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Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis

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Abstract: The renewable power-to-hydrogen (P2H) technology is one of the most promising solutions to fulfill the increasing global demand for hydrogen and to buffer the large-scale fluctuating renewable energies. The high-power high-current ac/dc converter plays a crucial role in P2H facilities to transform the medium-voltage (MV) ac power to a large dc current to supply the hydrogen electrolyzers. This work introduces the general requirements and overviews several power converter topologies for P2H systems. The performances of different topologies are evaluated and compared from multiple perspectives. Moreover, the future trend of eliminating the line-frequency transformer (LFT) is discussed. This work can be future guidance designing and implementing of power electronics-based P2H systems.

Keywords: High-power ac/dc converter; IGBT; power-to-hydrogen; water electrolysis; thyristor

1. Introduction

Nowadays, hydrogen is widely used for industry-scale ammonia production for fertilizers and fossil fuel processing (e.g., hydro-cracking). The global demand for pure hydrogen has been rising for recent decades, and it accounted for 74 million tonnes in 2018 [1]. Due to the global ambition to achieve net-zero carbon emission and the transition of using hydrogen-based e-fuels to replace fossil fuels, the future demand for hydrogen is expected to increase by a factor of more than ten in 2050 [2]. However, the mainstream of global hydrogen production is based on steam reforming of natural gas, and this fossil hydrogen production generates CO₂ emission of approximate 830 million tonnes per year [1].

One of the other methods for hydrogen production is water electrolysis, where water is split into hydrogen and oxygen by using electric power [3]. It accounts for 2% of the global hydrogen supply [4]. The water electrolyzer typically consumes 50 kWh electricity power for producing 1 kg of hydrogen. Therefore, the CO₂ emission of hydrogen from water electrolysis is highly dependent on ways of electricity generation. Using coal-based electricity will lead to heavy carbon emissions, whereas renewable power, e.g., wind turbines and photovoltaics, involves no carbon emissions. Hence, this renewable hydrogen production via water electrolysis is promising to fulfill the increasing worldwide hydrogen demand and to achieve net-zero carbon emissions by 2050 [5].

On the other hand, the global warming crisis also led to booming interests and investments in renewable energy over recent decades. As such, a large number of wind farms and photovoltaic power plants are being built worldwide [6]. However, the high penetration level of renewable energies brings a fluctuating nature to the power grid and causes instability issues, as their electricity productions are highly dependent on climate conditions [7]. The power-to-hydrogen (P2H) facilities can act as energy storage units by transforming the excessive energy delivered by renewable sources to hydrogen when low electrical demands are present. The hydrogen storage can be converted back to

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39 electricity via fuel cell converters during high electricity demand periods. In both ways,
 40 the intermittent nature of renewable power can be balanced to well match the demand
 41 profile of power grids [8–10]. Moreover, The generated hydrogen can be utilized as
 42 green fuel for mobility as well as raw material in the chemistry industry.

43 Due to the emission and grid-support features of the renewable hydrogen system,
 44 in recent years a booming number of demonstration and commercial plants are newly
 45 built worldwide [11–13]. Figure 1 demonstrates the general architecture of the renewable
 46 hydrogen system [14]. Renewable energies typically comes from wind turbines and
 47 photovoltaic power plants, which are connected to medium-voltage (MV) or high-voltage
 48 (HV) ac power grid via the ac/dc/ac frequency converter and dc/ac inverter, respectively.
 49 The generated renewable electricity then transmits through power grid to the hydrogen
 50 production site. The P2H converter plays a crucial role in this renewable hydrogen plant
 51 as it converts the MV ac electricity from the grid to a controlled high-current dc power
 52 flow, which is fed into the water electrolyzer for large-scale hydrogen production. The
 53 produced hydrogen can be directly used or further converted to methane and methanol,
 54 which are widely used in various industries, such as oil refining, mobility, and electricity
 55 generation.

