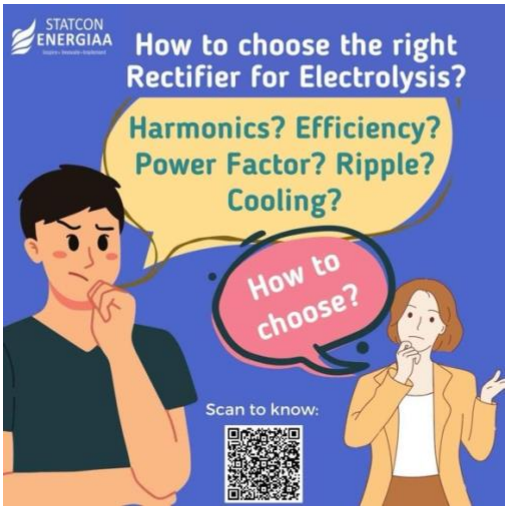
Choosing the right rectifier to maximise Green Hydrogen production

What is the role of Rectifier in Electrolysis and Green Hydrogen production?

Green hydrogen (GH2) production and the essential role of the Electrolyser, which requires green electricity to function optimally, are hot topics in sustainable energy discussions. Although the focus often lies on the electrolyser's ability to maximise hydrogen output, the efficiency of **electricity usage**—specifically how many kilowatt-hours (kWh) are needed to produce one kilogram of hydrogen—is also a critical conversation across various platforms. From the standpoint of electrical performance in GH2 production, AC-DC converter or **rectifier**, has garnered significant attention. These components, which convert AC to DC power, have been around for a long time but previously didn't receive much focus. However, they are now the subject of intense scrutiny by electrical engineers, sparking curiosity and raising numerous questions.



There are generally two methods for supplying this green electricity to the electrolyser: "**Direct DC-DC**" from a solar array and the more popular "**AC-DC converter**" setup involving a grid-tied solar network with grid availability. Due to their widespread use and demand, this long-form blogpost will focus primarily on AC-DC converters.

You can read more about the various kinds of Rectifier technologies available globally, vis-à-vis, Thyristor (SCR) controlled rectifier, Diode Rectifier with IGBT chopper and IGBT-based Active Front End (IGBT-AFE) technology, here. In this blogpost, we explain various aspects of rectifiers to help you choose the most suitable converter to power your electrolyser.

What are the selection criteria for Hydrogen Rectifiers/ Power Supplies?

1. **Use of MV Transformer for AC-DC converter & its efficiency**
2. **Input line current harmonics & Point of common coupling (PCC)**
3. **Input line Power factor (PF)**

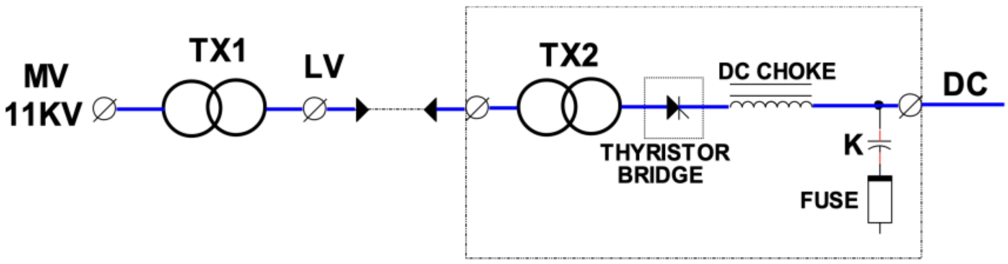
4. **AC-DC Converter Technology & efficiency**
5. **AC ripple in DC output vis-a-vis electrolyser behaviour**
6. **Overall AC (MV) to DC efficiency & its measurement**
7. **Air vs Water-cooled Rectifier**
8. **Enclosure**
9. **Conclusion**

Based on our 35+ years of experience designing and manufacturing high-power AC-DC convertors and our interactions with many Indian EPC companies in the GH2 field, we at Statcon Energiaa try to explain the above in this blogpost.

