GREEN HYDROGEN POWER DISTRIBUTION TOPOLOGIES

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Abstract - Green hydrogen power distribution topologies are presented for both low harmonic / high power factor rectifiers (small/medium scale) and thyristor-based rectifiers (large scale). Alternative distribution topologies are outlined for large thyristor-based projects with alkaline and polymer electrolyte membrane electrolysers. Optimisation is achieved by a combination of revised voltage level selections, incoming switchgear configurations, supplementary phase shifts between rectifier transformers, incoming three winding transformer phase shifts and application of synchronous condensers. The solutions are shown to be suitable for various operating and supply conditions supported by harmonic load flow simulation results. Significant harmonic reduction and power factor improvements are achieved to minimise/eliminate the need for further compensation equipment which otherwise would have been some of the most expensive equipment in the power distribution system. Furthermore, ride-through and plot space improvements are achieved. Generic distribution guidelines for small to mega scale projects are provided while considering redundancy options with an optimum design approach.

Index Terms — Power distribution, Rectifiers, Green Hydrogen, Electrolysers, Harmonics.

I. INTRODUCTION

Green hydrogen is defined as hydrogen produced by electrolysis (splitting water into hydrogen and oxygen) using renewable electricity. Associated application areas are described in [1]. Most suitable application areas (where direct electrification is not feasible) include crude oil refining, ammonia production, methanol production and steel manufacturing. Other applications include aviation, heavy duty trucking and marine shipping. Niche applications may include power generation and long duration energy storage. An overview of worldwide projects is provided in [2].

The input power to hydrogen facilities can act as energy storage by transforming excessive energy delivered by renewable sources to hydrogen when low electrical demands are present. Similarly, hydrogen storage can be converted back to electricity via fuel cells / generators fuelled by hydrogen during high demands for electricity. This can provide support to balance the intermittent nature of renewable energy with the demand profile of the power grids. This green hydrogen process energy storage approach has presently an inherently low efficiency but can provide longer term storage with surplus renewable power which may be considered where battery storage is not practical for balancing. Higher efficiency technologies are being developed but are not readily available today. Electrolyser systems can also support further ancillary services, e.g. support with frequency and voltage control, by utilising the rectifier and power factor control systems for load and reactive power control, which may improve business cases [3].

The cost of hydrogen production can be minimized by taking full advantage of electricity tariff schemes, (e.g. agile / real time pricing schemes) and maximizing production during attractive electricity price values. This may be implemented in conjunction with secondary storage schemes (e.g. air or hydro) [1]. Nevertheless, the variability of the specific project should be analysed, and an appropriate electrolyser technology and power distribution and conversion topology should be selected suitable for the specific project variability.

It is shown in [4] that the cost of power supply and electronics is a significant portion of the total installed cost of green hydrogen projects. An emphasis on the optimum associated electrical design and power distribution is therefore of great importance.

II. GREEN HYDROGEN TECHNOLOGY AND PROJECTS

A. Overview of Electrolyser Technologies

An overview of electrolysis technologies is provided in [5]. The main technologies are Alkaline Water Electrolysis (AWE), Polymer Electrolyte Membrane (PEM), Solid Oxide Electrolysis Cell (SOEC), Anion Exchange Membrane (AEM) and also newer technologies with higher claimed efficiencies not yet commercialized, e.g. Membraneless Water Electrolysis (MWE) [6]. In all cases electrolysers require DC current with the need of rectification where AC supplies are utilised.

B. Overview of Industry Project Ranges

Projects can generally be classified into the following:

- Small single unit projects (various electrolyser topologies)
- Large single array/unit projects (PEM/AWE) (e.g. 20 MW)
- ~50-100 MW scale projects with a combination of “smaller units”, e.g. in 5 MW groups
- Medium scale projects, typically 100-300 MW with integration of arrays / units
- Large projects > 300 MW
    - AWE e.g. ~ 2.2 GW for [7], typically with 20 MW units or 40 MW sections
    - PEM e.g. of 20 MW PEM array integration for a GW scale plant [8]

SOECs are expected to be used for efficiency improvements especially where there is an external source of heat / steam available [5]. Example application cases are illustrated in [9] for green hydrogen production and e-fuel production, with electrolyser loads of 700 MW and 900 MW respectively, where heat from existing process units is available (brown field). Similarly sustainable aviation fuels projects (green fields) are on the horizon where other heat/energy sources are available (e.g. sustainable biomass).

