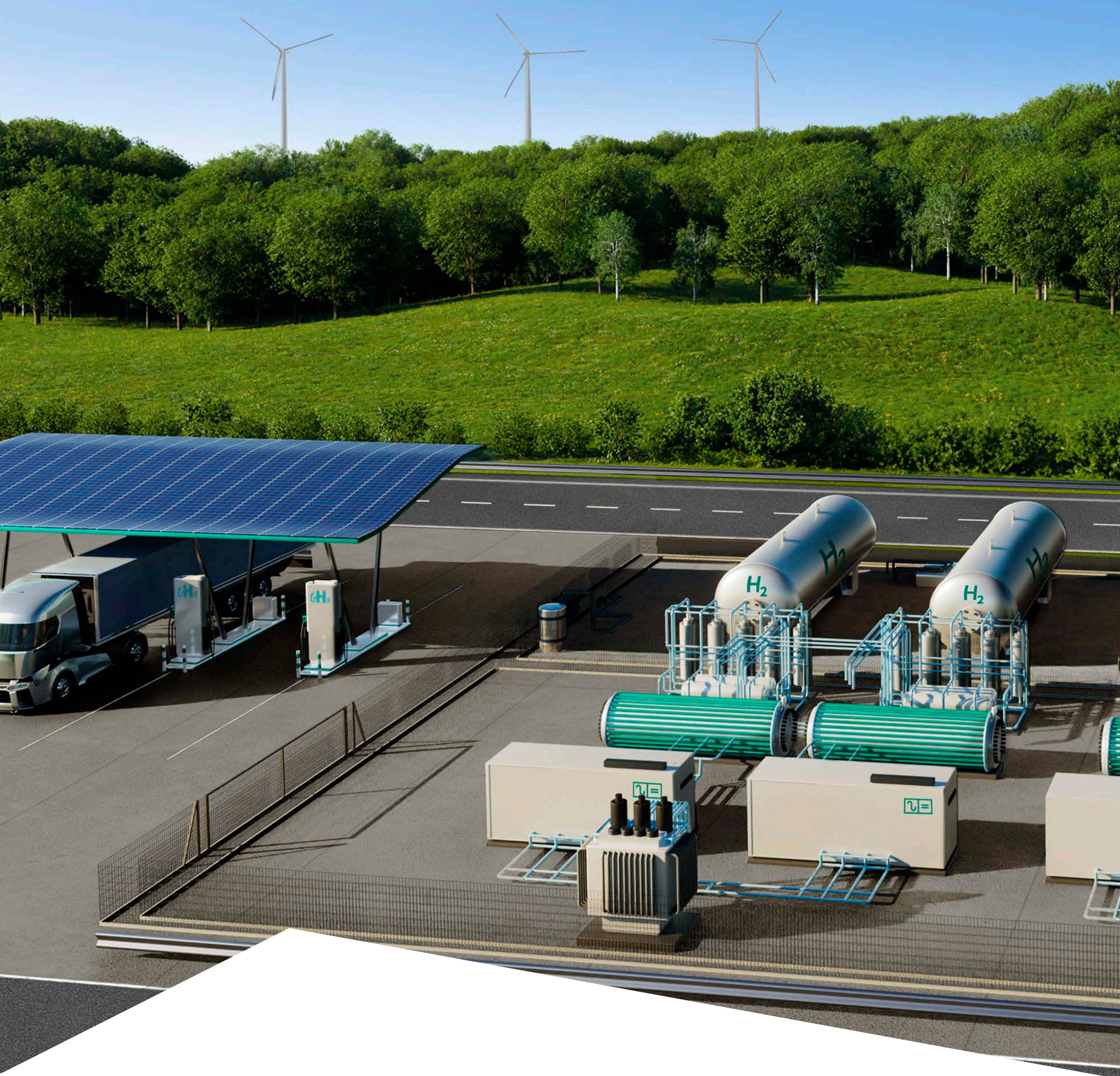

WHITEPAPER

The importance of power conversion technologies in the production of green hydrogen

Edition: v1.0
Date: 05/2024

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Abstract

Global demand for green hydrogen is high and rising fast. Some studies predict that the electrical power demand to produce green hydrogen will be 4500 GW by 2050, compared to today's (2023) electrical power demand of around 25 GW. This exponential growth will be fueled by green hydrogen which will reduce the carbon footprint of existing industries that use hydrogen as a feedstock, and by the development of novel methods for storing and transporting energy.

Most hydrogen production today is heavily dependent on fossil fuels and is, consequently, a significant contributor to carbon dioxide (CO_2) emissions. There are growing environmental, political, and economic pressures to make hydrogen production carbon neutral. Water electrolysis will hence play a significant role in hydrogen production in the future. It will also impact how energy systems are set up. Currently responsible for only around 2% of the global hydrogen production, water electrolysis generates green hydrogen by harnessing renewable sources of energy, such as wind and solar power, as inputs in the process.

Water electrolysis requires high and stable levels of DC electrical current and, therefore, power conversion systems are crucial in any hydrogen electrolysis plant. A green electrolysis plant must be capable of using electricity from wind farms or solar arrays, either directly or via the power grid. It must also be able to convert the input from these sources into stable electrical power outputs with the characteristics required to generate hydrogen economically.

This paper examines the factors driving growth in the hydrogen market, briefly, before focusing on the Power Conversion System (PCS) required for electrolysis. Some typical electrolysis plant layouts are introduced, along with the topologies for both AC-DC and DC-DC power conversion. As a global leader in power semiconductors, Infineon's comprehensive portfolio offers a wide range of choices to designers of PCS. The paper will conclude with an overview of Infineon's products and capabilities.

