered for the design for both technologies

Electrical design considerations	ASUs plant	Electrolyser plant- multi array
Most critical consumer in terms of power ratings	*Large MV motors* 15 MW to 65 MW(typical range)	*Electrolyser unit* 20 MW
Reactive power demand	*less* when compared to ELY plant	*quite high*
Harmonics	*Transient condition* LCI drives are used for starting of MV motors	*Permanent condition* Rectifiers are major source of harmonics
Load profile	Mostly *fixed*, less variation	Load is *variable* (based on PPAs profile)
Flexibility of Medium Voltage	More *flexibility* in terms of voltage choice depending on plant size	For multi array electrolyser projects choice is 30kV
Stress on Electrical equipments	Continuous operation in fixed mode is resulting in less stress on equipments	*Dynamic* operation require careful analysis of system, limited mechanical operation
Raw material	*Air+ Electricity* 70% of Oxygen cost is driven by electricity	*Electricity + Water* 60-70% of H2 cost is driven by Electricity
ATEX zone	No Hazardous zone in general	Hazardous area classification analysis is performed and selection of E&I equipment and design to follow the ATEX regulations
Grid services	Not applicable	Grid ancillary services can be provided

Table 2 : Major design consideration differences between ASU and Electrolyser plant (w.r.t. Electrical)

For that reason, it was necessary to launch new technical discussion to understand the challenge of designing a reliable electrical architecture for such a plant.

III. PPAs principle - Green H2

PPAs are long-term renewable energy contracts considered as a reliable way of decarbonising the electricity consumption, contributing to the energy transition.
For clients, they prove the renewable origin of their electricity consumption and demonstrate their commitment to short supply chains and to a local approach.
For operators, these contracts reinforce their capacity to develop renewable energy parks with greater capacity, and to take advantage of the best locations for producing more profitable energy. Yields from offshore wind or land wind farms in windy areas are higher, as are those from solar PV installations in sunny territories.
In the business case of our multi-array unit, the H2 shall be green certified, then the Electrolyzers shall be supplied with renewable energy (while the Balance Of Plant (BoP) will be supplied from the grid).
We are talking about “off-site’ PPAs, Energy that is consumed by the plant is not linked to a defined site. We benefit from the PPA offer: a fixed long-term rate and guarantees of origin of renewable assets, while continuing to be supplied by the operator.

At a macro level, the electrolysis plant shall be considered as an electrical power consumer which shall fit its consumption with the electrical energy targeted for an external given Power Set Point while maximizing the Hydrogen production

IV. HV Network characteristics

The ELY plant is connected to the national grid where the technical characteristics are well known.
The installed power (200MW) makes the plant connected to the HV grid (225kV for our ND’Hy project).
The connection demand to ensure power capacity is available to feed the plant is to be anticipated as the electrical infrastructure is a little bit congested (quite a huge number of on-going projects).
The power provider is imposing a power factor as well as a THDu (about 8%) which forces us to install a harmonic filter and PF compensation dedicated system on the MV network.
The High voltage system is to be designed by Air Liquide and the preferred choice is Air Insulated HV network, however given the space requirements Gas Insulated options are also evaluated with the suppliers.
The Overall design of the electrical architecture is done internally and considered to consolidate the final calculations with the supplier (especially for the harmonic filter design which requires specific skills).

V. Load variation (EoL versus BoL)

In conventional electrical systems, loads are generally constant and therefore design is relatively fixed in comparison to the Electrolyser load which consist of stacks or modules which further consist of various numbers of cells i.e anode and cathode, and as cells degrade over a period of time, this degradation results in overall increase in power consumption of module/stack. The expected degradation rates are provided by electrolyser suppliers during purchase however in practice it depends on the various conditions such as quality of water, operating scenarios that include fluctuating nature of renewable energy, and also quality of maintenance.

So, while designing an electrical network special attention is needed to evaluate the performance of the plant with respect to two base cases (several sub-cases as per typical engineering practices are not considered). First case is Beginning of Life conditions, or sometimes even called as Start of run condition that means the condition of electrolyser load with new cells and the power consumption in this case is lower than second case which is referred to as End of life or End of run condition where cells are degraded or aged and for same amount and quality of Hydrogen production consumes more power. As shown in the conceptual electrolyser load graph below, for the same amount of current (100% corresponding to rated Hydrogen production) voltage required during EoL is higher than BoL.