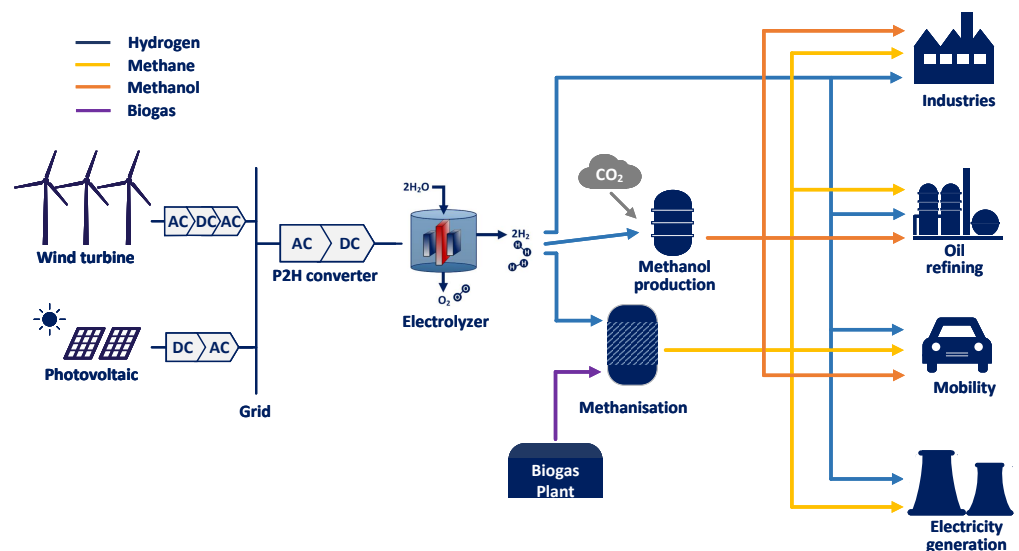


Figure 1. The general architecture of renewable hydrogen system including the renewable energy generation, the distribution and conversion of electricity, the P2H electrolysis, and the application of renewable hydrogen.

56 The power quality, efficiency, cost, and reliability are several of the P2H system's
 57 critical performance metrics, which can be significantly affected by the topology of P2H
 58 converters. Thyristor-based ac/dc power converters have been dominating solutions
 59 in high-power ac/dc applications due to their high robustness, high efficiency, and
 60 low cost [15–22]. A commercial thyristor-based converter can supply 1.5–10 kA dc
 61 current with a dc voltage of 1 kV, delivering 10 MW power in maximum per unit [22].
 62 Nevertheless, the large firing angle operation of thyristors can result in heavy current
 63 distortion and low power factor at the ac input. Hence passive/active power filters
 64 and reactive power compensators are mandatory, increasing the system-level cost [16].
 65 Moreover, a significant trend in recent years is to use Buck-type chopper as the rear stage
 66 of diode/thyristor rectifier [20,21,23–28]. A commercial chopper rectifier can supply
 67 a maximum of 10.4 kA and 1.1 kV at the dc output, delivering 10 MW power to the
 68 electrolyzers [28]. This brings better power quality and higher power factor throughout
 69 a wide operation range of the converter. Moreover, the emerging active-front end (AFE)
 70 based on the B6 converter can also be an attractive option for the power-to-hydrogen
 71 application [29]. It brings much fewer input current distortion by fully regulating the

72 input ac current waveform. In this way, the active/passive power filters and the reactive
73 power compensators can be eliminated.

74 In the literature, there are some comparative works available. In [19], four thyristor-
75 based ac/dc high-current rectifier topologies are compared, where the chopper-rectifier
76 and AFE solutions are not covered. Reference [20] reviews the thyristor phase-controlled
77 rectifiers, IGBT chopper rectifiers, and pulse-width modulated current source rectifiers
78 for various industry applications requiring kilo-amperes supplies. It is concluded
79 that the IGBT chopper rectifier has had fulfilled field experience to perform as an
80 alternative for supplying kilo-amperes current. Reference [21] overviews the diode- and
81 thyristor-based multi-pulse rectifiers with on-load tap changing transformer as well as
82 the chopper-rectifier topologies. A future research trend on modular converter topologies
83 with medium-frequency transformer (MFT) and high-frequency transformer (HFT) is
84 introduced in [21]. Nevertheless, none of the aforementioned provides an insight into
85 the P2H water electrolysis system. Moreover, the performance matrix of using AFE
86 converter in such P2H water electrolysis system is not investigated in prior-art.

87 This paper focuses on the P2H water electrolysis system and serves as the overview
88 and comparison of P2H power electronic converter topologies. This paper first intro-
89 duces the general requirements of P2H converters from both the electrolyzer side and
90 grid side in Section 2. Then, several power converter topologies used in P2H water
91 electrolysis are introduced and studied from multiple perspectives in Section 3. The
92 comparative conclusions regarding the power quality, efficiency, cost, reliability, and
93 control complexity are drawn in Section 4. The future trend of using the modular multi-
94 cell converter to eliminate the bulky line-frequency transformer (LFT) is discussed in
95 Section 5. Finally, the conclusions are drawn in Section 6.

96 2. General Requirements

97 2.1. Load Specifications

98 A simplified electrical model of a hydrogen electrolyzer is exhibited in Figure 2,
99 where U_{rev} and R_{Ω} are the reverse voltage potential and ohmic resistance during the
100 water-splitting reaction. Furthermore, components C_{dl} and R_{ct} describe the charge trans-
101 fer resistance and double layer capacity, respectively, which are temperature-dependent.
102 It is noted that R_{Ω} suffers a parametric increase along with the aging process of the
103 electrolyzer. Thereafter, the loading ranges, i.e., dc current and voltage level, of the
104 hydrogen electrolyzer at its beginning of life (BOL) and end of life (EOL) are presented
105 in Figure 3.