The global hydrogen market

Supplying hydrogen for industrial use is a major global business, with demand rising threefold since 1975 [1] and continuing to grow. Hydrogen production today, however, is almost entirely based on fossil fuels. It consumes around 6% of the global natural gas and 2% of global coal supplies [1]. Global CO2 emissions from hydrogen production are currently estimated at 830 million tons annually – equivalent to the combined CO2 emissions of the United Kingdom and Indonesia. Together with the rising demand for hydrogen, this level of emissions is not compatible with global efforts to limit climate change.

The focus, therefore, is on decarbonizing hydrogen production. A recent report from the International Energy Agency (IEA) describes how green hydrogen is receiving unprecedented political and business support. It concludes that the time is right for green hydrogen technologies and infrastructure to be scaled-up. Manufacturers worldwide have recently announced their plans for expanding green hydrogen production facilities, aiming to reach a total manufacturing capacity of 155 GW/year by 2030. It is expected that by 2050, 60 to 80% of the global hydrogen supply will be decarbonized.

Water electrolysis is a key component in the green hydrogen infrastructure. As the infrastructure scales up, the demand for electric power in hydrogen plants that integrate renewable energy sources will also grow significantly – up to 4500 GW electrical by 2050 (see Figure 1).

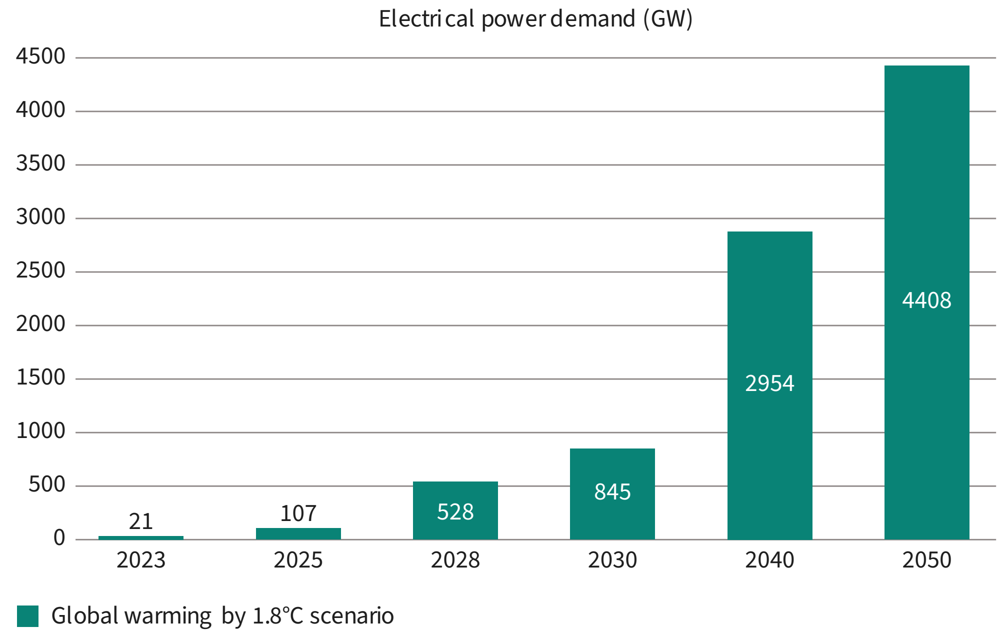

Figure 1 Installed electrical power required to meet demand for green hydrogen production for carbon neutrality as defined by Paris Climate Agreement [2].

Water electrolysis

Electrolysis produces hydrogen by using electric power to split water into its components – hydrogen and oxygen. The process requires high levels of Direct Current (DC). Theoretically, assuming no energy losses, a minimum of 32.9 kWh of electrical energy is required to split enough water molecules to produce 1 kg of hydrogen [3]. An electrolyzer normally contains the following components:

- An anode and a cathode – positive and negative electrodes where the electrochemical reactions occur
- An electrolyte, either liquid or solid, that conducts ions between the electrodes
- A catalyst to accelerate the reaction rate
- A separator to prevent the hydrogen and oxygen produced at the electrodes from mixing
- A power supply – or power-to-hydrogen converter – to provide the electrical energy required for electrolysis

There are three main types of electrolyzers, categorized by the type of electrolyte used:
Alkaline: These electrolyzers use an alkaline solution and are the most common. They are known for their durability and low-cost operation. However, they are less efficient than other types of electrolyzers

Proton Exchange Membrane (PEM): These use a solid polymer electrolyte, offer high efficiency, fast response times, and a compact design. However, these are more expensive than alkaline electrolyzers because they use precious metals, such as platinum, as catalysts

Solid oxide: These electrolyzers use a solid ceramic material as the electrolyte. They can be highly efficient but require high operating temperatures and have a slower response time than the PEM electrolyzers

Although the potential of green hydrogen in future energy systems is well understood, its production cost is high compared to the hydrogen produced from fossil fuels. This, and the lack of appropriate infrastructure, are some of the challenges that need to be addressed to stimulate the widespread adoption of green hydrogen. Efforts to reduce costs focus on improving the efficiency of individual components, such as the electrolyzer cell, power conversion systems, and compressors, and also on improving economies of scale by building larger plants. As electrolyzers are a critical element of the green hydrogen production infrastructure (see Figure 2), their performance and efficiency will be very important in future energy systems.