Offshore wind power may be considered for onshore electrolyser application (via HVDC link interconnection), e.g. as illustrated in [10]. Offshore electrolyser power systems (mainly associated with wind energy systems) are outside the scope of this paper, however some principles and findings may still be applicable.

C. Rectifier Topologies

An overview of rectifier topologies and associated diagrams is provided in [11], [12]. Electrolysers with higher DC voltages result in lower cost power electronic blocks due to lower current [4]. This is applicable to all topologies.

Modular Multicell Converter (MMC) systems are described in [11], also with options to eliminate the MV/LV conventional transformer. Transformers occupy significant space for electrolyser projects and hence further research has been conducted to propose optimal MMC solid state transformer topologies to reduce the transformer equivalent footprint [13]. Proven market solutions are however not yet available.

Modular stack rectifiers are, however, available on the market. Modular solutions (with SiC devices) are typically associated with smaller overall unit ratings with a combination of various stacks. The systems are associated with high efficiency and can benefit from utilizing a standard MV/LV transformer (potentially reducing lead time). The rectifier portion footprint/MW should however be evaluated. Cost, reliability and maintenance data should also be evaluated to confirm suitability for specific project needs.

Large scale power rectifiers such that those required to supply the electrolysers are widely used in the Medium Voltage (MV) Adjustable Speed Drive (ASD) field, the Current Source Inverter (CSI) thyristor technology Load Commutated Inverter (LCI) has initially dominated, however various Voltage Source Inverter (VSI) topologies emerged with an increase in power ratings. The VSI technology has improved power factor and lower harmonics compared to the LCI solution and is therefore mostly preferred above LCI technology, except for very large power ratings where the VSI technology has not yet been fully proven in the field. MMC topologies specifically gained in popularity not only for MV ASDs but also for STATCOM applications. Similarly, it is expected that alternative technologies including those listed in this section will gradually become the preferred choice above the thyristor technology, and increasingly so for higher power ratings as the technologies mature. In [4] active control IGBT technology is recommended for future (2030) with transformer rectifier power blocks which may include multiple parallel units. This is mainly due to the minimization / elimination of harmonic filter and power factor compensation equipment. However, if the technology has not sufficiently been proven in the field, the conventional thyristor technology needs to be applied and hence power distribution recommendations are also provided for the conventional thyristor technology that is still expected to be applied or large projects and/or for cost reasons. The costs, footprint and losses of the power factor and harmonic compensation equipment should always be evaluated in addition to the rectifier to determine if the rectifier topology and power distribution are indeed more cost effective.

In certain applications a DC bus system may have merit with DC-DC and DC-AC converters to connect electrolyser(s) & batteries and the incoming grid & motors respectively for example in [14]. Similarly, PVs can be connected to the electrolyser via a DC-DC converter [14].

Low harmonic, high power factor technologies available in the market today include IGBT active front end, IGBT active front end chopper, diode rectifier and IGBT chopper, thyristor rectifier with power factor correction/harmonic filters on LV, thyristor front end and DC/DC converter (IGBT chopper) including filters and SiC based converters.

III. DISTRIBUTION TOPOLOGIES - SMALL AND MEDIUM SCALE PROJECTS

Electrolyser manufacturers often select low harmonic high power factor technologies for smaller electrolysers units/arrays/clusters/sections e.g. 1 – 10 MW. Several of these can be utilised for a facility of approximately 100-200 MW. Normal power distribution principles are applicable for these projects since harmonic and power factor challenges are minimized. Key considerations should include the selection of the distribution voltage level, fault level and reliability configuration. Consideration examples for a 100 MW plant with 10 MW electrolyser feeders are outlined below. Each E block in the figures in this section represents a transformer rectifier combination of the low harmonic high power factor type as well as the electrolyser module/unit. Even though HF/PFC feeders are shown, these are often not required with low harmonic high power factor topologies. The Balance of Plant (BOP) / Auxiliary (AUX) loads are not shown.