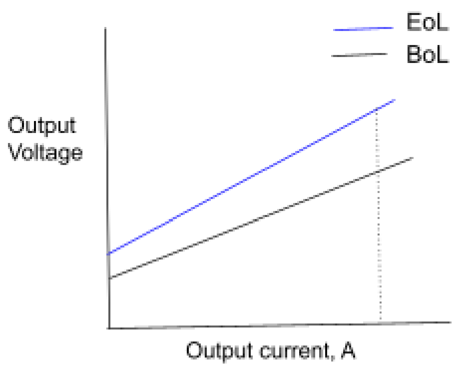

Figure-1 Conceptual load slope of the Electrolyser

It is important to pay attention to the fact that for the electrolyser plants, electrolyser load alone is approximately 80% of total plant load for the scale of 200 MW and therefore the design conditions must be evaluated for both BoL and EoL cases.

VI. MV and LV architecture of Electrolysis plant

Medium Voltage System:
The selection of the medium voltage for electrolysis plants depends on the following:

Scale of the plant: The total installed capacity of the electrolyser unit plays an important role in determining the voltage level. For a small scale plant, for instance, on-site type of installation typically with voltage ranges from 6.6kV to 10kV could be a reasonable choice as electrolyser load can vary from 1 MW to 5 MW.

For large scale installation projects like NormandHy, which is 2 trains of 100 MW, 30kV is selected as the operating voltage of the plant due to the fact that 36kV insulation is the maximum available voltage level with most of the suppliers in the switchgear industry. Also, taking into account the maximum current rating (3150 A at 36kV) it was found that connecting 6 electrolysers each rated approximately 20 MW is the cost effective architecture for one 30kV bus system that connects 6 electrolyser called as one Train-1 and similar architecture for Train-2.

Type of plant: Green field or Brown field plant can also influence the choice of Medium Voltage. In a brown field project, the existing voltage can be chosen if spare power is available and extension of medium voltage switchgear is feasible.

Plant compression strategy: For an electrolyser operating at atmospheric pressure, the power demand for the compression system could be high depending on the final delivery pressure while for medium pressure electrolyser the demand for compression could be relatively lower. The redundancy concept for either case is studied by Process/Rotating in consultation with AL operation and maintenance guidelines and form the basis of design for Medium Voltage level. This voltage level for the compression system is often lower than the assigned voltage level for the electrolyser system.

Low Voltage System:
The rating of the Low Voltage system for European projects is normally 400V. The electrolyser auxiliaries, compression system auxiliaries, plant auxiliaries are designed for this voltage level. AL investigated the DC charger and UPS as potential sources to supply critical consumers and concluded that for Electrolysis plants DC charger is a cost effective and reliable solution and reduces the demand for UPS which is reserved for instrumentation and IT networks. This solution also reduces the footprint of the electrical substation

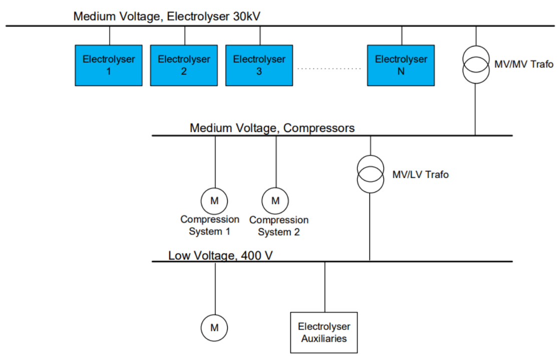

Figure 2: General power distribution architecture of ELY plant

VII. Back-up system

When we are talking about a back-up system; we are not addressing the gas back-up as the gaseous H2 will not be put in a vessel nor in a trailer.

In this application, the H2 produced by the Electrolyzer is filling the H2 pipeline owned by the company in the area.

The H2 pipeline is also fed by SMRs (Steam Methane Reformers) and they will compensate for the lack of molecules in case of PPAs drop down.

On this H2 pipeline are also connected H2 filling stations dedicated to trailers for market distribution (including fuel cell quality).