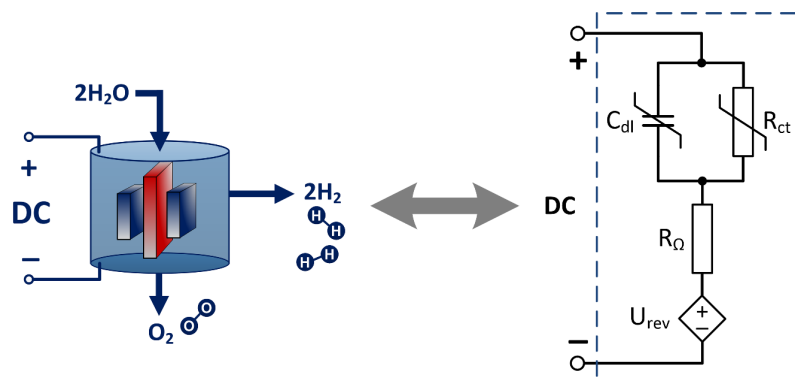


Figure 2. The electrical model of a hydrogen electrolyzer. [30]

106 According to the electrolyzer's specification, the general requirements of a power-to-
107 hydrogen power converter are listed in Table 1. The output voltage is in the range of 640–
108 1000 V (see Figure 3) due to variations of the current level and electrolyzer degradation.
109 The output power can reach 10 MW using two sets of 5 MW electrolyzer stack, with a
110 rated load current up to 5 kA for each. A future trend of the load specification is to have
111 a current ripple of less than 5%.

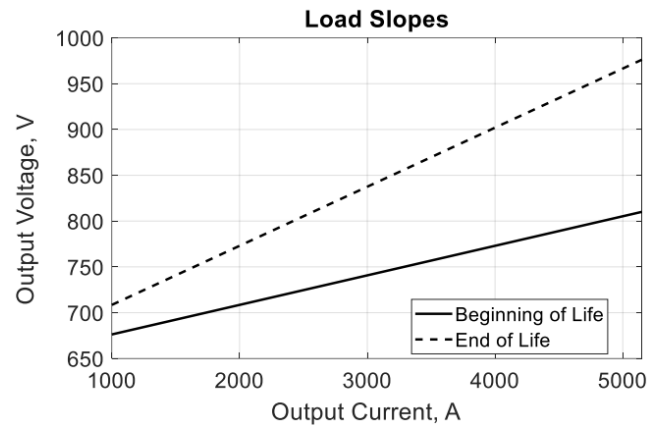


Figure 3. Load slopes of the electrolyzer for the beginning and end of lifetime.

Table 1. General requirements of power-to-hydrogen power converters.

	Present	Future
Input voltage	Typical 6.6–35 kV, 50/60 Hz	
Output voltage	640 – 1000 V	
Output power	5 MW × 2 (2 sets of electrolyzer stack, 5 kA each)	
Output current ripple	N/A	≤ 5 % of rated current
Efficiency	> 94 %	> 98 %
Power factor	> 0.90	> 0.99
THD _i (2–40 th)	< 5 %	
Standards	IEC 60076 series (transformer) IEC 60146-1-1 (semiconductor converter) [31] IEC 61000-6-2 (immunity) [32] IEC 61000-6-4 (emission) [33] IEC 61000-3-6 (distortion) [34] IEC 61000-3-7 (voltage fluctuations) [35] IEC 61000-3-13 (unbalanced installations) [36]	

112 2.2. Grid Requirements

113 Typically, the MW-level power-to-hydrogen converter is connected to a MV 6.6–35
 114 kV power grid, where a step-down LFT is mandatory in between. From the grid's
 115 perspective, there are several requirements for power-to-hydrogen converters as con-
 116 sumption installations. First, the converter should maintain regular operations under
 117 background frequency and voltage deviations, in the range of 47 – 63 Hz and 90% –
 118 110% of the nominal voltage, respectively. Furthermore, the regular operation of power
 119 converters should not cause severe power quality issues, e.g., voltage imbalance, rapid
 120 voltage change (i.e., 4%), and flickers [35,36]. Moreover, harmonic distortions and inter-
 121 ferences in 2 – 9 kHz should be attenuated, according to IEC 61000-3-6 [34]. The current
 122 total harmonic distortion (THDi) and power factor at the connection point should be
 123 less than 5% and greater than 0.90, respectively. In order to fulfill the electromagnetic
 124 compatibility requirements, standards IEC 61000-6-2 [32] and IEC 61000-6-4 [33] apply
 125 for P2H power electronic converters.

126 3. State-of-the-Art Solutions

127 3.1. 12-Pulse Thyristor Rectifier (12-TR)

128 The multi-pulse thyristor rectifier is one of the most mature and prominent solutions
 129 in high-power rectification applications. The block diagram of a 12-pulse thyristor
 130 rectifier (12-TR) is depicted in Figure 4. A three-winding wye-delta-wye LFT is connected
 131 to eliminate the 5th and 7th order harmonic currents. Then, two 6-pulse thyristor rectifiers

132 are connected to the two secondary windings of the LFT. The electrolyzer current can
 133 be regulated by adjusting the firing angle α_f of the dual thyristor rectifiers. A large
 134 firing angle α_f is generally adopted for low-power operating conditions, leading to more
 135 harmonic and reactive components. The power factor and total demand distortion are
 136 pretty dependent on the firing angle, and a large firing angle leads to a lower power
 137 factor and more waveform distortion. Consequently, it is mandatory to compensate for
 138 these harmonic currents and reactive power at the connection point. Passive trap filters
 139 tuned at 11th and 13th order of line frequency are commonly used for P2H converters
 140 based on this 12-TR topology. Moreover, a shunt passive high-pass filter may also
 141 be implemented to bypass those high-order current harmonics. Besides, a static VAR
 142 compensator or static synchronous compensator shall also be mandatory to provide
 143 significant reactive power due to the large-firing-angle operation of 12-TR [16].