A. High Reliability 33 kV – Dual/Two Winding Transformers

The configuration (Fig. 1) has the advantage that transformers operate in parallel (2N) and that there will be no interruption following the failure of a transformer. The double bus bar option also offers increased flexibility.

The main disadvantage is that the 150 MVA transformer capacity cannot be significantly increased (for larger plants) due to the parallel operation and associated fault level constraints (note that the tertiary winding shown is a stabilisation winding, however projects may also have, for example Dyn two winding transformers instead, depending on the grid interface and project requirements).

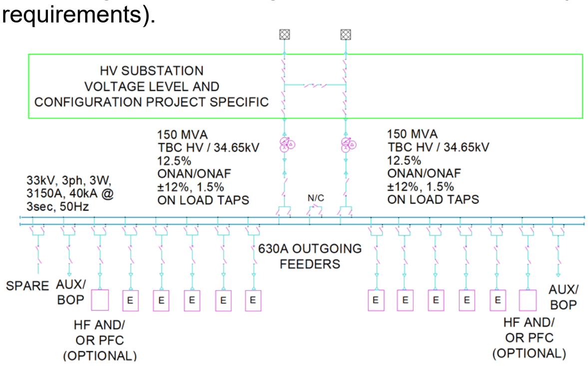


Fig. 1 High reliability – two winding transformers

B. 33 kV – Dual/Two Winding Transformers – Open Bus (Secondary Selective)

It has been shown in [15] that a N+1 or secondary selective configuration (single busbar system, open bus section with a lower switchgear fault rating) can result in switchgear capex savings of approximately 40%. The single line in principle remains the same but with a reduced fault level of 31.5 kA and a single busbar open tie breaker bus arrangement.

C. High Reliability 22 kV – Three Winding Transformers – Open Bus (Secondary Selective)

A further switchgear capex of 20% can be saved by reducing the voltage level to 22 kV [15]. Further improvements may be possible by utilizing 3 winding transformers as shown in Fig. 2. It is also possible with this configuration to increase the bus rating to 3150A and incoming transformer rating to 240/120/120 MVA and to increase the overall plant rating (e.g. to 140 MW).

It is recommended to keep the plant symmetrical, e.g. 120 MW plant instead of a 110 MW plant, will have 3 electrolyser feeders on each bus instead of 2/3. In cases where Harmonic Filter (HF) Power Factor Correction (PFC) is required, a symmetrical arrangement will allow for standardized sizes of the HF/PFC.

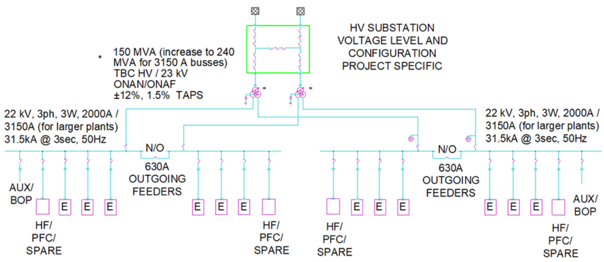


Fig. 2 Alternative voltage and distribution

D. Radial Systems

In projects where high reliability is not required, radial distribution schemes may be considered for further cost savings (similar to Fig. 2.) but without the 2nd transformer and associated bus ties.

E. Larger Projects

Section IIB indicated that there are application opportunities for significantly larger projects. While it is possible to multiply the arrangements of the ~100 MW plant to achieve a large-scale plant rating, larger transformer rectifier combinations should be more cost effective due to economy of scale and more compact overall plot plans. In the case of PEM, feeders of 20 MW are recommended for transformer rectifier combinations [8] and 40 MW feeders are shown in [7] for AWE. The next two sections describe optimization for these large-scale projects, all based on thyristor technology which is presently the only suitable solution for large scale. As previously described, the main disadvantage of thyristor technology is inherently low power factor and high harmonics which normally require cost intensive mitigation measures.

IV. DISTRIBUTION TOPOLOGIES - LARGE SCALE PEM

A typical SLD is illustrated in [8] for a gigawatt scale project. It is shown in [8] that harmonic filtering and supplementary power factor (also at 380 kV connection level) correction were required. A similar diagram, based on the same ratings, is shown in Fig. 3.