Regarding the electrical loads, it is also needed to consider the critical ones, loads affecting personal and operational safety whether directly or indirectly and inducing risk of major damages on installation or equipment. These loads are connected to switchgear with an emergency source of power which may be backed up by an external power line or an emergency generator. On loss of normal supply, the equipment shall be restarted automatically or manually by the operator and re-fed from the emergency generator (2).

For electrolyser projects other than conventional consumers that are considered as emergency consumers such as fire water pump, control system, fire and gas panels etc, additional consumers such as critical HVACs, High Voltage control, some auxiliary hydrogen compressor devices are also installed on the emergency bus.

Electrolyzer is not a complicated technology, the challenge is mainly to deal with H2 safety. These critical load management will be improved through operation experience in the coming years.

VIII. Reliability/ Cost

To compare between the reliability and cost let's have a quick glance on the two cases:

Figure 1 above shows the simple electrical architecture of an Electrolysis plant without redundancy.

Figure 2 below shows the redundant electrical architecture from the high voltage side to the low voltage side. The benefit of such a design is the increased reliability of the plant. However, as evident from the architecture, the cost of electrical equipment and footprint is significantly high in comparison to architecture shown in Figure-1. Also, the cost of reactive power compensation/filtration due to two separate medium voltage bus systems is doubled.

Air Liquide investigated both the solutions during internal proposals and examined several solutions that can be implemented on the process and control design side such as redundant pumps for critical applications or investment in advance diagonstic features in order to lower the capital cost and to have better reliability

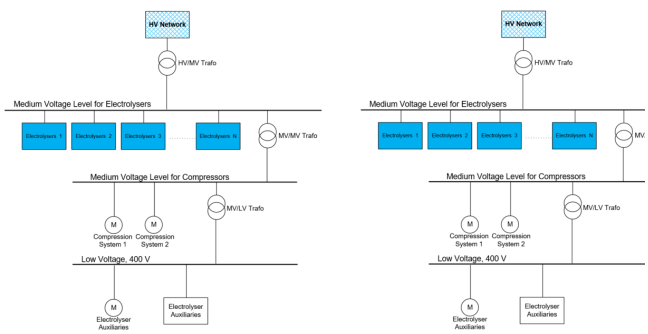

Figure 3: Electrical architecture with redundancy concept

Description	Non Redundant architecture (Figure 2)	Redundant architecture (Figure 3)
Redundancy	Low	High
Reliability	Medium	High
Cost	Low	Very High

Table 3: Comparison of Electrical architecture

The study to compare connection of Medium to low voltage transformers a.) when connected to the same voltage level as Electrolyser plant b.) when connected to the voltage level as an MV compression system is done inhouse that show interesting results and further opportunity to save cost, the results vary according to scale of the plant.

IX. Reactive power management and Harmonic compliance in electrolysis plant

The technology of the power convertors plays an important role in managing and further development of reactive power management.

In general, judging solely on the basis of reactive power and harmonic, IGBT technology performance is found to be better than conventional Thyristor technology. A drawback of the Thyristor-based technology power converter is the unavoidable consumption of reactive power, which originates from the switching angle of the thyristor. The switching angle delays the start of the electric current flow compared to the sinusoidal voltage wave, which causes a phase shift between electric current and electric voltage. Among others, this is the main reason for the significant reactive power demand of a Thyristor-based power convertor. However, when factoring in cost, power density of the thyristor and control system, it is found that thyristor technology is better suited for the large-scale electrolysis plant connected to the conventional grid.

While for thyristor technology based power converters, power factors range around 0.9, the power factor for IGBT technology can be from 0.9 to even 1 in exceptional cases if agreed during the purchase. IGBT technology often is the good solution for the lower scale or on-site type installation where investing more in IGBT technology, the cost of capacitor banks or filtration requirements can be reduced. However for large scale electrolysis projects (200MW), Thyristor technology based power convertors are better option, provided the connection to the plant is via conventional grid (not through stand alone renewable plants with weak grid characteristics)

Harmonics:

The main source of harmonics in an Electrolysis plant is the power converter which is a non-linear load. Nonlinear loads are loads in which the current waveform does not resemble the applied voltage waveform due to a number of reasons, for example, the use of electronic switches that conduct load current only during a fraction of the power frequency period. Therefore, we can conceive nonlinear loads as those in which Ohm's law cannot describe the relation between V and I.(1)