Being at such a nascent stage in India, this subject has generated a lot of curiosity among consultants/ EPC engineers, and correct standardised answers are still awaited. Plus, Google search without the full context of the requirements has fueled the fire. The purpose of this long-form blogpost is to generate awareness and invite critical comments with justification, for which participation on an open forum is welcomed as it will only help in consolidation and better understanding of the same parameters, etc.

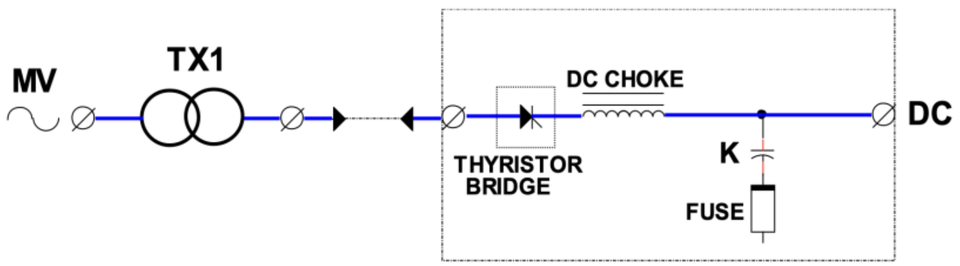
Use of MV Transformer directly for AC-DC Converters and efficiency

Conventionally, 400V/415/440V LV AC from TX1 LV was fed to any such converter in the past, as shown in Fig 1. Using this, even MV DC Rectifiers are being manufactured, and they have been in use for decades. This has also affected overall efficiency due to the efficiency of two transformers (Tx1 and Tx2 in Figure 1) in series getting multiplied.



AC/DC CONVERTER
FIG.1

However, with overall AC-DC efficiency measured from MV winding to DC be output being critical, it is expected that the LV Converter Transformer is avoided as far as possible, as shown in Fig 2. In this, the secondary (LV) windings are selected to suit the output DC voltage and MV supply variations considered.



AC/DC CONVERTER
FIG.2

However, there are restrictions recommended on the max kVA of such an MV to LV transformer as per standards (as is recommended in standard IS 1180 Part-1 & CEA guidelines published in March 2023). This is also due to the very high current rating of the LV winding. Generally, such industry restrictions are up to 5000 kVA for 33 kV. High MVA designs are possible, but they do not meet the techno-economic considerations.

Next comes the **peak efficiency** of any such transformer. It is a very standard industry norm to declare the peak efficiency of any such MVA transformer, in the range of 99 to 99.2%. But this is invariably the calculated efficiency. At times, these are even verified by measuring both magnetic & conductor winding losses, which may have errors because all surrounding environmental & electrical conditions are not considered.

Even during type tests, with what accuracy this can be measured even at the site is debatable considering the facts that:

1. AC voltage fed will have harmonics (unavoidable in a Grid) affecting the additional magnetising loss and

2. The accuracy of measuring instruments is in question, which has to be 5-10 times better

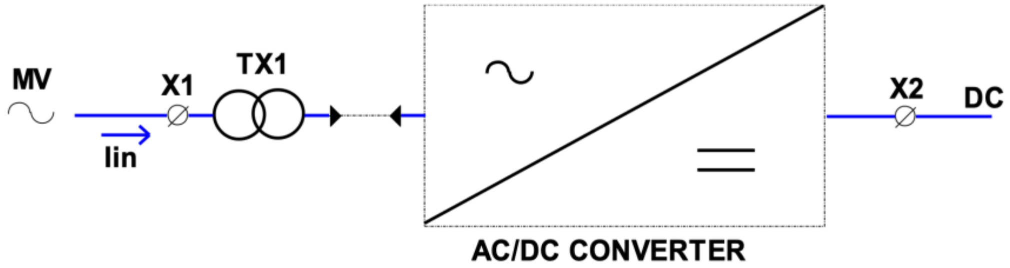
3. A pure resistive load bank is needed to load any such Transformer.