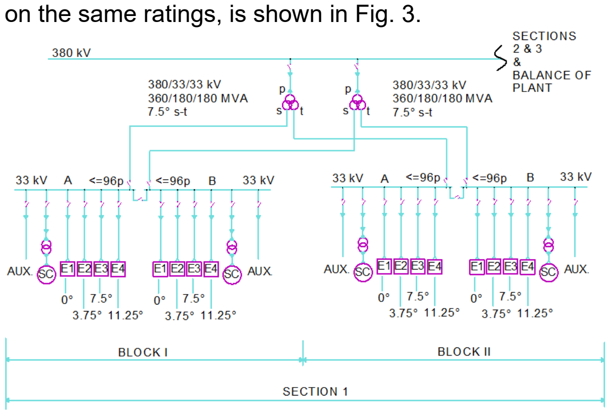


Fig. 3 PEM SLD with 24p 20 MW arrays (normally open tie breakers)

Each E block in Fig. 3 represents a typical electrolyser array shown in Fig. 4. Each array is a 24-pulse system with the input current harmonic spectrum shown in [8]. The fault level of the 380 kV system is selected as 43.2 kA to achieve approximately the same Voltage THD of 4.26%, as indicated in [8], at the 380 kV bus (without improvements).

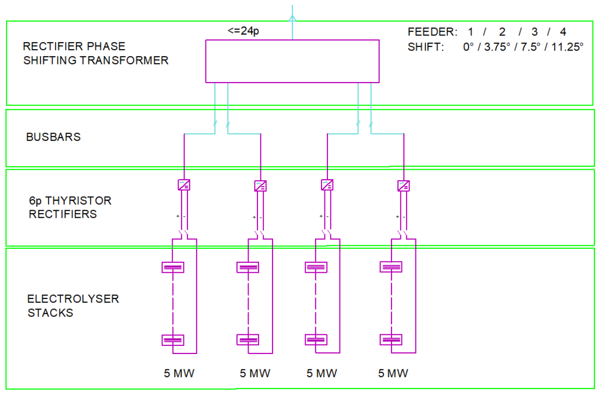


Fig. 4 PEM 20 MW array

Transformer phase shifting is not addressed in [8] apart from phase shifting on rectifier transformer windings to achieve the 24-pulse system. Phase shifting theory is described in [16]. Since 4 rectifier transformers are connected on bus, a theoretical 96 (24*4) pulse system can be achieved with further phase shifting. The phase shift angle (α) between transformers can be determined from [16], where p is the pulse number:

$$\alpha = 360°/p \qquad (1)$$

The required angle for phase shift between recti-formers is therefore 3.75°. Various rectifier transformer phase shift winding arrangements can be considered to achieve the supplementary phase shifting between feeders on a bus. The transformers are also equipped with tap changers to assist in regulating the power factor. An alternative arrangement for a similar effect is two 12 pulse phase shifted transformers with 2 feeders per electrolyser. A typical transformer phase shifting configuration for this alternative arrangement is shown in [16]. In this case the feeders should still have a phase shift of 3.75° implemented between transformers (8 x 12-pulse feeders per bus to obtain a 96 pulse system) as per (1).

An additional improvement can be obtained by introducing phase shifting between the secondary and tertiary of the main three winding transformers. In this case the pulse number of the individual arrays should be considered, i.e. 24. According to (1), the angle should be 7.5° for a 48-pulse effect since under worst-case unbalance conditions between feeders the spectrum on the bus may resemble significant content of the original 24-pulse waveforms.

The power factor can be improved and controlled to a limited extent by capacitors in combination with Thyristor Controlled Reactors (TCRs) and Thyristor Switched Capacitors (TSCs) [7]. STATCOMs are a recommended option to avoid additional thyristor interaction that needs to be considered [7]. Alternatively, Synchronous Condensers (SCs) may be considered which also has flexible controllability and in addition ride-through and fault level contribution advantages [17]. Synchronous condensers have been selected for this paper which also contributes to harmonic reduction due to a lower fault level. Resonance avoidance benefits may also be achieved [17]. The condensers have been selected to obtain a typical power factor of >=0.95 at 380 kV.

The impact of these improvement measures, based on harmonic load flow analysis with the parameters in the Appendix, is indicated in TABLE I.