Also, for a large-scale electrolysis project with compressors, another case for harmonic study is necessary for evaluation that includes power convertor used for electrolyser and variable frequency drive for compressors to account for harmonics generated from both sources and have a design and solution to mitigate both sources of harmonics. A frequency scan study as part of Harmonic analysis is also conducted to check and avoid parallel resonance conditions in the electrical network.
Both reactive power compensation and harmonic compliance analysis are done together at point of common coupling in accordance with requirements of local regulation of grid companies as well as IEC 61000-2-6 for European projects. As the solution to mitigate Harmonics and meet the required power factor, in Air Liquide, we have used Active and Passive filters and concluded that Passive filters are economically better choice compared to Active filters for large scale Electrolysis projects on Medium voltage level. The design of the passive filter in different steps/stages connected to the main bus allows it to take care of mitigating different harmonics frequencies, better control of voltage, power factor and also provide desired operational flexibility. The attention is paid to reduce the overall losses in the system design

X. Control philosophy of Electrolysis plant

The concept of green hydrogen production using electrolysis is dependent on renewable energy. As it is evident that the nature of renewable energy is very intermittent, the performance of the plant highly depends on technology which is suitable for operation with intermittent renewable electricity.

In this regard, the ramp rate of PEM technology allows more flexibility (operation possible with varying load without compromising the product quality and plant safety) in comparison to alkaline technology that prefers stability in power supplies. Please refer to the table below for ramp rate of ELY techno... Also, the ramp rates of conventional/existing technologies are provided in Table 2.

	PEM	AEL
Aging	**1,5%/year**	**1,5%/year**
Loading rate	**10%/sec**	**4%/sec**

Table 4: Ramp rate of PEM and AEL technology

Techno	**SMR**	**ATR**	**ATR/SMR-CCU**
Max ramp rate, per minute	**3%**	**3%**	**1.50%**

Table 5: Ramp rate of SMR, ATR and ATR/SMR-CCU

As evident from the above table, PEM technology can offer the fastest possible ramp rate while maintaining the operational reliability. Thus, it enables the plant owner to accomplish maximum flexibility in terms of optimal plant load to avail the lowest cost of operation. This particular benefit of PEM technology becomes further attractive when the plant operation is solely dependent on renewable energy PPAs.

In the overall electrolysis plant control philosophy, behavior of balance of plant equipment in terms of time response expected with respect to grid services is also analyzed and studied.

The Air Liquide plant NormandHy has also added complexity when it comes to the control strategy as the production demand is to be managed not only by Electrolysis plants but also by nearby SMR plants (see Figure 2 below) in order to maintain continous hydrogen supply and pipeline pressure. Although the plant is powered by grid, operation of the plant is dictated by the renewable energy profile in which daily ramp up and ramp down is the normal plant operation mode. In the NormandHy basin, the electrolysis plant will be the primary supplier of hydrogen into the pipeline and SMRs will be secondary to maintain the customer supply and pipeline pressure. The electrolysis plant will also provide certain grid services mainly limited by the SMRs ramp up/down capacity.

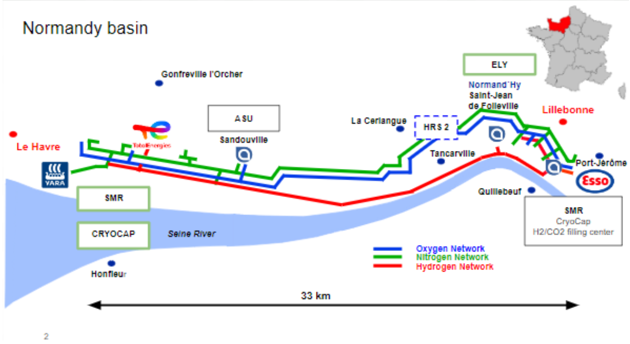

Figure 4- NormandHy basin and AL pipeline network

XI. Implementation of Electrical control system

Considering the proportion of electrical assets in an electrolysis plant, an Electrical Control System is planned to collect and to build the information required to perform accurate asset diagnostics and to exchange the relevant inputs to BPCS to ensure the control and protection of the plant. Electrolysis Plants operate with the constraints to monitor, capture fast signals and need a significant amount of data to control the process.

Electrical control system not only helps with increasing diagnostics capabilities for Electrolysis plants but also enables the Learning and historical data collection which will be useful data for future prediction and measurement of degradation of relationship between various electrical parameters (process relationship with degradation can be analyzed in BPCS).