So the very practical efficiency figure that needs to be considered reasonably should be **98.5%** at best.

This is true of any of the 3 technologies, i.e. a ‘Thyristor converter’ or ‘Diode bridge + Buck chopper’ or ‘IGBT front-end + Chopper’ technology, since all of them shall need HV to LV transformer.

Input Line Current Harmonics and Point-of-Common-Coupling (PCC)

Input Line Current Harmonics is a crucial power quality electrical parameter that has attained focus due to increased awareness and its necessity in Green H2 production, where generally, the AC supply is fed through DC-AC Inverters (Solar/Wind) with Grid present.



Due to the AC-DC conversion process, the input line current I_{in} suffers where current harmonics are generated, which are harmful and pollute the AC line/ grid. So, there are regulations on this to the extent to which these can be permitted. Generally, the standard referred to for this is IEEE 519-2014, which was recently amended as IEEE 519-2022. Hence, this standard itself is very new and refers to Point-Of-Common Coupling (PCC) for all measurements.

This has led to many interpretations/ curiosity and overreactions by electrical engineers in India, where our grid is ridden with high Total Harmonic Distortion (THD). So, in this race, as expected, we start specifying/expecting even up to 3% THD in a Grid of 5-7% V_{THD} without even considering the impact of source impedance which might badly affect the whole picture. Please remember that any converter can only restrict the I_{THD} generated by it and not improve the existing grid quality.

Similarly, its measurement method also comes under question; what makes the whole subject crucial is that all of these are MW rectifiers. Hence, @ 100% load, factory/ lab tests are not possible, and at sites, there might not be any control over grid quality. Then measuring instruments/ methods, etc., become a challenge and, hence a matter of debate. Needless to say, even TYPE-TEST in the same MW rating also cannot be done due to the non-availability of a clean (MW) AC and a DC Load bank.

So, one of the ways out is to carry out the TYPE-TEST at a much smaller rating and then use the same topology/ technology and extrapolate it for drawing results. The discussion would be incomplete without a mention of the THD on different technologies, which are mentioned below:

1. A Thyristor Bridge-based, 24-pulse (effect) convertor can (at best) create between 3.5 – 5.5% current THD at its input line.
2. A Diode bridge-based 24-pulse (effect) convertor can (at best) create between 3-5% current THD at its input line.
3. An IGBT based Active Front End (AFE) converter can create 3-4% current THD at its input line.

However, in such a MW range (>350V + High current in 1000's), an IGBT/ AFE converter that has been in successful operation for, say, 2-3 years is still to be presented and verified.

Input Line Power Factor (PF)

As electrical engineers, we all know very well about the effect of PF on the quality and cost of electricity. In the order of its effect, in the three technologies available for MW AC-DC converters, the PF figures achievable are:

1. In Thyristor converters, it is possible to achieve up to 0.90 to 0.95, and this may also take into account the KVAR added on the MV side. To avoid the other harmonics available in the grid feeding into this capacitor, some L&C combination on the MV side will be needed.

2. In “Diode + Chopper” converters, while the maximum limit will be within 0.93 to 0.96, it remains stable irrespective of wide DC load voltage variation.

3. In IGBT/ AFE technology-based converters, approximately 0.98-0.99 PF can be obtained throughout the range, which is their biggest advantage.

However, there might be some special L&C filters available globally to get better PF, but they will add to the cost and loss of end-to-end efficiency. There is also Active PF Correction Technology available to improve this PF dynamically.

AC-DC Converter efficiency (rectifier efficiency in Green Hydrogen)

A lot is being talked about the AC-DC converter efficiency, which is supposed to be quite high, but it needs to be understood with reference to the calculated efficiency plus efficiency measurement method on the test bench, or efficiency measured on the actual product during installation. Each one is described below with respect to its circuit and losses.