TABLE I illustrates that the harmonic voltage distortion increases with 1 and 2 electrolyser feeders on each 33 kV bus out of operation. This is because the theoretical 96-pulse system is disturbed due to asymmetry. The distortion is, however, still within IEEE 519 380 kV levels, even during single ended conditions and well below the original levels, before improvement measures have been implemented. Bus voltage waveforms and spectrums before and after improvements are show in Fig. 5 and Fig. 6.

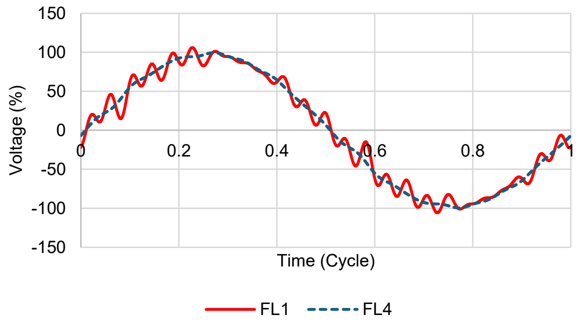
The simulations consider symmetrical operation within each array. Operation within each array should be kept symmetrical as far as possible (e.g. equal aging of stacks, the secondary and tertiary windings of the rectifier transformers should be operated with the entire array associated with the transformer connected). Arrays should therefore be controlled and switched as a unit. This should be practical considering there are 48 x 20 MW arrays in the overall system.

Actual fault levels on renewable power systems may however be significantly lower at 380 kV. The results indicate that the system is also suitable for a low fault level (TABLE I). Integrated harmonic studies should still be performed with the upstream HV equipment non-linear components which may include wind farms, solar farms, battery energy storage systems, STATCOMs etc.

In summary, the recommended measures eliminate or reduce the need for harmonic filters and supplementary power factor correction at the incoming 380 kV station. The addition of synchronous condensers may also support the overall system stability, especially with renewable grids which have no or limited synchronous generators.

TABLE I
PERFORMANCE - PEM

Description		Scenario	380 kV V THD (%)	33 kV V THD (%)
	IEEE 519	-	1.5	5
Full load	No improvement measures	FL1	4.27	12.77
	Phase shift between rectifier transformers added	FL2	1.32	3.89
	Phase shift between secondary and tertiary of 380/33/33 kV transformers added	FL3	0.36	2.31
	Synchronous condensers added	FL4	0.32	2.10
Part load / unbalanced (with all improve-ments)	A-E1, B-E1 out of service in every block	PL1	0.32	2.58
	A-E1, A-E2, B-E1, B-E2 out of service in every block	PL2	1.30	3.94
	Unbalanced loading between feeders (%) 10/50/70/80	PL3	0.31	1.66
Single ended (one transformer out of service, with improve-ments)	All rectifier transformers in service	SE1	0.29	3.77
	A-E1, B-E1 out of service in every block	SE2	0.29	3.85
	A-E1, A-E2, B-E1, B-E2 out of service in every block	SE3	1.18	6.07
	Low grid fault level (7 kA), A-E1, B-E1 out of service in every block	SE4	1.33	4.18