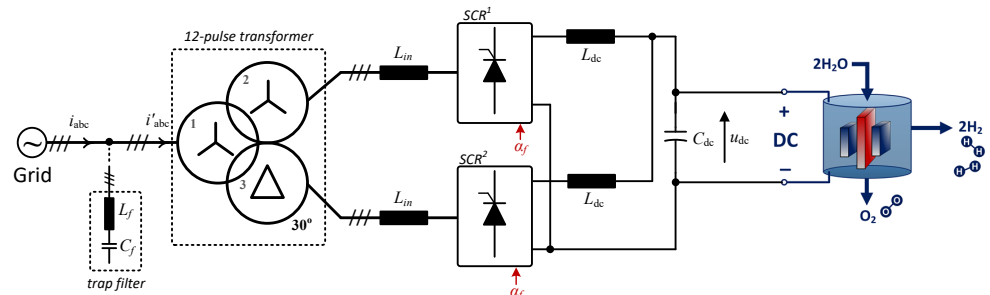


Figure 4. Circuit diagram of a 12-pulse thyristor rectifier with passive trap filter (12-TR).

144 3.2. 12-Pulse Diode Rectifier with Multi-Phase Chopper (12-DRMC)

145 Another trendy topology used in P2H power electronic converters is the 12-pulse
 146 diode rectifier with multi-phase choppers (12-DRMC) [20,23,24,27], as is illustrated in
 147 Figure 5. The multi-phase chopper bridges are implemented by silicon (Si) IGBTs and
 148 freewheeling diodes, as arranged in an interleaved manner to attenuate the current
 149 ripple through the electrolyzer. The electrolyzer current/power can be regulated by
 150 varying the duty ratios of chopper IGBTs. Compared with the 12-TR, one significant
 151 merit of the 12-DRMC is the improved power quality, in terms of relatively lower current
 152 distortion and constantly high power factor throughout the variable operation range of
 153 the P2H converter. Nevertheless, measures are still needed to improve the power quality
 154 at the connection point. The widely adopted method involves 11th and 13th-tuned shunt
 155 passive trap filters as well as a shunt high-pass filter. Nowadays, the technology of the
 156 high-current chopper-rectifier becomes mature [28], and its overall cost decreases as it is
 157 presently comparable with the aforementioned 12-TR system [24].

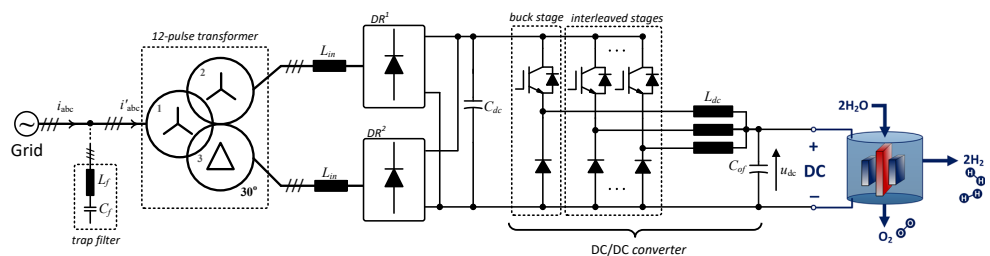


Figure 5. Circuit diagram of a 12-pulse diode rectifier with multi-phase chopper and passive trap filter (12-DRMC).

158 3.3. 12-Pulse Thyristor Rectifier with Active Shunt Power Filter (12-TRASPF)

159 Considering the advantages and disadvantages of the above two topologies, a
 160 hybrid architecture, a 12-pulse thyristor rectifier with active shunt power filter (12-
 161 TRASPF), is proposed [16], as is depicted in Figure 6. The electrolyzer is supplied by

162 the 12-TR, since it features lower costs and high-current capability. The power quality
 163 issues of the 12-TR are compensated by a low-power shunt active power filter. Although
 164 the loss and cost of the 12-TRASPF system can be more significant compared to 12-TR,
 165 promising power quality can be expected.