(i) Thyristor bridge technology

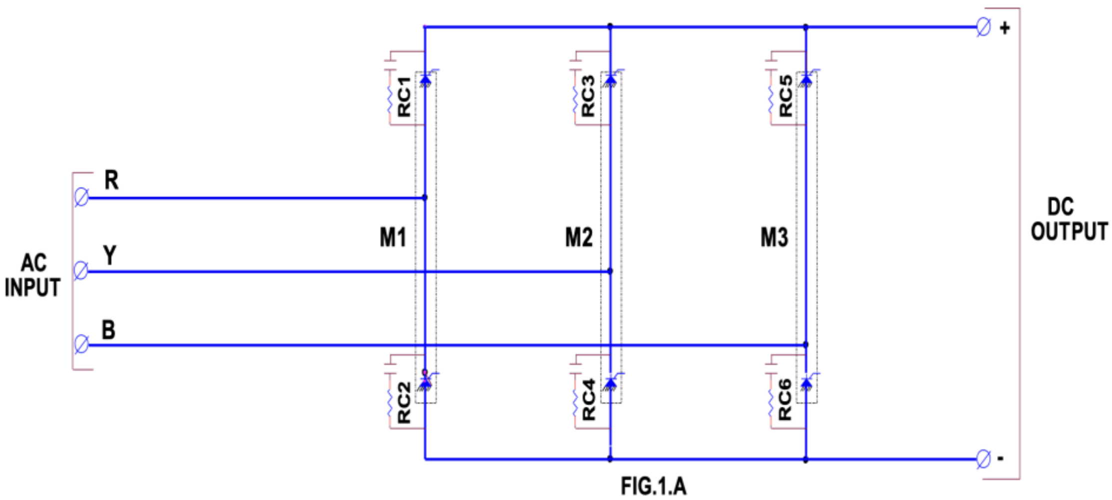


FIG.1.A

Fig 1.a Basic Thyristor converter bridge

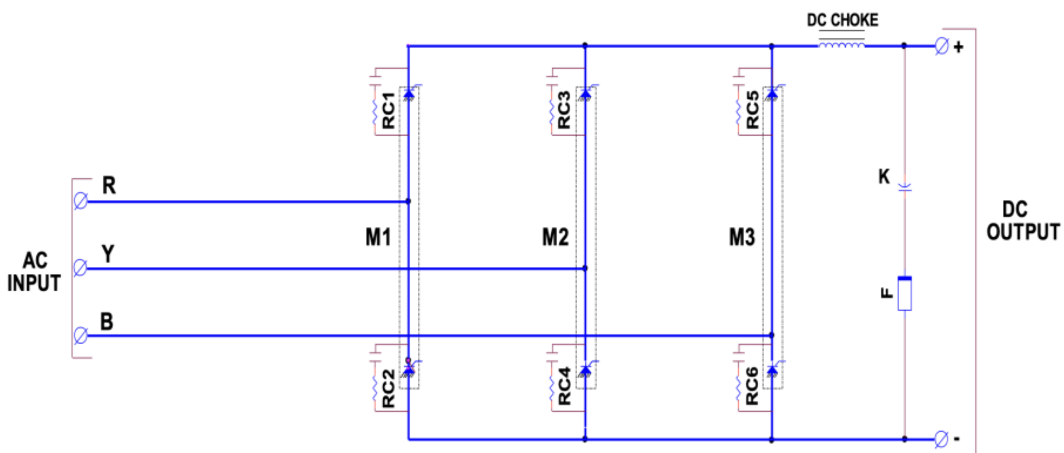


FIG.1.B

Fig 1.b Basic Thyristor converter bridge with DC filter

Fig 1.a shows a basic Thyristor bridge, and if the conversion losses are calculated, it consists of $P_W = (I_{rms}^2 \times r) + (V_o \times I_o)$ where I_{rms} is the rms current through Thyristor, r is its on-state resistance, V_o is its on-state voltage and I_o is average DC current through device.