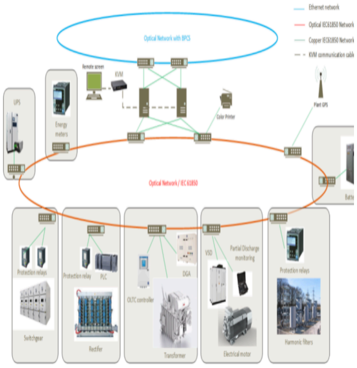

Figure 5- Concept of ECS

XII. Maintenance and availability

The technology used for the NormandHy project is PEM atmospheric type of ELY technology; which means that compressors are needed to compress the H2 from 1 barg to the pressure of the H2 pipeline (35 barg for NormandHy plant) with a purification in between. The huge advantage of the atmospheric solution is the fact that we will have very limited ATEX area in the ELY building (few centimeters around some piping flanges) which will allow having many arrays in a single building.

Calculations were carried out about electromagnetic risk on site for the humans to identify the area to be closed during operation.

The operation of arrays while having one in maintenance in the same building is possible.

The performance of such equipment is today not well-known as the technology is not mature enough in this type of continuous operation (during the last 50 years electrolysis was more used by batch to fill vessels). The operation using PPAs profile is also a parameter we shall better understand in the coming months/years.

There are also questions around the behavior of the BoP equipment as compressors, where we can anticipate troubles due to “unstable” operation which will lead to many starts and stops.

XIII. Capitalization from running projects

Electrolyser projects at the scale of 200MW are Firt-Of-Its-Kind projects and to continue moving forward it is paramount that attention must be given to capitalize on each phase of the projects to leverage on the cost of the next project as well as improving the design, and update of internal stanndards.

From experience of a 20 MW pilot plant in Oberhausen, Germany we learnt a lot, especially about the design of explosion project concepts, time efficient and safe erection methodology, equipment handling at site, also optimization on commissioning activities, improvement on BoP design, certification topics etc…

To internally handle these capitalization AL has an in -house tool called “My Cap”, the database of all these are managed by Quality Team.

The next step is now collecting data in order to have a better understanding of the plant performance (stack deterioration, EoL behavior, maintenance needed..).

XIV. CONCLUSIONS

The electrolyser plant's future is promising however various challenges such as geopolitical scenarios, availibility of enough renewable resources, compatibility of national grid infrastructure with renewable, update of grid codes etc are the hurdles to be overcome by the industries. Also, the availability of operational plant data in the coming 20 years will further shape the technology. At Air Liquide we believe that investment in Electrolyser plants is a necessary step forward towards the clean energy goal.

NOMENCLATURE

PPA	Power Purchase Agreement
PEM	Proton Exchange Membrane
AEL	Alkaline.
MV	Medium Voltage
SMR	Steam Methane Reforming
ATR	Auto Thermal Reforming
CCU	Carbon capture unit
ECS	Electrical control system
BoP	Balance of Plant
ELY	Electrolysis
BoL	Beginning of Life
EoL	End of Life
IGBT	Insulated Gate Bipolar Transistor
BPCS	Basic Process Control System
FOIK	First of Its Kind

ACKNOWLEDGEMENTS

We acknowledge our colleagues who are supporting us on a daily basis and especially the ones who have contributed to review the document.

REFERENCES

[1] Harmonic and Power system, Taylor & Francis Group, LLC

[2] AL internal standard G-EP-7-0-4

VITA

Cécile Gaudeaux graduated from Polytech’Lille (France) in 199l with a honors degree in Electrical engineering. She has started her career as a commissioning engineer for industrial plants with ALSTOM company. After various experiences in engineering companies, she joined Air Liquide in 2004.

With a background of electrical engineering and digital, she is today in the Electrolysis department as EngineeringDirector..
cecile.gaudeaux@airliquide.com

Tripti Mishra graduated from Uttar Pradesh Technical University in 2012 with bachelor's degree in Electrical Engineering. She has been working with Air Liquide Global E&C solution as Electrical design engineer after graduation and has held different global job roles at design offices and construction sites within AL group. She is currently based in Frankfurt in the Electrolysis Product unit as Senior Electrical Engineer.
tripti.mishra@airliquide.com