POWER CONVERTER SELECTION GUIDELINES FOR GREEN HYDROGEN PRODUCTION

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Abstract - Production of green hydrogen by water electrolysis requires AC to DC power conversion between the grid and the electrolyzers. During this conversion the grid, but also the electrolyzer operation can be impacted if the converter technology is not selected properly. Depending on their technology, alkaline or PEM electrolyzers can be sensitive to the current quality of output in terms of DC ripple, regulation dynamics and accuracy. In this paper 3 types of power converters are compared: pure diode, SCR based rectifier, and an active front end rectifier. The operational constraints of green hydrogen production or maintenance can impose partial load operation, or unbalanced load. Grid codes impose to comply with power quality constraints such as harmonics and power factor. This aspect if often neglected in the designs, being presumed easy to solve, but it is key to guarantee the compliancy of the operations to the grid in downgraded mode. Simulations with EMTP-ATP software enable to model transformers, cables and electrolyzers in sufficient details to demonstrate the impacts of such operation. The paper intends to provide guidelines to properly select converters and associated power systems components according to operational constraints.

Index Terms — green hydrogen, power electronics, power system, power quality.

I. INTRODUCTION

Hydrogen is one of the projected key elements of the energy transition, aimed to reduce the carbon footprint in heavy industries. It can be used for multiple purposes, such as green steel [1], heating, energy storage, green mobility. Currently almost 96% of hydrogen production is based on carbon intensive processes in oil and gas industries [2]. Obviously, a massive application of hydrogen in industry decarbonization requires itself to be produced in a less carbon intensive manner. Water electrolysis is a method of H_2 production which is of the most environment-friendly, especially when the electrical energy is supplied by low carbon sources, renewable or nuclear. The production of hydrogen from electrolysis is using DC current supplied to the anode and cathode of the electrolyzer obtained by rectifying an AC input. There are multiple technologies and architectures to develop the rectifier, as well as control laws of various complexity [3]. They mainly use 3 semiconductor types interacting with the power system: diodes, thyristors (SCR) and IGBT. So far, the main flow of research is dedicated to how these technologies can be combined in multiple architectures to supply the electrolyzer with as smooth as possible DC current. However, also due to lack of sufficient installed base, few, to say no information can be found regarding how these power electronics systems will be integrated at scale in a power system. Few experiences exist also in how the control and electrolyzer will react to a variable quality and quantity of the electrical energy supply [3]. Therefore, the power quality problem is getting key when the design is aimed to scale and foresee unbalanced operation and partial maintenance activities on site. This paper is aimed to help the understanding of the stakes in this direction with parallel consideration of the electrolyzer technology constraints. The paper is structured as follows. In chapter II are discussed in more details the electrolyzer technologies and their constraints on the power conversion performances and technologies. In chapter III will be reviewed the principal power conversion technologies and how they will impact the power quality of the electrical system. Chapter IV will then present the power system architectures applicable to solve the quality issue, illustrated by a simplified case study to illustrate the power quality figures through simulations. In chapter V, a methodology and design recommendations are proposed.

II. ELECTROLYZER TECHNOLOGIES

A) Definition

Electrolyzer is a system that will split water into H_2 and O_2 thanks to a DC current that provides the energy needed. The process is well known and is used for decades to produce high quality Hydrogen or Oxygen.

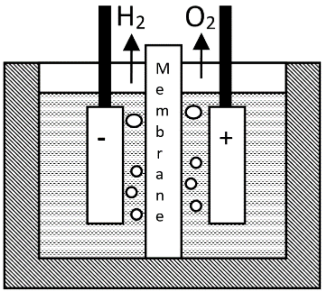


Fig. 1 Electrolysis principle

Hydrogen has no color but to illustrate the way it is produced, it has been named as: grey for the most common SMR process that generates almost ten times more CO_2 than H_2; blue when adapting the SMR technologies with carbon capture solution; white for the natural resources; pink for the low carbon H_2 from electrolyzer supplied by nuclear power and finally green when it is powered by renewable energy.

B) Need for green energy

From renewable sources, solar and wind are most often associated to green H_2 as they are intermittent and non-controllable. This is not the case of most of the hydraulic resources that are controllable and ensure the primary reserve for the network stability.

These two main properties of renewables are among the main drivers in the selection of the electrolyzer and the rectifier tandem as the power demand should dynamically follow the intermittent power generation.