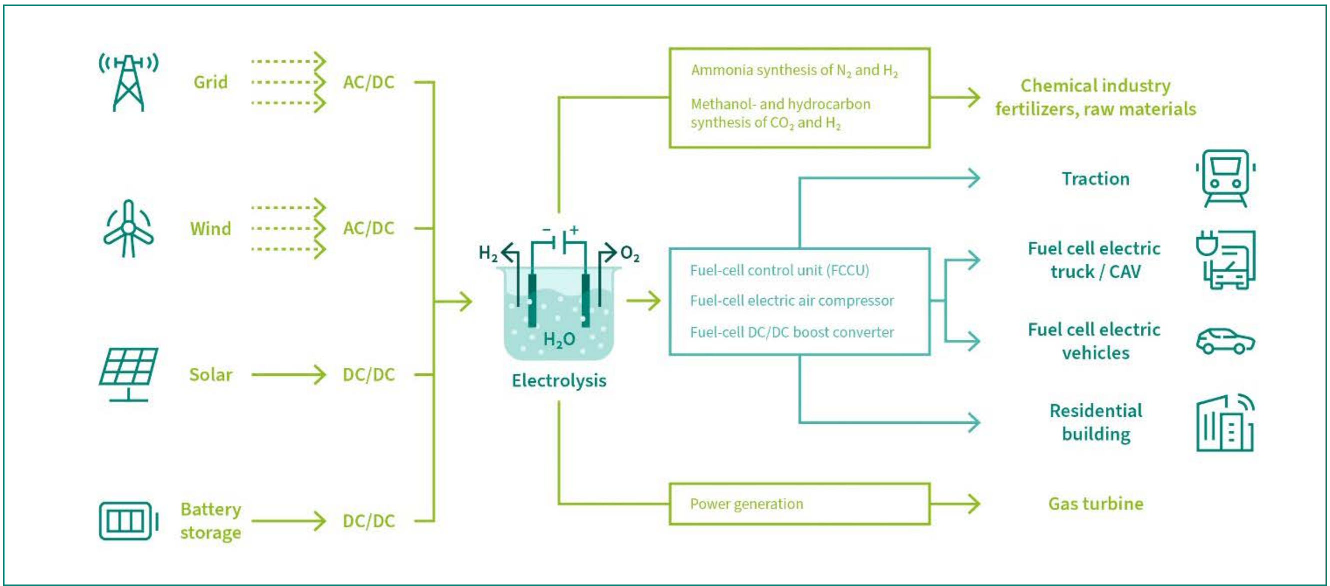

Figure 2 Hydrogen electrolysis – a part of future energy systems [4]

Electrolyzer plants can improve the utilization of existing and new renewable energy systems by absorbing any excess energy produced by them. This will ease the stress on the electrical grid by offering another lever to operators for network balancing. As shown in Figure 2, green hydrogen can be used in various industries:

- As a fuel or energy carrier (based on ammonia or methanol synthesis) in heavy industries with high energy demands such as metallurgy, cement, heating, chemicals, and agriculture
- As feedstock in fuel cells to generate electrical energy for a wide spectrum of applications such as traction, commercial and agricultural vehicles (CAV), fully electric vehicles, and commercial and residential buildings
- As a fuel for power generation in gas power plants to offset the use of natural gas and reduce their carbon footprint
- As a seasonal energy storage medium in the future to utilize renewable energy plants better

The development of an efficient, green hydrogen production infrastructure that can operate at scale depends heavily on a PCS that can deliver quality electrical power efficiently to the electrolysis process. Much research has gone into power conversion in recent years. In the next section, we will examine the key conversion topologies being considered for deployment in the PCS.

Electrolyzer plant system requirements

As described in the previous section, electrolysis requires high levels of Direct Current (DC), which is supplied by a green hydrogen plant's PCS. The PCS converts Alternating Current (AC) from the grid or wind application, or current from a DC grid (solar or battery energy storage system) into an output that meets the needs of the electrolyzer (see Figure 3). The design of this converter significantly affects the overall efficiency, reliability, and cost of the green hydrogen plant. Possible converter topologies are discussed in the next section.

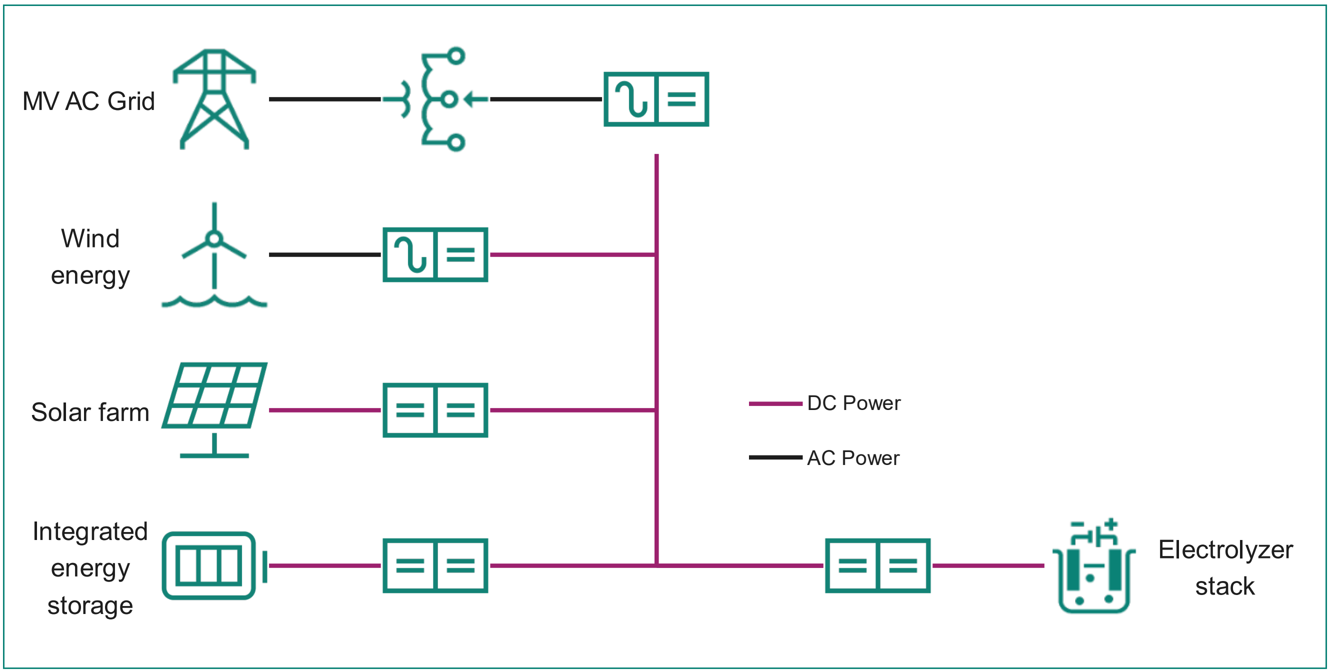

Figure 3 The PCS is a key component of the P2H plant [5]

A potential PCS system must meet multiple requirements, broadly classified into electrolyzer cell requirements and grid connection requirements.