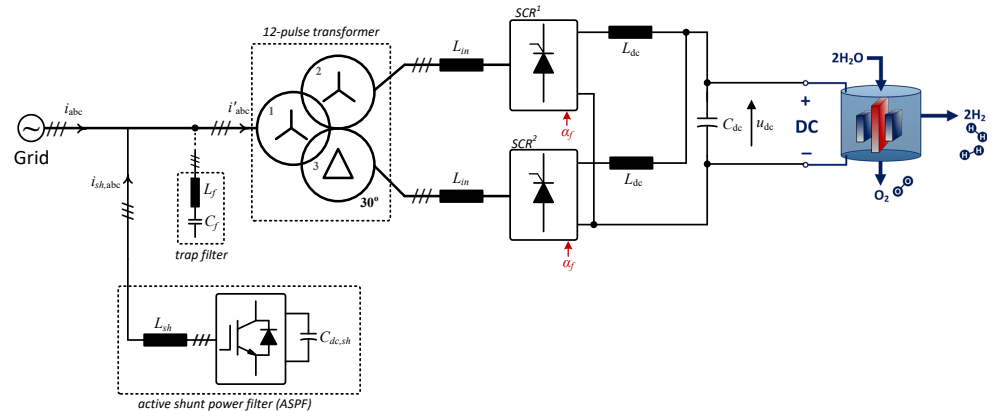


Figure 6. Circuit diagram of a hybrid system with 12-pulse thyristor rectifier and active shunt power filter (12-TRASPF).

166 3.4. Active Front End (AFE) Rectifier

167 Another attractive topology candidate is the active front end (AFE) rectifier [29],
 168 as is depicted in Figure 7. The popular B6 converter can be utilized, which consists
 169 of three IGBT half bridges. Under the case where wide-range operation capability is
 170 required, another B6 + chopper architecture may be used to achieve the adjustment of
 171 output current and voltage, as depicted in Figure 7 [37]. To simplify, this work focuses on
 172 B6-AFE, and conclusions drawn from B6-AFE can also be extended to B6 + chopper-AFE.

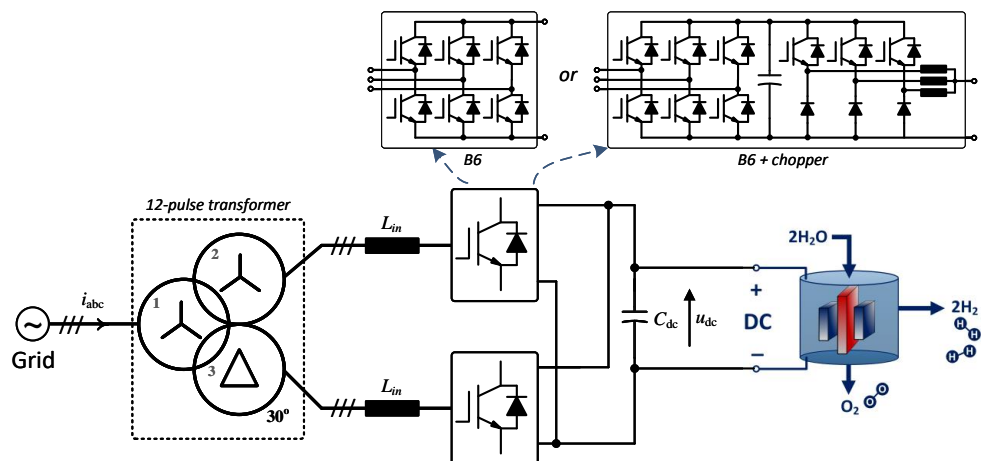


Figure 7. Circuit diagram of an active front end rectifier (AFE).

173 Due to the current-rating limitation of commercial IGBTs [38], multiple (≥ 2) IGBT-
 174 based B6 converter stacks configured in parallel are mandatory for a power level of 10
 175 MW. Three-winding LFTs used in 12-TR and 12-DRMC can still be employed in AFE
 176 systems to achieve the desired power rating, provide galvanic isolation, as well as to
 177 mitigate the $6k \pm 1^{th}$ ($k = 1, 3, 5, \dots$) harmonics, although these harmonics are minor
 178 components for a B6-AFE system.

179 In the AFE rectifier system, the input-side ac current can be controlled to be sinu-
 180 soidal by shaping the duty ratio of the Si IGBTs, so that much lower current harmonic
 181 distortion shall be expected for such AFE rectifier systems. Moreover, the phase shift
 182 of ac current with respect to grid voltage can also be manipulated by adjusting the

183 modulation signal of the B6 converter so that a high power factor value can be achieved
 184 simultaneously. Therefore, one unique advantage of using the AFE rectifier system is its
 185 superior power quality regulation capability. No additional passive/active harmonic
 186 filters and VAR compensators will be needed.

187 The AFE rectifier system can also be implemented using the emerging SiC MOSFETs
 188 as a substitution of Si IGBTs. The SiC-based AFE rectifiers are demonstrated in [39,40].
 189 One unique feature of the SiC-based B6-AFE rectifier is that the SiC MOSFET can be
 190 operated under the synchronous rectification mode by its channel reverse conduction,
 191 which features low conduction loss. It is reported in [40] that the AFE rectifier achieves
 192 1.2% efficiency promotion by utilizing 1200-V SiC MOSFETs.