The non-controllable behavior implies that the energy may be generated at a time where there is no need for it and hence, either it is lost, or it is necessary to connect loads to use it. In this condition the electrolyzer will act as a controllable load that convert this renewable energy into a storable energy, transforming the electrical energy in H_2 molecules.

This energy storage can be sufficient for a day-to-day balancing (night over day for solar for example) or for seasonal storage, converting summer solar energy in usable energy in winter.

Electrolyzers can also act as controllable loads to contribute to peak shaving of production, enabling the growth of the renewable part in the energy mix and cross the limit of the 25% of the installed power of a country without creating instability issues, [5].

C) Need for decarbonization

Green H_2 can be stored for short (intraday) or long duration(seasonal) and is a perfect and can act like pumped hydro energy storage (PHES) does in country with mountains, we will then speak about power-to-power solution combined with fuel cell installation.

But there is also plenty of usage for the heavy industry where H_2 will allow a drastic reduction of CO_2 emissions like refinery, ammonia production needed for fertilizer, methanol product. Another good example is green steel to avoid coal burning of classical melting process or methane usage in modern direct iron reduction. It can be used also in many processes as alternative to gas or when electrical heating would not be suitable like for glass melting in existing furnaces. In cement industry where high temperature is needed in one hand and a lot of steam is wasted; steam can be re-used to produce hydrogen or synthetic gas (syn gas) with higher efficiency.

D) Electrolyzer technologies

The table below summarizes the main characteristics of existing electrolyzer technologies:

TABLE I. Main electrolyzer technologies

Electrolyzer type	**Alkaline**	**PEM**	**SOEC**
Description	Slow	Fast	Slow start Fast
Material availability	High	Limited (PGMs)	High
Efficiency	54kWh/kg	52kWh/kg	39-46kWh/kg if heat is not re-used
Cost	Low	High	Medium
Durability	High	Medium	Low
Footprint	High	Low	Medium

Alkaline electrolyzers are well fitted for the mass production with low or no power variation. The footprint is considerable as it cannot support high current density and they need additional equipment and hence footprint to store the potassium and prepare the alkaline mixture. New generation of pressurized alkaline electrolyzers [6] brings improvements in footprint and output H2 pressure to this mature and robust technology.

PEM or Proton Exchange Membrane electrolyzers provide a compact and reactive means to fit with renewable energy generation. They benefit of all the research done on fuel cell technologies and will continue to further improve. One advantage PEM electrolyzers have generally is their high output pressure around 30 bars. This is a clear advantage when the hydrogen has to be stored and transported as it will save some compression stages.

Anion exchange membrane is still a marginally developed technology aiming to combine the advantages of the other technologies [3].

SOE for Solid Oxide Electrolyzers are operating at high temperature, allowing to save energy in the breaking of the H_2O molecule. When wasted heat source is available from a nearby process energy consumption can further be improved. In this case, SOE can bring higher efficiency compared to the other technologies.

III. POWER CONVERSION TECHNOLOGIES

Electrolyzers are supplied in Direct Current (DC), requiring an AC/DC conversion as electrical energy is almost always generated and distributed in Alternative Current (AC).

This AC/DC conversion is based on different rectifier technologies: Diodes, Silicon Controlled Rectifiers (SCR) and Insulated Gate Bipolar Transistors (IGBT) for chopper and Active Front End (AFE).

Rectifiers are mainly characterized with response time, efficiency, power factor, harmonics.

For hydrogen applications, the DC voltage has to be adjustable to compensate the ageing of the electrolyzer. It can be done by the rectifier itself (SCR and IGBT) or with an upstream oil transformer associated On Load Tap Changer (OLTC) for diodes technology. Eventually this can be achieved using DC to DC chopper downstream to the rectifier.

Even if SCR rectifiers allow to control DC voltage, it leads to a massive reactive power absorption and low power factor (PF) which generally requires to add a capacitor bank [13].

The technology, diodes / SCR / Active Front End (IGBT) and the topology of the rectifiers, 6-pulse, 12-pulse, etc., also impact on the power quality on grid side.

Current harmonics and total harmonic distortion (THD) on grid side mainly depend on the number of pulses for diodes and SCR rectifiers and modulation strategy and frequency for IGBT active front end (AFE) rectifiers.

Multi-pulse rectifiers are obtained by using several 6-pulse rectifiers in parallel, 2 for 12-pulse, 3 for 18-pulse, etc.