Electrolyzer cell requirements

Constant Direct Current (DC) is an electrolyzer cell's basic power requirement. For maximum utilization, it must be operated at constant load. The electrolyzer cell takes time to start up and ramp down. Depending on the technology, it can be from a few minutes to hours. The trend these days is of shorter reaction times to integrate with renewable energy better without requiring a battery buffer.

Another important aspect of the electrolyzer cell is its tendency to increase operating voltage as the cell ages. The quantity of hydrogen produced by the cell depends on the current flowing through it. Due to various aging mechanisms in the electrolyzer cell, the voltage required to generate the same amount of hydrogen (from the same current) increases as the cell ages. Therefore, the PCS that supplies power to the cell must be able to increase the output voltage over its lifetime. It should ideally also have a robust current control to integrate into the balance of the plant. This will ensure that the compressors and pumps handling the gases and liquids operate within limits.

Electrolyzer cells can operate over a wide range of conditions depending on multiple factors, including the plant layout and cell technology. There is no one size fits all PCS. A general operating range within which a plant designer could establish the requirements for a PCS is listed below:

- Output voltage: 400 to 1500 V_{DC}. Alkaline technologies have a limited max stack voltage (~800 V_{DC}) because of the parasitic currents. The PEM technology on the other had does not have this limitation and is moving towards higher voltages to improve loss performance and reduce metal costs.
- Output power: 20 kW to 30 MW per single unit. Larger systems with higher power ratings are preferred to reduce the Levelized Cost of Hydrogen (LCoH). Larger systems are built by paralleling smaller units.
- Current ripple: < 5%. This is not yet an established requirement for all cell technologies but can emerge in the future if its effect on the electrolyzer cell's lifetime and efficiency are significant. This may affect PEM technology more than alkaline technology.

As mentioned earlier no single PCS meets all the above conditions. Therefore, system designers must carefully consider the specific requirements of the electrolyzer when deciding the optimal topology.

Grid connection requirements

Majority of the recently announced green hydrogen products are grid-connected electrolyzers. Depending on the size of the plant and the region of installation, local grid codes can affect the design of the plant/PCS. Small plants in the range of, for example < 1 MW, may not have a significant impact on the grid and in most regions do not need to meet the special low voltage ride-through (LVRT) or power factor requirements.

However, many of the newer projects are in the over-100 MW range. These may be subject to specific requirements with respect to power factor compensation and startup and shutdown performance during LVRT. These requirements are derived from regulations for large loads, and extensive discussions are currently taking place to update the grid regulations [6]. The main motivation for updating these codes comes from the increased load on the electrical grid as well as the reduced mechanical inertia. The mechanical inertia is reducing because rotating machine electrical plants are closing and inverter-based electrical plants are being installed.

One example is the recently published paper by the four transmission system operators (TSOs) in Germany defining the fault ride-through (FRT) and modeling requirements for electrolyzer plants beyond what is generally considered in the VDE-AR-N 4130 [7].

Power supply topologies

Figure 3 illustrated the requirement for both AC and DC-coupled power conversion technologies within the electrolysis plant. AC inputs from the grid or from wind-generated electricity sources need to be converted to a suitable DC power for the electrolyzer. DC inputs from photovoltaic or energy storage systems must also be converted to suitable voltage levels. A variety of power conversion topologies can, therefore, be found within an electrolysis plant. Some of which are:

AC-coupled topologies
AC-coupled configurations include a single rectifier directly supplying power to an electrolyzer stack (see Figure 4) or a central rectifier supplying a DC grid within the P2H plant (see Figure 5).

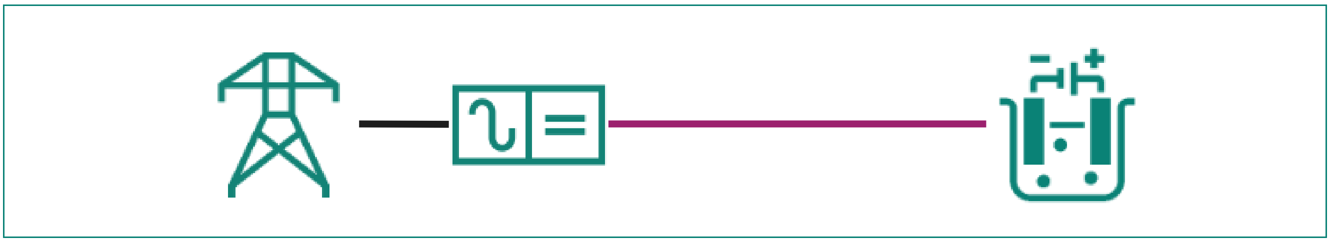

Figure 4 Single rectifier configuration [8]

