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TOWARDS OPTIMIZATION OF HARMONIC CURRENTS EMISSIONS IN PLANTS FOR PRODUCTION OF GREEN HYDROGEN

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Abstract

This paper aims to present one approach to minimise harmonic current emissions in electrolyser plants through optimal design and layout of electrolyser units and grid components under varying operating conditions. Harmonics pose significant challenges in power systems affecting the quality of supply, stability and efficiency. The methodology used involves modelling a green hydrogen plant and its harmonic-generating components using DigSILENT PowerFactory and conducting frequency domain simulations with the Harmonic Load Flow tool. Rectifiers in electrolyser units, key sources of harmonic emissions, are modelled as balanced harmonic current sources with its magnitudes and phase angles for each harmonic order. Harmonic voltages and currents at various busbars and lines are calculated using the respective harmonic impedances. Four primary scenarios were developed based on different electrolyser plant configurations, each with an 80 MW nominal capacity, comprising electrolyser units rated at either 1 MW or 5 MW. Located near to a 120 MW wind power plant, both plants are connected to the HV distribution network via a Point of Common Coupling (PCC). Extensive simulations identified an optimal configuration in each scenario with minimal harmonic current emissions. This study demonstrates that the harmonic emissions of electrolyser plants can be significantly reduced through optimal plant layout and operation of electrolysers, facilitating easier grid connection.

1 Introduction

In the next years the most countries globally must intensify their efforts towards reduction of greenhouse gas emissions. Green hydrogen, produced sustainably through water electrolysis using renewable energies, is anticipated to play a vital role in this transition towards clean energy. It is estimated that by 2030, a global installed capacity of approximately 350 GW for water electrolysers will be necessary [1].

The central electrotechnical component of the electrolyser unit is the rectifier, which provides the DC power for the electrolyser itself. Especially in large-scale electrolyser units with very high DC current levels rectifiers based on thyristors are often utilized, which in turn generate large values of harmonics to the supplied voltage and current.

Up to now, electrolysers with non-controllable power semiconductors such as thyristors have been very often used to produce green hydrogen mainly for cost reasons. Electrolyser units with these components have very high harmonic current emissions compared to modern, fast-switching power semiconductors such as IGBTs [2]. Therefore, optimising harmonic emissions in high-power electrolyser power plants equipped with thyristors is particularly important and can have a very positive effect both when connecting to the grid and during operation.

The starting point for this master thesis are results of a long time measurement from a solar PV power plant, which was build using a large number (> 50 units) of identical PV inverters. The measurement results recorded at the main LV busbar of this PV power plant showed lower harmonic current emissions compared to the expected values for different orders, due to negative superposition/ canceling of harmonic contributions from different units [3].

2. Methodology

Modelling of the Hydrogen Plant and its components which are responsible for generation of the harmonics, in DigSILENT PowerFactory and performing simulations in Frequency domain using the Harmonic Load Flow tool was the methodology for this investigation [4]. The rectifiers of the Electrolyser units, which seem to be the major source of Harmonic Current emissions are modelled as balanced Harmonic Current sources. For the fundamental frequency and selected harmonic orders, the current emissions are provided with their magnitudes and phase angles. The harmonic voltages at the different busbars are calculated with the harmonic impedances at the respective busbars.

Four main scenarios with respect to the used electrolyser units and its plant internal grid configuration were developed and furthermore a larger number of operational cases considering the electrical operational limits of available electrolysers were elaborated within a master thesis [5].

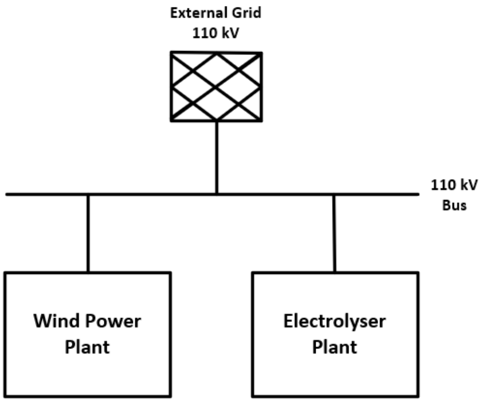

Fig. 1 Schematic overview of the Power Plant configuration

Fig. 1 provides a simplified schematic overview of the Power Plant configuration. For all four scenarios the Electrolyser plant has a rated capacity of 80 MW, consisting of different numbers of Electrolyser units rated either 1 MW or 5 MW. The Electrolyser plant is located within a short distance to a 120 MW wind power plant. Both plants (Electrolyser and Wind power plant) are connected to the public 110 kV transmission network via one joint grid connection point (PCC).