They are supplied by a three (or more)-winding transformer with suitable phase-shift to mitigate harmonic on grid side.

When used for VSD application, 18-pulse topology is most of the time sufficient to meet IEEE 519 standard [8].

The table below summarizes the different rectifier technologies with the main differences in performance.

TABLE II . Power conversion technologies & power quality performances under rated power

Power conversion technology	**Diode**			**SCR**			**AFE**
Nb of pulse	6	12	24	6	12	24	NA
Voltage regulation	OLTC (or chopper)			SCR control			AFE control
THDi (1)	~30 %	<10 %	<5%	~30 %	<10 %	<5%	< 4%
DPF (1)	Close to 1			Acc. to firing angle			Close to 1
IEEE compliant (1)	No	No	Yes	No	No	Yes	Yes
PF Correction	Not required			Required			Not required
Harmonic filter	Required		Case by case	Required		Case by case	Not required

(1) Without PFC and harmonic filter

With diode bridge rectifiers a chopper can be an alternative to manage the voltage adaptation instead of a transformer with OLTC.

For SCR bridge rectifiers, the use of a chopper enables to address the full voltage range while limiting the firing angle value and its impact on the DPF [13].

Usually, multi-pulse configurations are dedicated to supply single heavy load like VSD for large motors. For H_2 applications, depending on electrolyzers connection the secondary and tertiary windings may not be operated under balanced operation due to:

- Maintenance/trouble shooting on an electrolyzer,
- Aging discrepancy between electrolyzers,
- Partial load operation.

IV. POWER SYSTEM ARCHITECTURES

Like for other electro-intensive applications, power system design for green hydrogen production must address:

- Supply connection constraints in terms of power quality and energy availability and/or kWh price variation,
- Process requirements, in particular power demand and continuity of supply.

A) Electricity supply

When low carbon electricity is available from hydropower, or any other low carbon emission controllable power plant or when it’s purchased from a PPA provider, the production may not be subject to modulation, except to comply with low price kWh.

However, when the electricity is directly connected to, or highly dependent from renewables [11], the balance of plant must be continuously adapted to the amount of available power at any time.

In such situation a special care shall be given to the selection of the converter technology, power system arrangement and operating conditions to prevent excessive power quality deterioration due to partial load operation. In paragraph C, the simulations are illustrating a configuration of partial load operation leading to an unbalance of a 24-pulse power conversion system.

B) Standards and grid code

When the production plant is connected to a grid, it must comply with the local regulation in terms of power quality and power factor at the point of coupling.

If target power factor and reactive power penalties policy is specific to each and every utility company, power quality regulation is in general referring either to IEEE 519 [8], either to IEC 61000-2-4 [9] and IEC/TR 61000-3-6 [9].

Without detailed information, a tan φ of 0.4 (ie cos ≥ 0.93) can be considered as the target to fulfill at the point of connection to the grid.

The objective of harmonic regulation is to limit the impact of connection of non-linear loads in terms of voltage distortion and avoid unacceptable disturbances applied to neighboring installations connected to the same supply network.

IEC 61000-2-4 [9] gives compatibility levels for industrial and non-public power distribution systems at nominal voltages up to 35kV. The compatibility levels are given for different classes of the electromagnetic environment. The compatibility levels for harmonic voltages are given in TABLE III.

TABLE III . Compatibility levels for LV and MV industrial systems class 2 (THDv ≤ 8%) acc. to IEC 61000-2-4 [7]

Odd harmonic non multiple of 3		**Odd harmonic multiple of 3**		**Even harmonic**	
Harmonic order	Harmonic voltage	Harmonic order	Harmonic voltage	Harmonic order	Harmonic voltage
5	6	3	5	2	2
7	6	9	1.5	4	1
11	3.5	15	0.4	6	0.5
13	3	21	0.3	8	0.5
17<h<49	2.27x(17/h) - 0.27	21<h<45	0.2	10<h<50	0.25x(10/h)+0.25

IEC 61000-3-6 [10] outlines procedures for evaluating harmonic emissions from facilities connected to MV and HV systems. The objective is to limit the harmonic injection from all distorting installations to levels that will not result in voltage distortions that exceed the planning levels. The indicative planning levels for THDv are 6.5% in MV and 3 % in HV.