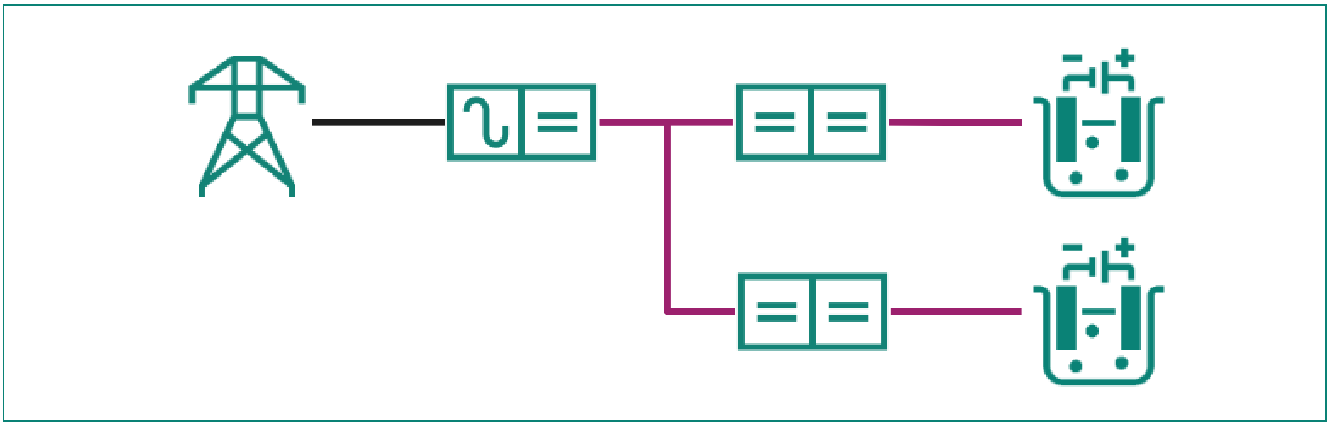

Figure 5 Central rectifier configuration [8]

Thyristor rectifiers
Multi-pulse (usually 12 or higher), thyristor-based converters (see Figure 6) are a popular choice for AC to DC power conversion because of their robustness, high efficiency levels, high current densities, and low semiconductor costs. They are an established and well-known technology.

A typical 12-pulse thyristor rectifier consists of a Y-Δ-Y power frequency transformer with two low voltage secondary windings. Two 6-pulse thyristor rectifiers are connected to the secondary windings and their outputs are connected in parallel or series. The output voltage and the current flowing into the electrolyzer is then controlled by the firing angle, α. As the electrolyzer cell ages and the voltage required for the cell stack increases, α also changes to maintain the current in the system. Most systems also include an On-Load Tap Changer transformer to increase the DC voltage over the plant lifetime. The inclusion of such requirements on the transformer depends on the system design, target operating points and filtering requirements.

Harmonic distortion, DC current ripple, and power factor are dependent on the firing α. The rectifier and transformer are designed with appropriate filters that cover the expected range of operation. These can take the form of a passive or active filter, such as a static synchronous compensator (STATCOM) or some combination of both. An approximate diagram is shown in Figure 6.

As mentioned earlier, the current ripple requirements are defined by the electrolyzer technology, and the power factor and harmonic requirements are defined by the grid.

Multi-pulse rectifiers (12-pulse or higher) inherently operate at a lower THD as compared to the standard 6-pulse rectifier. This also makes paralleling of semiconductors for higher DC currents easier.

Power factor correction with a STATCOM increases the bill of materials (BoM) of the overall P2H plant and can also affect its efficiency. Large industrial parks, such as metal refineries or cement plants, have a central STATCOM to manage the power factor of the plant as a whole, or a local power plant to limit the adverse effects of current spikes or low power factor on the power supply gird. Thyristor topologies are ideal for such systems because the compensation can be optimized for local requirements.

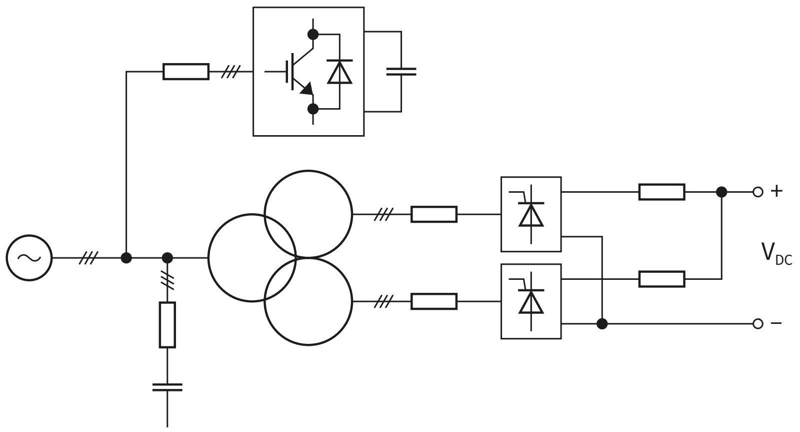

Figure 6 A 12-pulse thyristor rectifier + STATCOM + passive filter [9]

Buck choppers are used at the rear of thyristor or diode rectifiers (see Figure 7). High current choppers are made by interleaving individual chopper modules. This is further described in the section on DC-coupled topologies. The electrolyzer current can be controlled more finely by varying the duty cycle of the chopper instead of the firing angle, α, of the thyristor rectifier. It reduces the necessary dynamic operating range required by the thyristor rectifier and allows for an optimized design. A 12-pulse diode rectifier with an interleaved chopper has lower current distortions and higher power factor as well as no need for an On-Load Tap Changer as compared to a standalone 12-pulse thyristor rectifier but the thyristor solution is more efficient as there are lesser semiconductor components in the chain. .

A commercial chopper rectifier can provide DC outputs of up to 10.4 kA and 1.1 kV, delivering 10 MW of power to electrolyzers with higher power factors across a wide operational converter range.