193 4. Performance Comparison

194 This work obtains the power factor and current total harmonic distortion (THDi)
 195 among 12-TR, 12-DRMC, and 12-TRASPF through simulation. Figures 8 and 9 exhibit
 196 the simulated power factor and THDi of the three topology candidates, respectively. It
 197 can be seen from Figure 8 that the 12-TRASPF features superior power factor values
 198 (≥ 0.99) since the ASPF module can also compensate for reactive power. The 12-DRMC
 199 also performs satisfactorily in terms of power factor, i.e., between 0.96 and 0.98, which
 200 is relatively flat according to the output variation. For 12-TR based systems, the power
 201 factor becomes unsatisfactory under small output-current conditions due to their large
 202 firing angles. Therefore, depending on their operating range of output current, the 12-TR
 203 requires external power-factor correction measures (e.g., a static VAR compensator, static
 204 synchronous compensator, or ASPF module) to compensate for their reactive power.
 205 Furthermore, it can be seen from Figure 8 that the power factor of the 12-TR system
 206 increases as the electrolyzer becomes more aged, given the identical amount of output
 207 current. This can be explained by the increase of electrolyzer resistance alongside its
 208 aging process (see Figure 3), leading to the increased portion of active power fed into
 209 the electrolyzer given the identical amount of current.

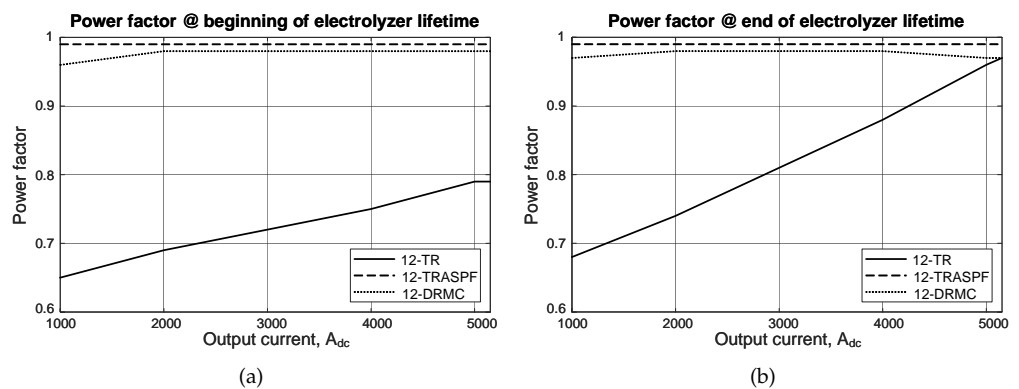


Figure 8. Performance comparison of power factor over the possible operating conditions: (a) At the beginning of electrolyzer lifetime. (b) At the end of electrolyzer lifetime.

210 In Figure 9, it is noted that the simulated THDi values of 12-TR and 12-DRMC are
 211 obtained without involving any power filters. It turns out that both 12-TR and 12-DRMC
 212 will need external passive power filters to attenuate their current harmonic levels, as
 213 mentioned in Section 3.1 and 3.2. On the other hand, using the ASPF can also be a
 214 promising solution to handle the power quality issue, as the THDi values of 12-TRASPF
 215 are well-regulated to be lower than 5%. On the contrary, the AFE rectifier does not seem
 216 to have power quality issues as both the phase-lag angle and input current waveform
 217 can be well controlled by IGBT-based B6 converters. The power quality rating of the
 218 four aforementioned topologies is summarized in Table 2.

219 Regarding the efficiency performance, the 12-DRMC system exhibits more losses
 220 than the 12-TR system. The excessive dissipation of 12-DRMC comes from IGBT's

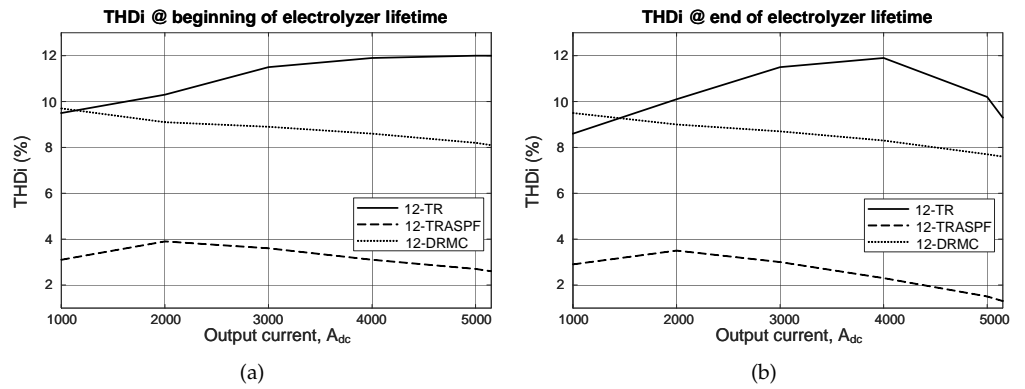


Figure 9. Performance comparison of THDi over the possible operating conditions: (a) At the beginning of electrolyzer lifetime. (b) At the end of electrolyzer lifetime.