So, the theoretical conversion efficiency is equivalent to just this loss, and for a low voltage, high-current converter, it might become 98.9%, while for a high voltage, it might become 99.5%. Thus, if just a converter bridge (module) is tested on the test bench, the losses can be calculated/ observed with accuracy. However, the fact is that it is not the accuracy of just bridge and all interconnections, busbar/cables, joints, DC filter chokes, fuses, etc. have to be taken into account while calculating the AC-DC conversion path losses which contribute to efficiency. Hence, at best, a practical efficiency value can be 98.5% to 98.8%.

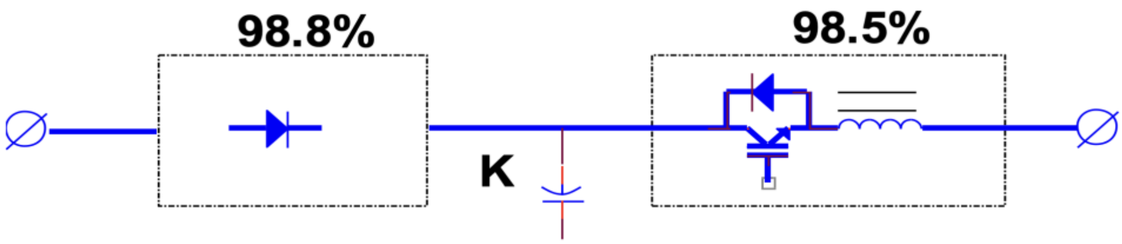


Fig 2a

On the contrary, in a Diode Rectifier-Buck Chopper Combination, as shown in Fig 2-a, assuming efficiencies of each chopper as 98.8% and 98.5%, respectively, overall calculated/theoretical efficiency can be around **98.8 x 98.5 = 97.3%**.

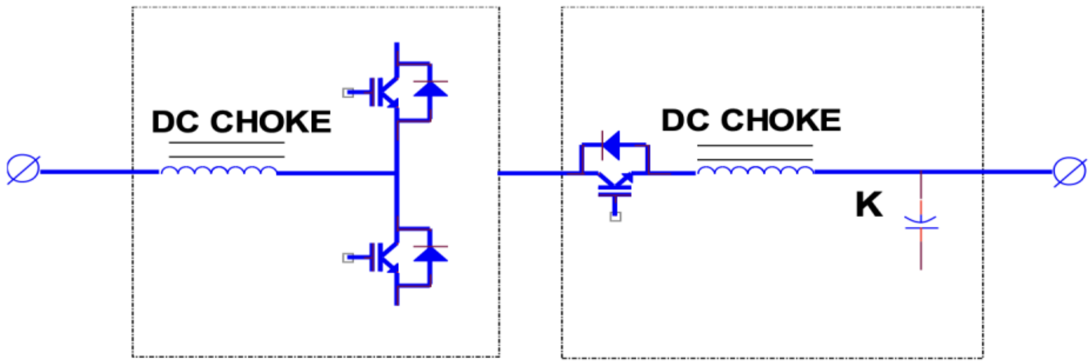


FIG.3

Similarly, in an IGBT/AFE converter also as shown in Fig 3, we get average efficiency of **~97.3%** only.

What is important to note here is that in switching converters, the peak efficiencies might be defined around 99.2% or so, which is under many specific conditions applicable to the test bench and maybe for a single module. But with many/ all modules interconnected with the working voltage and current of all such converters to their rated value, we actually end up getting values that are much lower than these values claimed. So, let us not get confused with these representations of data in the technical specifications of catalogues.