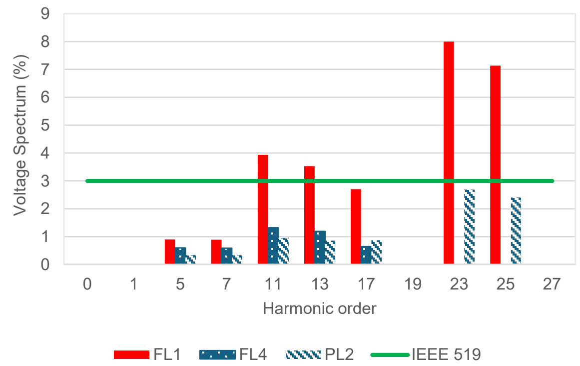


Fig. 5 Bus voltage waveforms and spectrum at 33 kV for selected scenarios

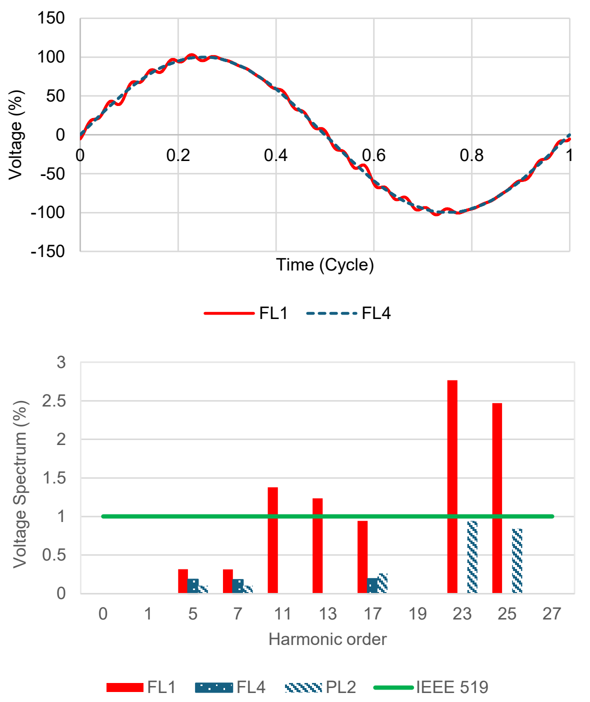


Fig. 6 Bus voltage waveforms and spectrum at 380 kV for selected scenarios

V. DISTRIBUTION TOPOLOGIES - LARGE SCALE AWE

Electrolyser distribution topologies, especially on a large scale are often not configured in redundant distribution configurations (i.e. not as shown in the previous section) since the failure of a transformer will not result in a total loss of load and for a renewable power source, full load can mostly not be utilized in any case.

A radial distribution scheme for 20MW alkaline electrolysers is shown in [7] for a total connected required electrolyser load of 2.2 GW. In [7], each feeder connects 2x20 MW (40 MW) electrolysers in a 12-pulse configuration represented by the E blocks in Fig. 7. Each E block consists of phase shifting transformer connected to a three winding transformer which connects 2x 6-pulse rectifiers connected to the electrolysers. This arrangement is depicted in a single line diagram format in [7]. The harmonic input current spectrum is shown in [7]. The spectrum of vendor B in [7] is considered for the evaluation in this paper. The spectrums have been phase shifted by means of the phase shifting transformers (impedance of the transformers have not been changed). It is shown with 3 feeders connected to a bus, a supplementary phase shift between feeders of 10° is applied [7]. This is in alignment with equation (1) for a 36-pulse system. Similarly, 2 feeders are connected to B2 busses with a 15° phase shift to achieve 24 pulses. The B2 bus arrangement is applied since 40 MW feeders are applied on busses, over 20x 33 kV busses to achieve 2.2 GW capacity, which means a standard 36-pulse symmetrical arrangement is not possible.

The harmonic load flow simulation results, without HF and PFC equipment improvements, are shown in TABLE II based on the parameters in the Appendix. All 5 cell rooms are included in the simulation and scenarios are equally applied to all cell rooms.

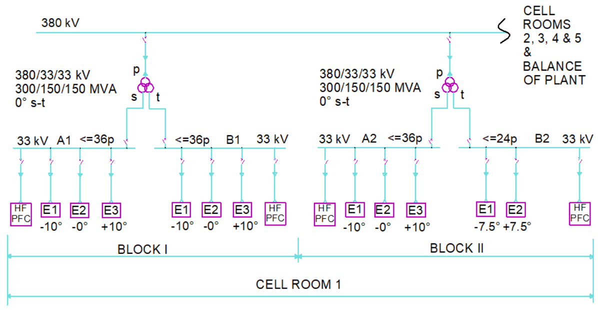


Fig. 7 AWE SLD – 33 kV configuration with 12-pulse 40 MW electrolyser feeders, based on [7]

Even with symmetrical operation on each bus, IEEE 519 values are not met. Unsymmetrical operation results in V THD % far above IEEE 519 figures as shown in TABLE II. This reaffirms the need for significant, complex filtering equipment in conjunction with PFC equipment (typically STATCOMs due to load variation requirements and many operating scenarios). Alternatives should therefore be explored to improve the power quality.