Table 2. Comparison among topology candidates. ++: Superior. +: Satisfactory. Δ : Neutral. -: Unsatisfactory.

Topologies	Power quality	Efficiency	Cost	Reliability	Control Complexity
12-TR	-	+	+	++	+
12-DRMC	Δ	Δ	+	+	Δ
12-TRASPF	+	Δ	Δ	Δ	-
AFE	++	Δ	-	Δ	-

221 conduction and switching losses. The percentage of IGBT's switching loss is dependent
 222 on its switching frequency and gate driver parameters. The 12-TRASPF system is also
 223 less efficient than the 12-TR, considering the extra losses dissipated in the active power
 224 filter. From a reliability viewpoint, the 12-TR system exhibits the best performance.
 225 The thyristors are considered as reliable components as they have demonstrated their
 226 maturity in utility-scale applications. The 12-DRMC is considered less reliable as multiple
 227 Si IGBTs are used as the output stage. Nevertheless, the industry is gradually gaining
 228 confidence in terms of the reliability of 12-DRMC, as more projects using 12-DRMC are
 229 being carried out [20,21]. It is noted that the reliability performance investigated in this
 230 work is a system-level concept. For the 12-TRASPF system, a single failure from either
 231 the ASPF or 12-TR is regarded as a failure from the system perspective. Although the 12-
 232 TR is reliable, the 12-TRASPF system is regarded as neutral in terms of reliability being
 233 comparable with the AFE rectifier, because commercial ASPFs use the IGBT-based B6
 234 topology, which is identical with the AFE rectifier presented in this work. The principles
 235 of their control and driver systems are also of the comparable level of complexity.

236 5. Future Trends and Opportunities – Modular Multi-Cell Rectifier

237 Among the aforementioned P2H converter topologies, the three-winding LFT is
 238 mandatory in the system. It is usually the bulkiest component in such a P2H converter
 239 system and brings challenges in transportation, installation, and footprint occupation.
 240 Therefore, eliminating the bulky LFT from such a P2H converter system is one of the
 241 emerging topics.

242 One promising topology solution is the modular multi-cell rectifier system, as
 243 shown in Figure 10. Modular configurations are employed, and each converter cell is
 244 implemented by the front-end ac/dc stage followed by a dc/dc stage with galvanic
 245 isolation. The highly modularized design enables high scalability and flexibility for
 246 the rectifier system. Figure 10(a) demonstrates a star-connected input-series output-
 247 parallel (ISOP) configuration to interface with the MV grid [41,42]. Due to the cascaded

248 configuration of converter cells per phase, 1200/1700-V Si IGBT and SiC MOSFET can
249 be used ahead of the dc/dc galvanic isolation in each converter cell [43].

250 Moreover, a star-connected input-parallel output-parallel (IPOP) configuration is
251 depicted in Figure 10(b). It is noted that the ac side can be configured as either a star
252 or delta connection, and the star type features lower voltage stress for each converter
253 cell [44,45]. When connecting the IPOP type to the MV grid, a single converter cell
254 that interfaces with the MV grid is mandatory, and the 10-kV SiC MOSFET is found
255 to be the significant enabling device [46]. A 25 kW 7 kV/400 V ac/dc converter using
256 10-kV SiC MOSFETs is successfully demonstrated in [47], and challenges in terms of
257 flashover fault, high switching losses, MV-cable oscillation, and dielectric dissipation are
258 addressed. In the near future, the magnetic components and dielectric materials should
259 be promoted to fully release the potential of this MV SiC-based IPOP-type modular
260 multi-cell converter. Furthermore, the IPOP type makes it compatible when connecting
261 the modular multi-cell rectifier to a low-voltage, e.g., 400 V, power grid using 1200-V
262 voltage-class devices.

263 The realizations of each ac/dc and dc/dc stages are well established. The single-
264 phase ac/dc stage can be implemented by a full-bridge converter with four active
265 switches, as shown in Figure 10(c). A soft-switching variant with the zero-voltage-
266 switching capability is proposed in [47]. Moreover, it is noted that the three-phase ac/dc
267 stage using a B6 topology is also promising for connecting to LV grids [48]. Under the
268 case where each converter cell is designed to bear high power rating, the three-phase
269 ac/dc gains advantage in terms of a higher efficiency. The dc/dc stage can be realized by
270 multiple converter topologies, such as the dual active bridge [49] (as shown in Figure
271 10(d)) and LLC converters [50]. Since HFTs/MFTs are to be used in the dc/dc stage, each
272 converter cell can be achieved with a small volume and lightweight. Compared to Si
273 IGBTs, Si and SiC MOSFETs are better choices for each dc/dc stage, as a higher MFT/HFT
274 alternating frequency can be easily achieved. Nevertheless, the highly modularized
275 design also brings high control complexity to the system. Each modular converter cell
276 needs to be able to regulate itself and equally share the operating power.