The philosophy of IEEE 519 standard, [8], is to limit the harmonic injection from individual customers and to limit the overall harmonic distortion of the system voltage supplied by the utility.

IEEE 519 states the joint responsibility involving both end-users and system operators. They must work cooperatively to keep voltage distortion below recommended limits indicated in TABLE IV.

TABLE IV . Voltage distortion limits according to IEEE 519

Bus voltage at PCC	**Individual harmonic**	**THDU (%)**
1 kV	5.0	8.0
1 kV < 69 kV	3.0	5.0
69 kV < 161 kV	1.5	2.5
> 161 kV	1.0	1.5

The limits for individual harmonic currents and total harmonic distortion are expressed as a percentage of the maximum demand load current IL (which is different from THD). The corresponding distortion is called the total demand distortion (TDD). The limits for current distortion should not be applied to either individual pieces of equipment or at locations within a user's facility.

The sites are categorized by the ratio of available short circuit current (ISC) to their maximum demand load current (IL) at the point of common coupling.

As indicated in table 3, harmonic limits become less stringent for systems with higher ISC/IL values.

TABLE V . Current distortion limits for systems above 69 kV through 161kV according to IEEE 519 [8].

ISC/IL	**TDD (%)**
< 20	2.5
20 < 50	4
50 < 100	6
100 < 1000	7.5
> 1000	10

C) *Modeling and simulation*

Let's consider the 80MW H2 production system represented on Fig 2. A modular set of 2 x 5MW electrolyzers is supplied by a 12-pulse power conversion system composed of 1 x 12MVA transformer with 3 windings, feeding SCR based rectifiers. Each 12-pulse system is combined in pair to another one to form an equivalent 24-pulse by phase-shifting the primary windings. Any unbalanced operation of the secondary windings, or stoppage of one transformer will impact the harmonic compensation at the primary side.

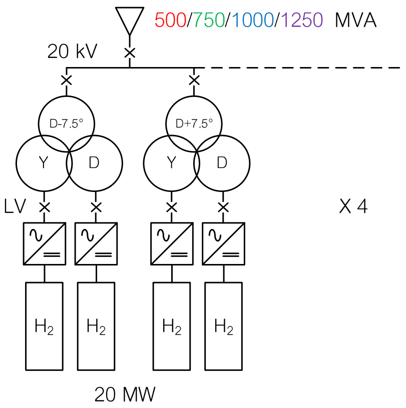
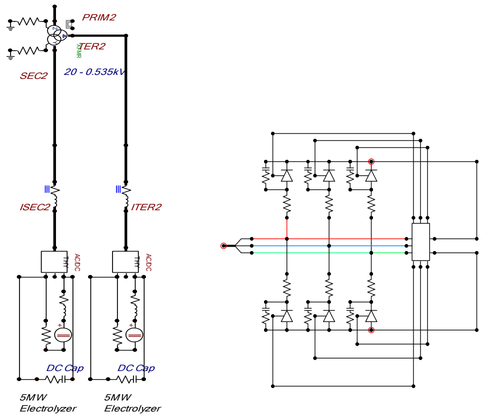


Fig. 2: 4 x 20MW electrolyzers supplied by 24-pulse power converters configuration.

To analyze the consequences of a partial or unbalanced load operation, the above installation has been modeled using EMTP-ATP [12] software, as shown on Fig 3. The electrolyzer models are composed of a DC internal source in series with a resistance. Such simplified modeling is suitable for the analyses, being focused on the MV part of the system in steady state operation. The rectifier control is allowing to reach steady state operation within the time of simulation, and thus in one simulation of several seconds can be shown a synthetized variation in the operations within long periods of hours or days. Such simplification implies that the transient behavior presented in the simulation is not representative for the same in the practice, only the steady state.



a) b)

Fig. 3: Graphical representation a) of the modular unit of electrolyzer, and b) its power electronics architecture and control.

In the simulation result presented below it has been considered:

- An initial operation at 100% of the capacity, ie 80MW available, with 4 modular blocks, at minimum short-circuit power of 500MVA,
- A change at 1.5s when 1 x 12MVA MV/LV transformer is left unloaded and the system operates with 3 x 24-pulse blocks and 1 block half power but 12 pulse,
- A change when the same transformer is reloaded on one side, simulating maintenance on 1 x 5MW electrolyzer, this transformer gives a 6-pulse operation.