TABLE II
AWE HARMONIC RESULTS WITHOUT IMPROVEMENTS

Description		Scenario	V THD (%)				
			380 kV	33 kV			
			-	A1	B1	A2	B2
	IEEE 519	-	1.5	5	5	5	5
Full load	All rectifier transformers in service	FL	3.41	4.72	4.72	4.76	6.45
Part load / unbalanced	A1-E1, A2-E1 out of service in every cell room	PL	5.01	9.38	5.69	9.24	6.44

Improvement can be achieved with a higher bus pulse number and a higher voltage level by connecting more feeders on a bus. Higher voltage is also proposed in [4]. Higher voltage does have the disadvantage of higher cost switchgear; however, the number of 380 kV feeders and transformers may potentially be reduced by half. It is also more practical to manage the outgoing cabling at a higher voltage.

A theoretical 72- (12*6) and 60- (12*5) pulse system can respectively be achieved with phase shifting on bus A and B. The required phase shift angle is 5° and 6° between feeders for bus A and B respectively as per equation (1).

A further phase shift may be introduced on the 3 winding transformer similar to the discussion in the PEM section. According to equation (1), the phase shift angle should be 15° for a 24-pulse effect, since under worst-case unbalance conditions between feeders the spectrum on the bus may resemble significant content of the original 12-pulse waveforms. The proposed configuration is shown in Fig. 8. The transformer size is however large for 3 winding configurations and may be a challenge for manufacturers. It is alternatively possible to apply transformers in parallel with half the rating (2x300/150/150 MVA instead of 600/300/300 MVA with the same phase shift).

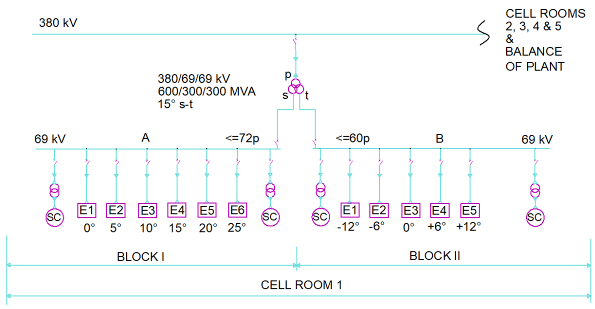


Fig. 8 AWE SLD – 69 kV alternative proposed topology with 12-pulse 40 MW electrolyser feeders

The results with the proposed configuration are shown in TABLE III. The IEEE 519 limits are met with all configurations shown. The table shows the worst case at 69 kV level. The V THD % level at 380 kV is however well within IEEE limits due to the compensation effect of the phase shifting on the 380/69 kV transformer for unsymmetrical operation. Bus voltage waveforms and spectrums before and after improvements are shown in Fig. 9 and Fig. 10.

TABLE III
AWE RESULTS - PROPOSED CONFIGURATION

Description		Scenario	V THD (%)		
			380 kV	69 kV	
			-	A	B
	IEEE 519	-	1.5	5	5
Full load	All rectifier transformers in service	FL2	0.46	0.69	0.62
Part load / unbalanced	A-E1, B-E1 out of service in every cell room	PL1	1.46	2.57	2.59
Part load / unbalanced	A-E1, A-E2, A-E3, B-E1, B-E2 out of service in every cell room	PL2	1.38	4.24	3.11

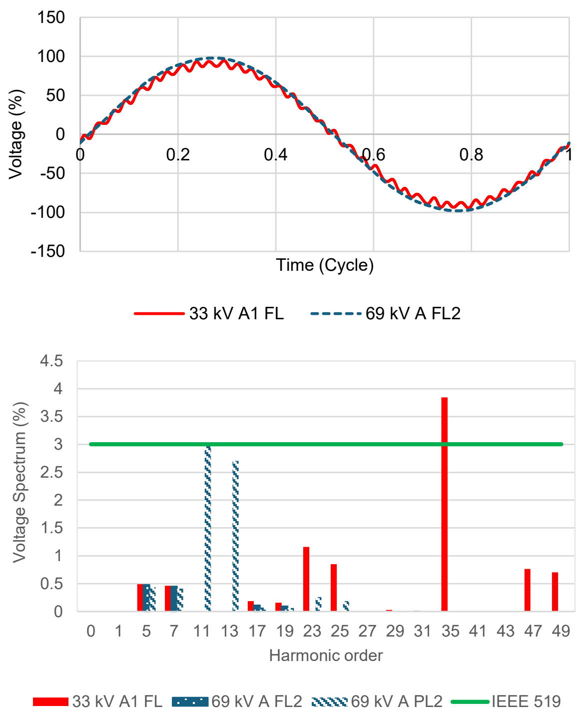


Fig. 9 Bus voltage waveforms and spectrum at 33 kV A1 (before) and 69 kV A (after improvements)