277 6. Conclusion

278 This work provides as an overview of high-power, high-current ac/dc convert-
279 ers for P2H water electrolysis applications. The general load specification (for water
280 electrolyzer) and electricity grid requirements are introduced first to help guide the se-
281 lection of the P2H converter topologies. Then, four state-of-the-art solutions, i.e., 12-TR,
282 12-DRMC, 12-TRASPF, and AFE rectifier, are reviewed in this work. Then, these four
283 different topologies are evaluated and compared from various perspectives, including
284 power quality, efficiency, cost, reliability, and control complexity.

285 The conventional 12-TR is characterized as superior in terms of efficiency, cost,
286 reliability, and control complexity, whereas power quality issues (both power factor and
287 current distortion) need to be addressed, especially under large firing-angle conditions.
288 The 12-DRMC exhibits a high power factor among full operation range compared to
289 12-TR, while the harmonic filter is still needed to lower its input THDi. The 12-TRASPF
290 is hybrid concept utilizing both conventional 12-TR and a B6 converter based active
291 shunt power filter, so that promising power quality can be expected with a bit more cost
292 and less efficiency compared to 12-TR. The AFE rectifier is a promising solution in terms
293 of superior power quality with no additional compensation measure. Nevertheless, it
294 may suffer from a higher cost as well as a more sophisticated control system.

295 However, the four aforementioned topologies all require a LFT, which is bulky and
296 with a large footprint occupation. Then, a future trend of eliminating the LFT from the
297 P2H converter is introduced in this work. A modular multi-cell converter is discussed in
298 detail in this work, which gives an interesting research prospective in the near future.

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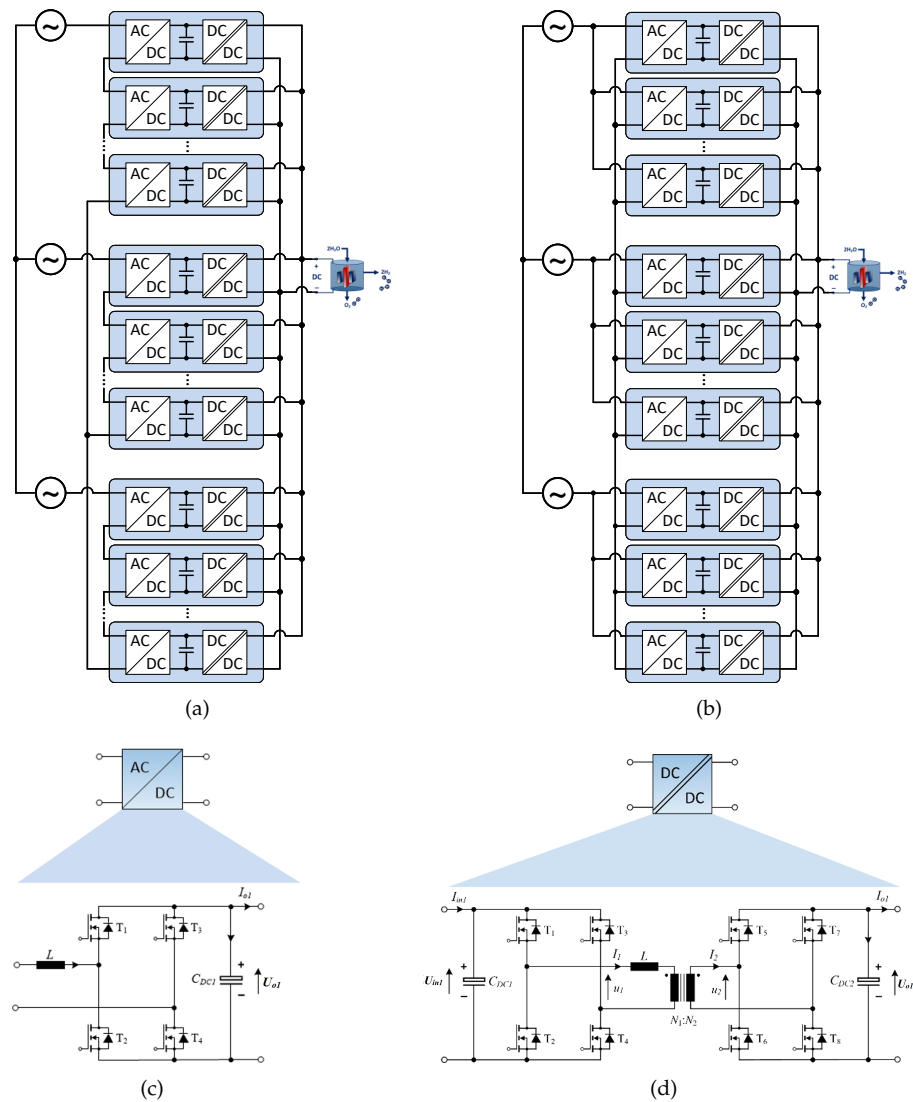


Figure 10. Circuit diagram of modular multi-cell rectifier. (a) The circuit architecture in a star-connected ISOP configuration. (b) The circuit architecture in a star-connected IPOP configuration. (c) The ac/dc stage realized by a single-phase full-bridge circuit. (d) The dc/dc stage realized by a dual active bridge circuit.

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