AC Ripple in DC Output vis-à-vis electrolyser behaviour

Any DC output has an AC component present called AC Ripple in a DC output. Depending upon the application, this ripple can cause different effects. For example, in an audio circuit, it might create noise in sound; in lithium-ion batteries, it might affect the life of the lithium-ion battery and so on. This AC component has two elements, namely:

- The frequency or frequency spectrum of this AC, and
- The amplitude i.e., peak-to-peak/ RMS content

Though not much is available on this but with some lab experiment results available, while the frequency of this AC ripple has no effect on electrolyser performance, its amplitude can affect GH2 production in 2 ways:

1. It can reduce H_2 production by up to 4% per kWh of electricity consumed
2. High AC ripple might affect the material of the electrolyser, i.e., its life

While it is possible to get, say, 1-2% RMS ripple in SCR-controlled converters, this ripple is generally much lower (<1% RMS) in both “Diode + Chopper” or “IGBT/AFE + Chopper” type of converters.

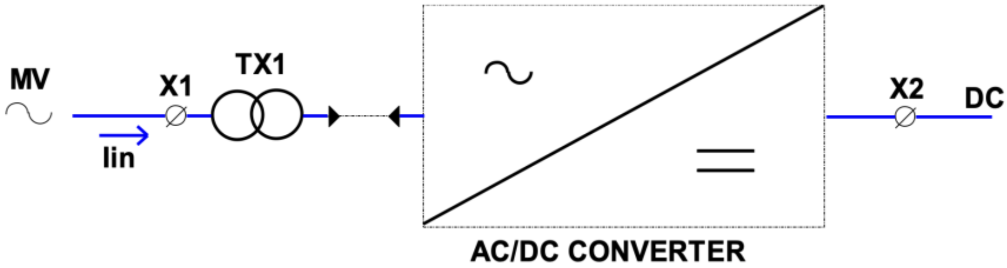
Though electrolyser manufacturers can best define this RMS AC ripple, it would be better to specify <1-1.5% RMS of maximum DC voltage.

Measuring overall AC to DC efficiency in MW Transformer-Rectifier

MW Transformer-Rectifier Effiency is one of the most crucial parameters to judge and then take forward for the needful assessment. It has already been argued that:

1. The efficiency of the transformer is only a calculated one based on ideal conditions and does not take into account all practical considerations that might occur at rated voltage-current, including the effect of voltage harmonics present at the (MV) AC supply present.

2. There could be different losses at connecting busbar/cables, joints, heatsinks, chokes, interconnections, fans plus other auxiliary, etc., which might account for end-to-end efficiency as measured between points X1 and X2 as shown in fig below:



3. Considering the above factors, a third major question arises about the accuracy of measurements, i.e., the AC V, I and Power Meter as well as the DC V & I meter. Generally speaking, for the measurement accuracy of, say, 1%, we may require meters with at least 0.5% accuracy, including that of current sensors.

4. Normally, such peak efficiency values as declared are being accepted. But this being a new subject in India, many questions are being raised about the accuracy of measurements at site to verify/ demonstrate and to the extent of putting penalty of deviations from declared efficiency values by even 0.1%. For this to be attained, the accuracy of measurements in AC and DC will have to be at 0.01% levels, which will make it too theoretical and not justifiable.

For such MW-level power, there has to be reasonability in inspecting the accuracy of measurements. Finally, the efficiency between points X1 to X2 has three major elements of efficiency:

(Efficiency of Transformer) x (Efficiency (Loss) in Tx to Converter Panel + auxiliary supply) x (Efficiency of AC-DC converter including DC filter)

So, taking very realistic figures, it could be ***98.5 x 99 x 98 = 95.5%*** in Thyristor converter.

But while measuring at the site, there can always be errors/ deviations depending upon grid quality and the accuracy of measurements.

Moreover, it is unclear in most project requirements as to 'who' will bear the onus of measuring the efficiency of the rectifier at site and 'how' will they measure it, given how sensitive the measuring instruments are to environmental and other factors such as grid quality.

While choosing the rectifier vendor, plant designers/ engineers must ask these questions to rectifier as well as the transformer manufacturers.