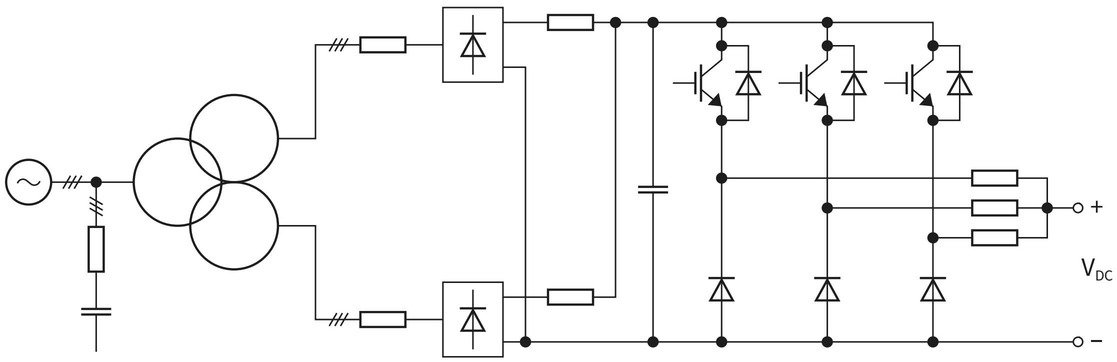

Figure 7 Diode frontend + chopper [9]

AFE rectifiers

Active front-end (AFE) rectifiers are IGBT-based converters. A typical B6 is shown in Figure 8. Multilevel topologies such as NPC1, NPC2, and ANPC can also be used. All of these topologies are versatile and can be implemented in various applications such as solar inverters, battery energy storage inverters, and inverter/rectifier for drives.
These topologies have two major advantages:

- Higher switching frequency: This reduces the harmonic distortion, and hence the size of filters and passive components
- Ability to control the AC current: It enables the PCS to operate at unity power factor and in certain cases, as defined by the relevant grid codes, also provides reactive power compensation

AFEs are also a popular choice among original equipment manufacturers (OEMs) who have experience with central PV/ESS inverters. The base design remains the same, only the operating point needs to be adapted to suit the system and grid requirements.

With the growing number of renewable energy plants on the grid, and limited or reduced inertia from synchronous generators, the focus is on grid service functions of large loads and IGBT-based AFEs can be designed to suit these requirements.

An important aspect of the AFE to note is that the DC voltage during normal operation is higher than the peak AC voltage. This is important to consider as the electrolyzer cell voltage range defines the DC voltage range which then affects the transformer voltage and design.

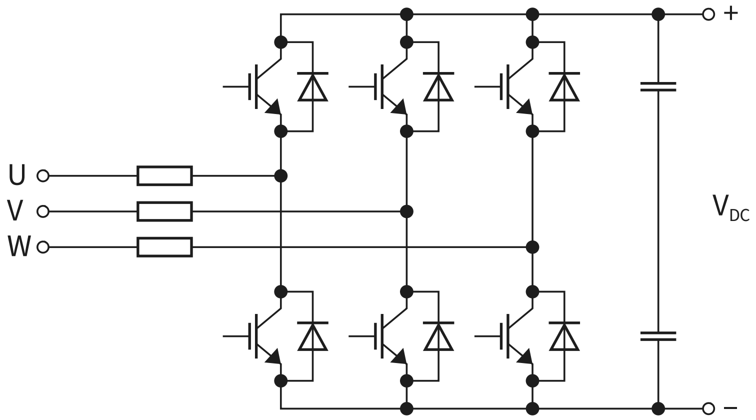

Figure 8 An AFE rectifier [10]

MMC rectifiers
Modular multilevel converters (MMCs) are extensively used in the high-voltage direct current (HVDC) industry. They are now also being considered as high-power rectifiers that can be connected to an HV grid. A typical 3-phase MMC (see Figure 9) comprises a DC terminal, an AC terminal, and a converter kernel with three separate phase legs. Each leg has two symmetric arms, referred to as the upper arm and lower arm. Both arms contain a group of identical submodules connected in series together with an inductor to suppress high-frequency components in the arm's current. MMCs offer modularity, scalability, low harmonics, high efficiency, and high reliability. They are extremely versatile – capable of converting AC-DC, DC-AC, and AC-AC.

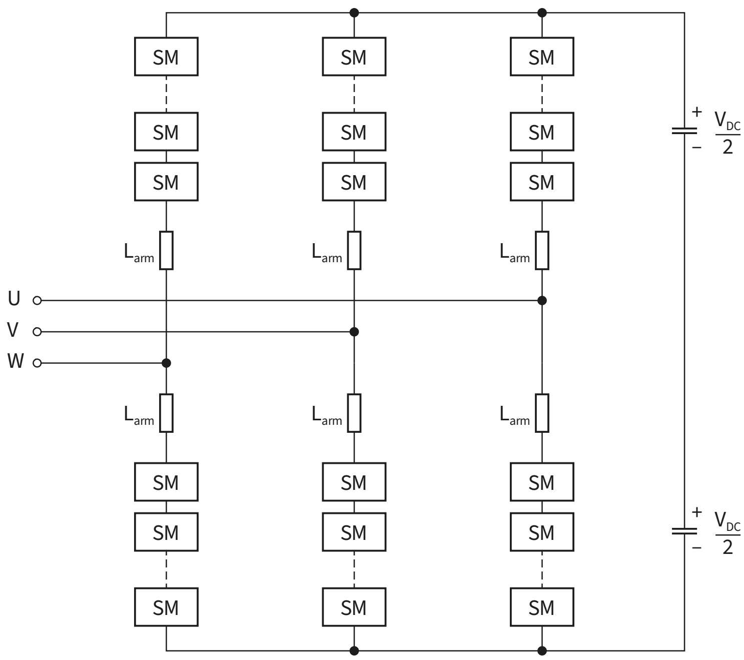

Figure 9 MMCs are now being considered for high and medium voltage DC applications, such as PCS for P2H plants [10]

A modular multilevel rectifier (MMR) derived from MMC retains all the benefits of the MMC.

DC-coupled topologies
DC-coupled topologies play an important role within the P2H converter. They enable the converter to connect to photovoltaic energy sources and energy storage systems, such as batteries. DC-DC converters are used for:
- Optimizing grid connections
- Improving the quality of power delivered to the electrolyzer by enhancing diode/thyristor performance
- Reducing current peaks and ripples
- Improving plant flexibility
- Enabling the construction of local grids to efficiently distribute power from front-end rectifiers to multiple electrolyzer stacks

Popular DC-DC converter topologies include the interleaved buck converter and the Dual Active Bridge (DAB) converter.