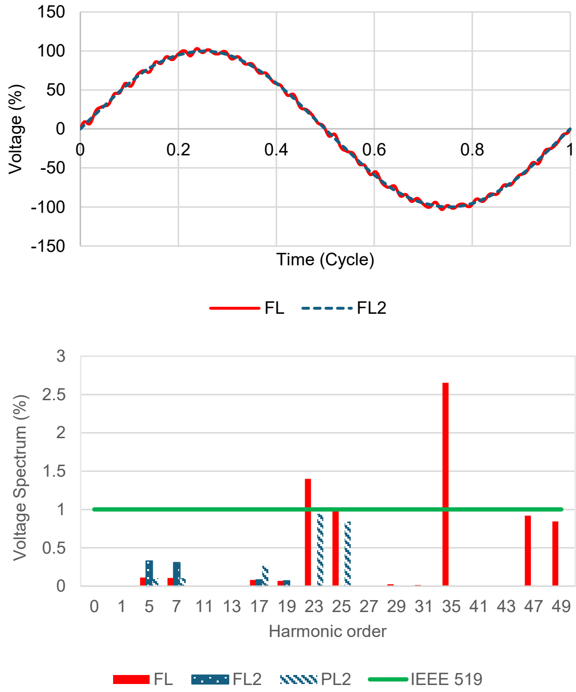


Fig. 10 Bus voltage waveforms and spectrum at 380 kV before (FL) and after improvements

Improved power distribution schemes with three winding transformer phase shifting, revised voltage levels and application of synchronous condensers are presented. Harmonic load flow results indicate that harmonics with thyristor rectifiers can be significantly reduced compared to previous configurations for AWE and PEM large scale projects. The power factor compensation needs can be met with synchronous condensers associated with stability and space saving advantages.

VI. CONCLUSIONS

A literature survey summarises green hydrogen application areas, electrolyser technologies and rectifier technologies. It is shown that many rectifier technologies are evolving or being developed to achieve low harmonics and high-power factor. Associated power distribution schemes are presented. Application needs for large projects however exist where only thyristor rectifier technology can presently be applied.

An opportunity may exist for transformer and switchgear manufacturers to improve solution offerings fit for purpose matching proposed configurations (e.g. 69 kV switchgear SF6 free switchgear with lower current ratings and transformers with the indicated phase shifting).

It is recommended to perform harmonic analysis and power distribution topology evaluation studies, similar to the studies presented in this paper, in feasibility or early FEED stages to influence the distribution topology which may be difficult to modify in later stages of the project.

Ultimately the overall electrical cost of large-scale electrolyser projects may significantly reduce since expensive harmonic filtering and power compensation equipment can be eliminated or significantly reduced.

VII. ACKNOWLEGEMENTS

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IX. APPENDIX

Key information for the simulation studies is summarised below:

PEM
380/33/33 kV transformers: 360/180/180 MVA Zp-s = 25% Zp-t =25% (360 MVA base)
Synchronous condensers: 25 MVA Xd=155%, Xd"=19%
Synchronous condenser transformers: 30 MVA Z=12.5%

AWE
Assumed fault level @380 kV: 10 kA
380/33/33 kV transformers: 300/150/150 MVA Zp-s = 25% Zp-t = 25% (300 MVA base)
380/69/69 kV transformers: 600/300/300MVA Zp-s = 25% Zp-t = 25% (600 MVA base) or 2x300/150/150 MVA Zp-s = 25% Zp-t = 25% (300 MVA base)
Synchronous condensers: 70 MVA Xd=155%, Xd"=19%
Synchronous condenser transformers: 75 MVA Z=12.5%

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