Whitepaper

Electrolyzers to support the grid

krecotec

Introduction

Electrolysis is a chemical process in which a direct electric current generates a redox reaction. Electrolysis is used, among other things, to obtain substances whose extraction would be more expensive or impossible using purely chemical methods, such as in the case of hydrogen. The DC power source that supplies the electrical energy and drives the chemical reactions is the focus of this document.

Electrolysis dates back to inventions from 1789:

- **1789**: A. P. van Troostwijk and R. Deiman conduct the first electrolysis of water using an electrostatic generator.
- **1799**: Alessandro Volta develops the first practical and powerful battery—the Voltaic pile.
- **1800**: William Cruickshank decomposes saltwater. William Nicholson and Anthony Carlisle demonstrate that two gases in a 2:1 ratio can be produced from water using electricity from the Voltaic pile.
- **1805**: Theodor Grotthuß describes the first theory of water decomposition.
- 19th century: Advances in the technical use of electrolysis and in the theory.
- **1902**: Development of the mercury vapor rectifier by Peter Cooper-Hewitt. This technology was used until the early 1970s.
- In **the 1960s**, thyristor rectifiers began to replace mercury vapor rectifiers.
- Since **around 2020**, IGBT technology has been increasingly used in the lower power classes of electrolyzers.

It is fascinating to see how quickly this technology has developed over time, with new semiconductors like silicon IGBTs and silicon carbide MOSFETs entering the market in various topologies for powering electrolyzers.

Technologies

2.1 The electrolysis stack

The principle of the electrochemical converter is currently based on four known water electrolysis technologies, each at very different stages of development. These are:

a) Alkaline water electrolysis (AEL; alkaline electrolysis), which has the most advanced technical status,
b) Polymer Electrolyte Membrane electrolysis (PEM electrolysis; Polymer Electrolyte Membrane),
c) High-temperature solid oxide electrolysis (SOEL; Solid Oxide Electrolysis), which is still the subject of intensive research,
d) AEM technology (Anion Exchange Membranes). This technology enables the combination of non-precious metal catalysts with established manufacturing processes and designs from PEM electrolysis fuel cells.

In the case of AEL (described here as an example), a DC power source is connected to the cathode (negative pole) and the anode (positive pole) of the electrolysis stack. The cell contains a mixture of water and potassium hydroxide solution, known as the electrolyte. Once all electrical resistances in the circuit are overcome, an electric current flows through the electrolysis cell. At the cathode, the water molecules are first converted into OH^- ions to form hydrogen gas molecules. The hydrogen molecules form gas bubbles, which detach from the electrode surface. With a constant electrode thickness and reactive surface area, hydrogen gas is produced uniformly across the entire electrode surface. If the cell is positioned vertically, the gas rises from the lower to the upper edge of the electrode surface across the entire width of the electrode.

The liquid content is high in the lower area, and the gas, i.e., the foam, known as the two-phase mixture, rises. Due to the voltage difference between the electrodes, the OH^- ions are guided through the diaphragm from the cathode to the anode. At the anode surface, they recombine with hydrogen atoms from the water to form water. Oxygen atoms are produced in the process, which immediately combine to form oxygen molecules, also forming gas bubbles that rise from the electrode. On the hydrogen side, exactly twice the gas volume is produced compared to the oxygen side.

2.2 The rectifier - the coupling between the grid and electrolysis

Basically, electrolysis requires a direct current to start the electrochemical reaction and supply it with energy.

Today, we distinguish between different topologies:

a) Uncontrolled/semi-controlled rectifiers with a buck converter (diodes/thyristors)
b) Fully controlled rectifiers with transformer tap changer (thyristors)
c) IGBT Active Front End (AFE) with/without a buck converter
d) Future Silicon Carbide (SiC) AFE with/without a buck converter or Dual-Active-Bridge

What they all have in common is the conversion of alternating current (AC) into direct current (DC).

The differences arise from the components used, the chosen rectifier design, and the implemented control approaches.

New grid connection regulations for hydrogen electrolyzers (Europe / Germany)

Since 1992, the world has been striving to reduce greenhouse gases following the Kyoto Protocol, with increasingly visible consequences.