The impact of this configuration is illustrated on Fig. 4

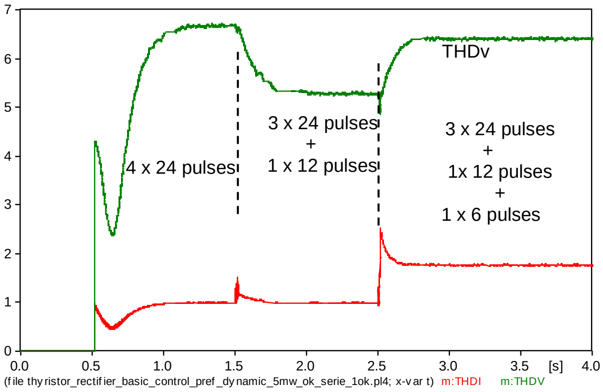


Fig. 4 THDv and THDi for balanced and unbalanced load operation comparison, unbalance occurs at 1.5s, and 2.5s.

The above THDv results show that unbalanced loading of a transformer (6-pulse) is much more impactful than a disconnection of a complete set of 12-pulse transformer and loads. It can be observed that overall THDi remains low at less than 2%, while the THDv value remains between 5% to 8%. Therefore, a harmonic mitigation solution may need to be evaluated despite the use of 24-pulse configuration. Note that the voltage pollution in the initial balanced state is higher than in unbalanced.

An illustration of the harmonic content evolution in the different operating modes is given on the next figure:

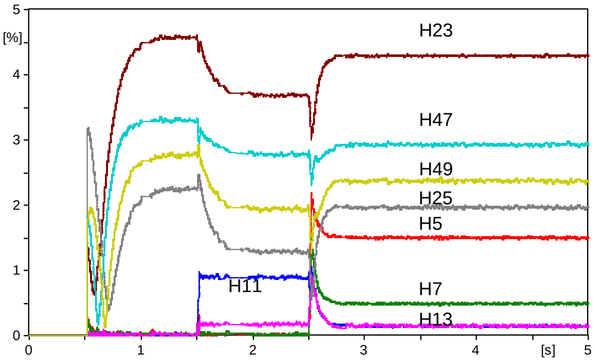


Fig. 5 Illustration of significant harmonic ranks in the voltage on source, during the operation stages

The harmonic ranks evolution shows that the voltage pollution is mainly created by the high harmonic ranks, H23, H47, H49, H25, which can be expected in a 24 pulse configuration. Compared to the relatively low current harmonic pollution THDi on Fig. 4, these high ranks explain how a small 2% THDi can lead to more than 6% THDv.

The fluctuation of harmonic content with the operation of the system can make tricky the design of passive harmonic filters. Indeed, harmonic filters tuned to mitigate H23 or H25 may produce an anti-resonance at lower frequency that could be activated by lower harmonic current.

Upstream power system intrinsic capacity due to cable must be evaluated as well to check their impact on the system impedance.

Reduced voltage harmonic pollution can be obtained with stronger networks, where the short-circuit impedance is lower. On Fig. 6 is shown the THDv evolution with the short-circuit power of the upstream system.

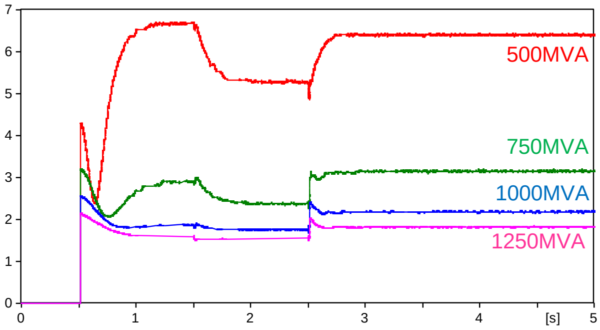


Fig. 6 Impact of grid short-circuit capacity on voltage distortion (THDv) for different sequences of operation.

The increase to 750MVA short-circuit power made the largest impact to the initial situation. However, this value is very high for the given rated voltage of the system and difficult to achieve even with grid connection. Therefore, harmonic filters will be most of the time necessary in hydrogen production, with renewable source fed systems, when the rectifier technology is not Active Front End.

Another configuration may be possible to operate the installation at 75% of its capacity:

- Adapting the capacity of each electrolyzer to 75%,
- Keeping 8 MV/LV transformers operated at partial load.