Interleaved buck converter
A simple design of the interleaved buck converter is shown in Figure 10. Each of its phase consists of a chopper module to reduce the input DC voltage to the required DC voltage. With multiple such modules in parallel and an appropriate interleaved control, the ripple in the DC current can be reduced significantly without increasing the switching frequency or the inductor size. The interleaved configuration also allows for easy paralleling of modules for higher DC currents. Each phase can be designed in a modular way for easy dimensioning between projects.

This configuration is easy to implement and can improve the performance of the diode and thyristor rectifier as described earlier. While the design is simple to implement, please note that the output is not galvanically isolated from the input. Galvanic isolation is important when connecting to a local DC network to handle the corrosion of the tank and electrodes of the electrolyzer cell.

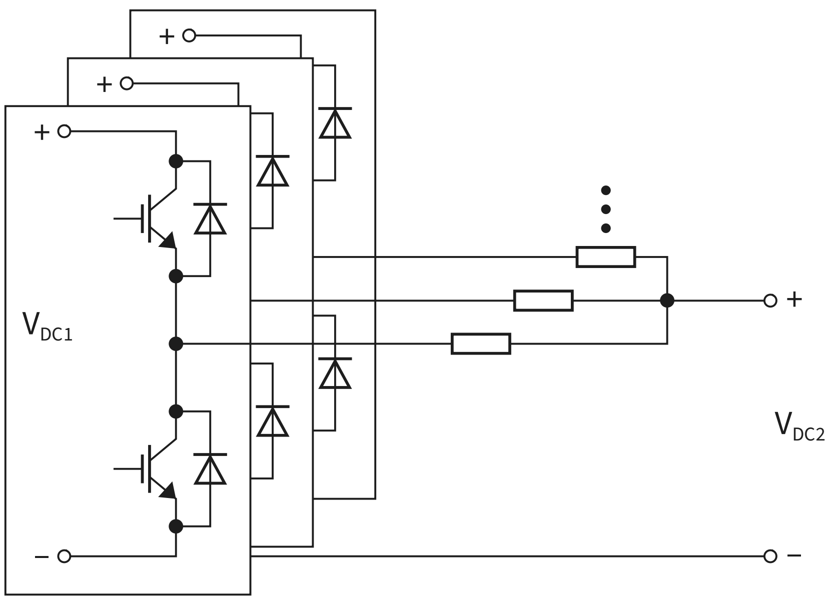

Figure 10 Interleaved buck converter [10]

Dual active bridge converter
Advantages of DAB converters (see Figure 11) include:
- Bidirectional power flow
- Low switching losses due to Zero Voltage Switching
- High power density
- Possibility for cascading and parallelism

The transformer within the DAB ensures efficient voltage step down and inherent galvanic isolation. With lower switching losses, these converters are generally operated at a higher switching frequency. This favors the use of SiC MOSFETs, which in turn can make the transformers smaller, further improving the power density of the PCS.

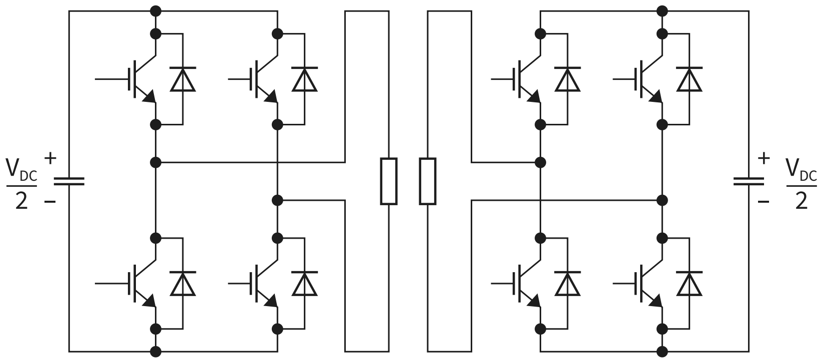

Figure 11 Dual active bridge converter [10]

Several options are available to the designers of the PCS. Choosing the right components is important for the efficiency, performance, and lifespan of the P2H plant.

Solutions from Infineon

The discussion so far has covered common topologies used in PCS and highlighted the requirement for a wide variety of power semiconductors, from thyristors and diodes to IGBTs and MOSFETs, in a wide operating range of voltages and currents. The comprehensive power semiconductor portfolio from Infineon (see Figure 12) offers a one-stop-shop for all power semiconductor requirements. It covers the full performance spectrum of AC and DC-coupled topologies for all power levels, from a few kW to several MWs.