08/2016: EU Regulation (2016/1388) on the Network Code for Demand Connection (DC) and the definition of grid-forming units (including electrolyzers).

12/2019: Proclamation of the European Green Deal with a 10-point plan for climate neutrality, aiming for "Net-Zero by 2050" in Europe.

02/2022: The independence from Russian natural gas, the necessary energy storage for the transition to renewable energy generation, and CO2 neutrality place hydrogen in a crucial position.

09/2022: ACER (European Agency for the Cooperation of Energy Regulators) launches public consultation on amendments to the grid connection rules based on EU Regulation (EU 2016/1388).

07/2023: Further public consultation on amendments to the grid connection rules. For the first time, specific requirements from grid operators in EU 2016/1388 on the Fault Ride Through (FRT) behavior of electrolyzers.

02/2024: Statement from the four German transmission system operators (4TSOs) concerning VDE-AR-N 4120/4130 for electrolyzer plants.

03/2024: Position paper from the 4TSOs on the FRT and modeling requirements for electrolyzer plants.

03/2024: Statement from the German Hydrogen Association (DWV) on the 4TSOs' position paper.

09/2024: Next scheduled meeting of ACER (EU Agency for the Cooperation of Energy Regulators) for consultations on EU 2016/1388.

It is to be expected that the transmission system operators (TSOs) in Germany will soon establish requirements for specific electrolyzer projects and set them as minimum standards.

Solutions of krecotec GmbH for grid connection

krecotec GmbH brings with its engineers over 25 years of experience in frequency converter development for wind turbines and their connection to the electrical power grid. Since its founding in 2022, we have been applying this knowledge to the analysis, simulation, and design of power electronics for megawatt-scale electrolyzer plants.

krecotec GmbH analyzes the technical requirements of grid operators and derives solutions for the power supply of electrolyzers. In doing so, krecotec considers the overall system, focusing on the interaction between the grid, "grid rectifier," and the electrolyzer stack.

The following points are currently considered critical in the market, for which krecotec offers corresponding solutions:

1

Robustness during temporary voltage fluctuations (<=3s):

Evaluation of system components and auxiliary supplies. Calculation of the necessary energy amount and design of power supply solutions for this time range. System design and development of control concepts for riding through voltage changes.

2

Resumption of active power consumption after grid faults:

Use of IGBT-based inverters with regulation times well below 1 second. System design and development of control concepts to limit the power gradient of the electrolyzer.

3

Load shedding and active power adjustments

In the case of active load control under LFSM (limited frequency sensitive mode), krecotec implements parallel control algorithms on the electrolyzer stack side, as well as active load control through, for example, temporary energy absorption (chopper mode, storage). This also allows for easy compensation between the parameters from BoL (Beginning of Life) to EoL (End of Life).

4

Regulation speed of electrolyzer active power / RoCoF robustness

The achievable ramp rates for active power consumption of the electrolyzer stack differ fundamentally between alkaline and PEM systems. Current data show, depending on the technology, approximately 0.075*Pn/min for AEL systems and approximately 0.1*Pn/s for PEM systems. krecotec regularly reviews the requirements set by grid operators.

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Reactive power compensation

The compensation of reactive power for hydrogen electrolyzers depends on the power supply technology used. By utilizing IGBT-based power supplies for the electrolyzers, full compensation of reactive power at the grid connection point is possible. Additionally, with appropriate sizing, variable grid services in both capacitive and inductive reactive power areas, as well as STATCOM operation in idle mode, can be realized.

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Simulation models

Simulation models for the planning and design of grid connections for generation and consumer plants have been standard practice for years. Based on the experiences from grid connections of wind power plants over the past 20 years, manufacturers and suppliers have agreed on standards in modeling. This is essential to ensure grid-compliant integration into the electrical power supply network and to assess system stability.

The different electrolyzer stack variants today lead to parameter definitions that in some cases have not yet been validated. However, this does not exclude the general modeling and simulation of overall system behavior in a grid model, as the grid behavior of an electrolyzer is largely influenced by the control of the power electronic rectifier. Both dynamic “electromagnetic transients” models (EMT) and root mean square (RMS) models are used to verify grid connection conditions (harmonic analysis, behavior during dynamic changes, grid recovery, etc.).

krecotec also derives generic EMT and RMS models for electrolyzer manufacturers and supports the determination of parameters for the electrolyzer stack with different power supply topologies and suppliers. This can make electrolyzer manufacturers independent of different modeling approaches and lead times from their suppliers, while also building up in-house expertise.