This configuration may be preferred to keep the entire system operated as a 24-pulse.

D) Impact of electrolyzer operation limits

The above recommendation of operation is reaching some limits implied by electrolyzer technology. It is hardly not efficient or even not efficient/possible to operate an electrolyzer below 30% of its capacity.

Therefore, not only continuous operation at nominal load must be considered while selecting AC/DC converters technology because:

- the highest impact on power quality may not be at highest power demand,
- the harmonic content varies with unbalancing
- the type of voltage control by transformer OLTC, by SCR (firing angle), by additional chopper or by AFE bring different level of flexibility in operation.

When voltage control is managed by OLTC the control applies to all connected electrolyzers:

- offering less flexibility than with control per each power converter (as shown on Fig. 6),
- but enabling balanced loading between secondary and tertiary windings of the transformer.

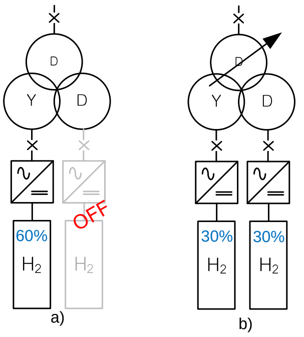


Fig. 7 Partial load operation a) with SCR bridge voltage control and b) with OLTC.

V. RECOMMENDATIONS FOR POWER SYSTEM ARCHITECTURES

Table II provides a generic comparison of power converters technology, their associated equipment and their impact in terms of power quality under rated operation (full load). It may be used as a first step in the power system design.

Then, as stated in above paragraphs, every site has its specific context considering:

- Type of power supply,
- Operation constraints,
- Grid electrical characteristics.

In TABLE VI is presented a principal comparison guideline of the main technologies and relation to the electrolyzer operation:

TABLE VI . Power conversion technologies & impacts on electrolyzers operation

Power conversion technology	**Diode**	**SCR**	**AFE**
Transformer	Multi-pulse	Multi-pulse	Standard
Rectifier supply per 1 secondary (Fig. 6 a)	6 pulse DC voltage ripple Unbalance secondary and tertiary windings in case of electrolyzers maintenance or aging discrepancy		NA
Rectifier supply between secondary and tertiary (Fig 6 b)	12 pulse DC voltage ripple Lower transformer power demand in case of electrolyzers maintenance or aging discrepancy		NA
Partial load operation	Per transformer if OLTC	Per secondary possible (1)	Per AFE
Impact of partial load on power quality	Yes	Yes	No
Impact of partial load on power factor	No	Yes	No
Minimum load	~30% per transformer (1)	30% per electrolyzer (2)	30% per electrolyzer

(1) Electrolyzers supply per 1 secondary winding

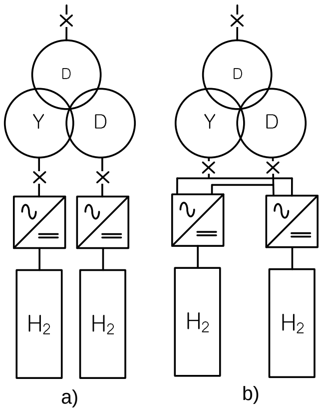


Fig. 6 Rectifier supply a) per 1 secondary control and b) between secondary and tertiary

In a second step it is recommended to perform power system studies to evaluate/compare the performances of the solutions according to this context.

In some cases, it may result that additional harmonic mitigation solutions will be required to fulfill the grid code requirements.

Finally, once the electrical performances of the evaluated solutions are known at system level then solutions can be compared according to:

- Efficiency,
- Footprint,
- Investment cost.

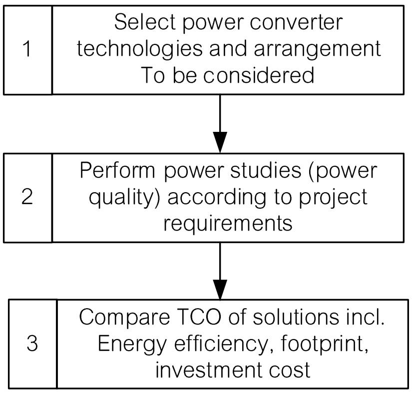


Fig. 7 Recommended qualification process for power system design.

VI. CONCLUSION

The entire power system for green hydrogen production plant from Electrolysis is impacted by the power converters unit's technology and their arrangement. Selection of the power converters needs to comply with electrolyzer technology to operate all along their life cycle. In addition, the selection must consider the impact on upper power system from power quality side to comply with standards and grid codes.