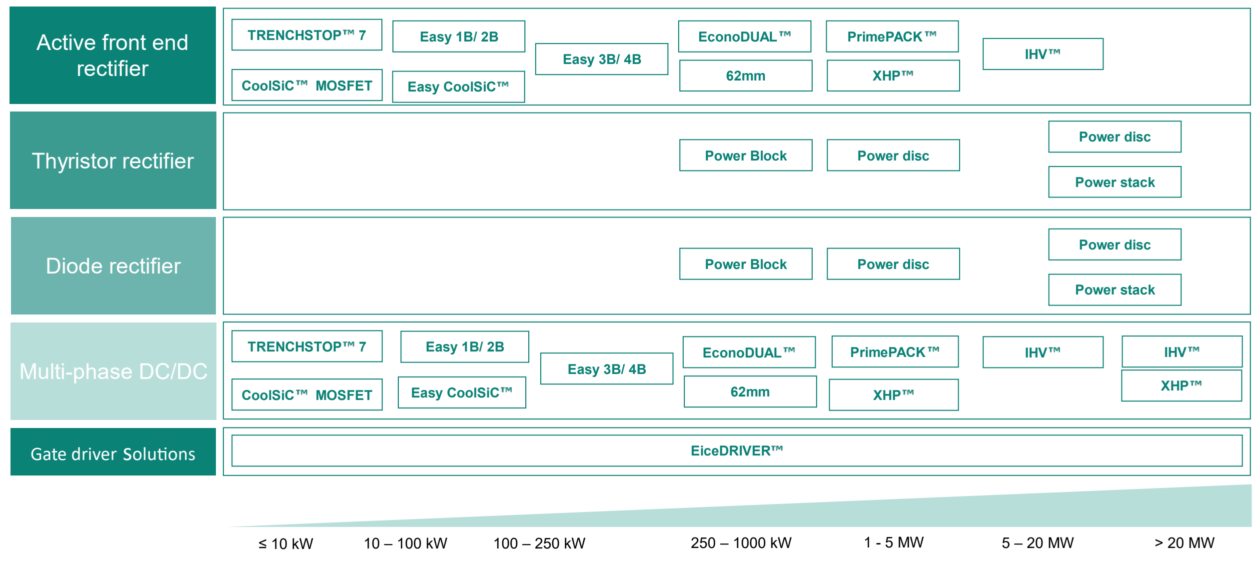

Figure 12 Infineon's power semiconductor portfolio covers the full performance spectrum for various AC and DC-coupled topologies [10]

Infineon's portfolio includes the following devices:

Thyristors

Thyristor rectifiers are commonly used in high current (>1 MW), AC-coupled applications. Infineon offers a wide range of thyristors suitable for use in high power, high current rectifiers. A range of phase-controlled thyristor discs and Power Block modules are also included. The power discs can be cooled on both sides and offer excellent current density and reliability. Infineon offers prebuilt, air-cooled stacks with 111 mm discs and a 5 MW water-cooled stack with 120 mm discs. Prebuilt stacks and modular cabinet designs can simplify rectifier designs and reduce go-to-market timelines. An example of a high current thyristor for energy-dense designs is T3841N18.

Figure 13 : T3841N18, thyristor disc [11]

IGBTs

IGBTs are used in AFE, MMC, interleaved buck, and DAB topologies. Infineon's extensive IGBT offering includes a range of packages from low power (discrete and Easy) to medium power (EconoDUAL™ and 62mm) and high power (PrimePACK™, IHV). Electrolysis applications typically require high DC currents and Infineon offers high current modules in every package. For example, the IKY140N120CH7 offers 140 A in a tiny TO-247PLUS package based on IGBT7 technology or, using similar technology, the FF800R12KE7 offers 800 A in the standard 62mm package. For the AFE topology, a larger diode is beneficial because the converter operates as a rectifier. Here, Infineon offers enhanced diode modules such as the FF1700XTRIE5D, which is optimized for rectification.

For solutions approaching the 1500 VDC limit, defined by the Low Voltage Directive, Infineon leads the market with FF1800R23IE7.

Figure 14 : IKY140N120CH7, 140 A in a tiny TO-247PLUS [12]

Figure 15 : FF800R12KE7, high current in standard 62mm package [13]

Figure 16 : PrimePACK™3+ package. FF1700XTR17IE5D, enhanced diode for rectification. FF1800R23IE7, 2.3 kV module for 1500 VDC link voltage [14]

SiC MOSFETs

SiC MOSFETS are particularly attractive for DAB and high switching frequency applications. Infineon's portfolio includes a wide range of SiC MOSFETs. It already addresses the 1500 VDC segment and offers 2 kV SiC modules in various packages. IMYH200R012M1H, for example, is only 12 mΩ in a TO-247-4-PLUS-HCC package specifically designed for 1500 VDC applications. In a more standard package, such as 62mm, the Infineon range includes a 2 mΩ FF2MR12KM1H for the 1.2 KV voltage class, and a 3 mΩ FF3MR20KM1H for the 2 kV voltage class.

Infineon also offers FF2000XTR33T2M1, a 2 mΩ SiC for the 3.3 kV voltage class in a low-inductive XHP2 package. This module is uniquely capable of 3 µs short-circuit robustness.

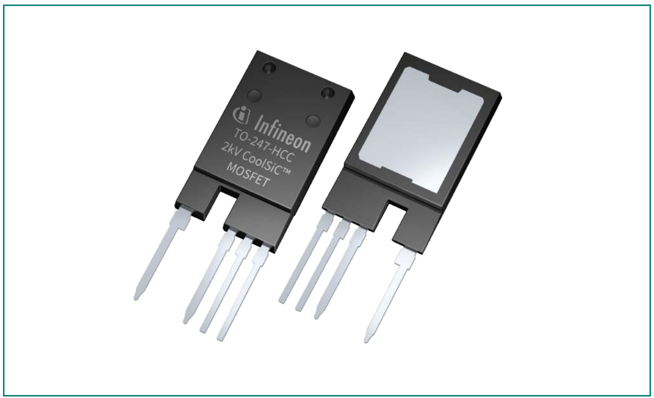

Figure 17 : IMYH200R012M1H, 12 mΩ in a TO-247-4-PLUS-HCC package specifically designed for 1500 VDC applications [15]

Figure 18 : CoolSiC™ in a standard 62mm package. FF2MR12KM1H and FF3MR20KM1H [16]

There is no doubt that the demand for hydrogen will continue to grow as the world seeks reliable and secure sources of energy that also help reduce the carbon footprints of heavy industries. To prevent an unsustainable rise in emissions, the production of hydrogen must increasingly be based on renewable energy sources. Significant investment in water electrolysis capacity is required to achieve this. Effective power conversion is critical for the efficiency and cost-effectiveness of electrolysis. With its expertise and extensive portfolio of power semiconductors, Infineon is a key partner in the development of the P2H infrastructure.

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Published by
Infineon Technologies AG
Am Campeon 1-15, 85579 Neubiberg
Germany

Public

Date: 05/2024

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