The same may be extrapolated for the other two technologies as well.

Air vs water-cooled rectifiers in Green Hydrogen production

A lot is being debated regarding water-cooled rectifiers due to the fact that both chilled water and DM plants are available at any GH2 plant. On the contrary, air-cooled conventional technology up to a single thyristor bridge of, say, 2200A to 2500A is regularly in use with high reliability. For very high ratings of a single bridge, there is no option but water-cooled unless we split the bridges to make them air-cooled.

Without going much into this, because a lot is being talked about by different Tx-Rect manufacturers, the following can be summarised:

1. Upto 2500A single Thyristor bridge, it is better to use air-cooled bridges because of their simple, reliable functioning.
2. A water-cooled system has pumps, flow meter protections, piping, and regular maintenance issues. And the such pumps also consumes continuous electrical power.
3. An air-cooled system will need an Air-inlet and Air-exhaust arrangement in a room.

Enclosures and degree of protection – Outdoor or indoor rectifiers in Green Hydrogen?

Unless special reasons are available, the issue of the degree of protection of an enclosure should be left to the manufacturers. It is generally found that IP55 is specified for Indoor/Outdoor use. But please remember that, unlike Europe/the US, developing nations like India have a lot of dust, which will choke the filter, resulting in the unit tripping or even failing at times. Under pressure, many times IP54/ IP55 enclosures are specified and supplied with such filters, which are thrown in the dustbin after a few months.

Further, the electrolyser terminals are invariably at the bottom/ lower side, and hence, the DC terminals requirement shall invariably be from the bottom side of the Tx-Rect. For large plants with a large number of Transformers and Rectifiers, since the transformers are invariably outdoor type, it may make sense to select Rectifiers that are outdoor container type, strategically located such that AC and DC costs are minimised and efficiencies are improved.

This may also give the following advantages:

(i) Flexibility in mechanical layout

(ii) Ease of maintenance

(iii) No need for air-conditioning

(iv) Good air inlet/ outlet possibility

(v) Stackable solution with future expansion

Please remember a container solution does not necessarily mean an ISO container; hence, ***costs do not add up***!

Conclusion

Though Transformer-Rectifier (TR) is not a new subject, but it has gained importance because it plays a crucial role in reliable and efficient Green Hydrogen production. Hence, this needs special attention getting out of the shadow of the Electrolyser.

The transformer is a very important portion of this TR, where MV transformer output is directly connected to the Rectifier circuit and its design and efficiency are carefully and practically considered. Input Line Current Harmonic generation requirement and PF need careful but practical consideration in the Indian Grid conditions. Similarly, the AC content in DC Output, i.e., Ripple, needs careful assessment, and Electrolyser manufacturers' intervention is necessary.

Despite the 3 main AC-DC conversion technologies being discussed, the most reliable, cost-effective, and time-tested one should be considered until other technologies are also proven. The whole plant's performance depends upon the reliability and availability of TR for its output, and hence, sometimes, performance should prevail over other factors.

Efficiency calculation considerations should be seen with a view of practical considerations instead of some text book equations only. The best example of this is Transformer, where only the calculated figures are considered without being probed further. Moreover, the plant engineers must be clear as to 'who' will bear the onus of measuring the efficiency of the rectifier at site and 'how' will they measure it, given how sensitive the measuring instruments are to environmental and other factors such as grid quality.

In terms of cooling, an Air-cooled enclosure solution is a better, more reliable, and time-tested solution for GH2 production applications. However, for special projects and requirements, cooling needs can be assessed accordingly.

By advancing our understanding of AC-DC converters, we pave the way for more effective and sustainable energy solutions, aligning with global efforts to combat climate change. We hope the discussions this post sparked will foster enhanced collaboration and innovation within the community, leading to the standardized solutions that the field so critically needs. Please share your comments and suggestions below or email us at comms@energiaa.in to know more.