Compared to other type of industrial applications using non-linear loads like VSD for motor control, in green H_2 applications:

- the ratio of non-linear loads is much higher, the damping effect of parallel linear load on voltage distortion is reduced,
- the diversity factors between non-linear loads is closer to 1 in continuous service, maximizing the summation of harmonics.

Therefore, power system study must be performed:

- As early as possible,
- Considering expected every operation profiles and not only rated continuous profile.

Anticipation of power quality impacts (harmonic and power factor) enables to select the most cost-effective solution including power converters, potential multi-pulse transformers and prevents to end-up with complex and expensive filtering solutions.

VII. NOMENCLATURE

AC	Alternative Current
AEM	Anion Exchange Membrane
AWE	Alkaline Water Electrolysis
AFE	Active Front End
DC	Direct Current
DPF	Displacement Power Factor
HV	High Voltage
IGBT	Insulated-Gate Bipolar Transistor
LV	Low Voltage
MV	Medium Voltage
OLTC	On Load Tap Changer
PHES	Pumped Hydro Energy Storage
PEM	Proton Exchange Membrane
PF	Power Factor
PPA	Power Purchase Agreement
SCR	Silicon Control Rectifier
SMR	Steam Methane Reformer
SOE	Solid Oxide Electrolyzers
TDD	Total Demand Distortion (acc. IEEE 519)
THDi	Total Harmonic Distortion in current
THDv	Total Harmonic Distortion in voltage

VI. REFERENCES

[1] Gajdzik, Bożena, et al. “Process of Transformation to Net Zero Steelmaking: Decarbonisation Scenarios Based on the Analysis of the Polish Steel Industry.” *Energies*, vol. 16, no. 8, Apr. 2023, p. 3384. *DOI.org (Crossref)*, https://doi.org/10.3390/en16083384

[2] IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition, International Renewable Energy Agency, Abu Dhabi.

[3] B. Yodwong, D. Guilbert, M. Phattanasak, W. Kaewmanee, M. Hinaje, G. Vitale, “*AC-DC Converters for Electrolyzer Applications: State of the Art and Future Challenges*”, in Electronics 2020, 2020, 9, 10.3390/electronics9060912, hal-02733976

[4] Sahin, M. “*A Photovoltaic Powered Electrolysis Converter System with Maximum Power Point Tracking Control*”. International Journal of Hydrogen Energy, 45, 2020, 9293-9304.

[5] Qu, Wanjun, et al. “An Energy Storage Approach for Storing Surplus Power into Hydrogen in a Cogeneration System.” *Energy Conversion and Management*, vol. 268, Sept. 2022, p. 116032. *DOI.org*

[6] Kuleshov, N. V., et al. “Development and Performances of a 0.5 kW High-Pressure Alkaline Water Electrolyzer.” *International Journal of Hydrogen Energy*, vol. 44, no. 56, Nov. 2019, pp. 29441–49. *DOI.org (Crossref)*, https://doi.org/10.1016/j.ijhydene.2019.05.044.

[7] Miller, Hamish Andrew, et al. “Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions.” *Sustainable Energy & Fuels*, vol. 4, no. 5, 2020, pp. 2114–33. *DOI.org (Crossref)*, https://doi.org/10.1039/C9SE01240K

[8] IEEE Standard for Harmonic Control in Electric Power Systems," in IEEE Std 519-2022 (Revision of IEEE Std 519-2014) , vol., no., pp.1-31, 5 Aug. 2022, doi: 10.1109/IEEESTD.2022.9848440.

[9] IEC 61000-2-4:2002, Electromagnetic compatibility (EMC) - Part 2-4 : environment - Compatibility levels in industrial plants for low-frequency conducted disturbances.

[10] IEC/TR 61000-3-6:2008, Electromagnetic compatibility (EMC) - Part 3-6 : limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

[11] S. Chetty, K. Hung, G. Bruandet, “Conceptual electrical designs & total control system concept for green hydrogen” PCIC energy Europe 2023.

[12] EMTP-ATP: https://atp-emtp.org/

[13] T. Tadlock, O. Rubio, D. Ristanovic, “The green hydrogen revolution – Integrating hydrogen into industrial applications PCIC 2022.

VII. VITA

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