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Verification procedures

The smallest electrolyzer unit consists of the power supply at the grid, the electrolyzer stack, and its auxiliary systems. As fundamental components for a verification procedure, krecotec considers the following points:

- Verification of the functionality of auxiliary power supplies in the event of a grid fault by calculating the necessary autonomy power and energy, as well as through unit testing.
- Verification of compliance with permissible grid impacts through EMT simulations to determine harmonics and appropriate filter sizing.
- Verification of the stability of the power supply to the grid through EMT simulations across the entire operating range (Pmin ... Pmax / Qmin ... Qmax).
- Verification of grid-compliant Fault Ride Through (FRT) behavior as a model proof through EMT simulations, as well as trouble-free passage through FRT characteristics via field tests conducted by manufacturers.

These points can form an initial verification in a timely manner (possibly also staggered over time) until unit certifications are further developed later on.

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FRT behavior and active current resumption

The measures described so far lay the foundation for assessing the robustness of the electrolyzer system. Unstable behavior can thus be identified and eliminated in advance.

The manufacturers of power supplies and electrolyzer stacks, by evaluating grid requirements, are able to implement additional technical measures if necessary through hardware or software adjustments.

As in the case of frequency control/load shedding, performance improvements can also be achieved here through additional, dynamically connected loads.
It should be noted that this approach has proven successful in the wind power industry since the introduction of grid connection rules.

9

FACTS

Modern power supply solutions can be adequately sized in advance and used for grid stabilization during operation with appropriate communication and control. This can even apply during times when electrolysis is not possible due to time or system constraints (e.g., in combination with renewable energy sources).

10

Communication

The interface descriptions between grid operators and wind farm operators today provide a solid basis for data exchange. krecotec relies on well-established interfaces that enable the exchange of current system data and requirements for electrolyzer systems during grid operation.

05

Summary and outlook

5.1 System stability in the context of coal phase-out

With the legal framework established in 2020 for the phase-out of coal-fired power generation in Germany by 2038 at the latest, and the complete phase-out of nuclear energy in 2023, the rotating masses of generators in Germany are gradually being reduced. These generators and their control systems have been considered the backbone of grid stability since the introduction of electric power supply. The Federal Network Agency monitors and the transmission system operators ensure the maintenance of system stability in Germany. In this context, the introduction and grid connection of new stability-relevant technologies (such as the current electrolysis technology) must also contribute to system stability. Refer to the System Stability Roadmap and the 2023 System Stability Report for more information.

5.2 Innovation and marketability

The example of wind energy in Germany has shown that different market participants can achieve a balance of interests. This process leads to the creation of new, innovative solutions that are also in demand on the global market. Against this backdrop, trust should be placed in modern technologies and new solutions to achieve the energy transition, rather than casting general doubt on the goals.

5.3 Outlook

Ensuring the stability of the electrical power supply system is a cross-border task that faces new challenges with the increasing share of converter-based generation and consumption systems and the resulting changes in the behavior of electrical grids. On the other hand, these flexibly and dynamically controllable converter systems offer opportunities to provide solutions for the aforementioned challenges.

In the area of electrolyzer power supplies, there is a significant advantage in that modern technologies (such as IGBT converters) from other fields of application, where they have been established in the market for a long time, can be easily adapted and implemented. Further potential optimizations, such as improving efficiency and reducing harmonics, are on the horizon with silicon carbide technology. As the market for this technology scales up, corresponding cost reductions will follow, just as mercury-arc rectifiers were replaced by thyristors 60 years ago.

At krecotec, we want to contribute our part to this effort. Our experts are always ready to assist you. You can reach us via email at info@krecotec.com.

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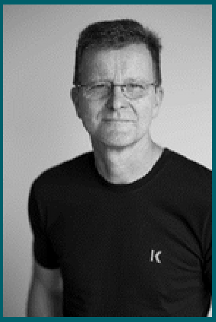

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