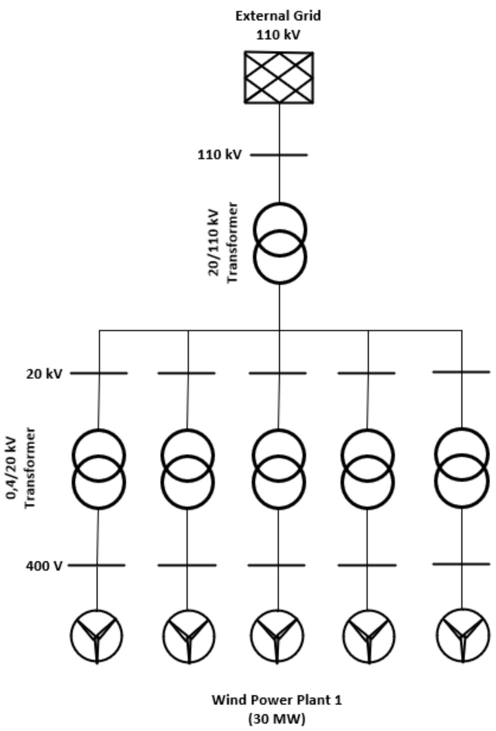

Fig. 2 Schematic overview of the Wind Power Plant (one segment)

The 120 MW wind power plant has a fixed configuration, consisting of 20 identical wind turbines with a rated capacity of 6 MW each. The entire wind power plant is grouped into four segments of 5 wind turbines (30 MW rated capacity). Each segment is connected to the 110 kV wind power plant busbar. One of these segments is depicted in Fig.2. The LV/MV transformers are part of each wind turbine, the 20 kV/110 kV transformer is responsible for connection of 5 wind turbines. The wind turbines, the different busbars and transformers are connected using underground cable lines, rated for their particular currents. All 20 wind turbines are based on the same 6 MW DFIG wind turbine generator (WTG) model from the DIgSILENT PowerFactory library. This WTG model considers also harmonic current emissions. The harmonic spectrum used for the simulations is shown in Fig.3 and remain consistent across all 20 wind turbines.

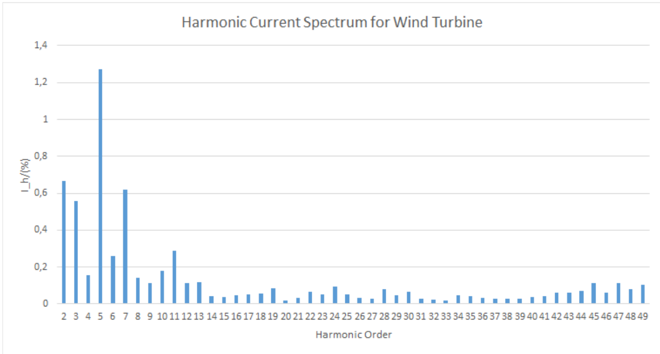

Fig. 3 Harmonic current spectrum of each wind turbine

Fig.4 displays one segment of the electrolyser power plant. As already mentioned, the electrolyser units have a rated capacity of either 1 MW or 5 MW at a voltage level of 6 kV. They are supplied from the upstream 20 kV and 110 kV distribution network using power transformers and short transmission lines. These network components have been selected and configured according to the rating of the electrical loads (electrolysers) using suitable models from the DIgSILENT PowerFactory library. Furthermore, it is essential for the analysis for the harmonic impact of an electrolyser power plant to use an appropriate model of the electrolyser unit itself, considering especially the AC-DC power conversion (the rectifier), the electrochemical processes and the auxiliaries. Although each of these components contributes to the overall harmonic emission in the electrolyser power plant, for the investigations it was assumed, that the power demand as well as the harmonic impact of the auxiliaries are negligible compared to the rectifier. Thereto the rectifier is the sole harmonic source within the electrolyser units.

Two different approaches / possibilities for modelling the harmonic behaviour of electrolyser units could be utilized:

a) Using harmonic current and voltage measurements of the planned electrolyser unit:

This should be the preferred method for modelling the electrolyser plant harmonic behaviour with respect to compliance assessment or optimisation of a specific electrolyser plant project. Mandatory precondition using this approach is, that the harmonic current / or voltage spectrum could be either derived from an existing test report (which are in principle available for all certified generation units) or have been measured at the AC terminals of the planned electrolyser with similar network parameters. In this case the measurements should cover all relevant operation conditions of the electrolyser unit including its auxiliaries.

b) Using the harmonic current spectrum from a generic rectifier (e.g. 12-pulse bridge rectifier):

This method is based on the utilisation of already existing harmonic current or voltage spectra of a rectifier from the model library of the simulation environment. This approach was used during this study and is appropriate for optimisation investigations of generic power plant configurations.

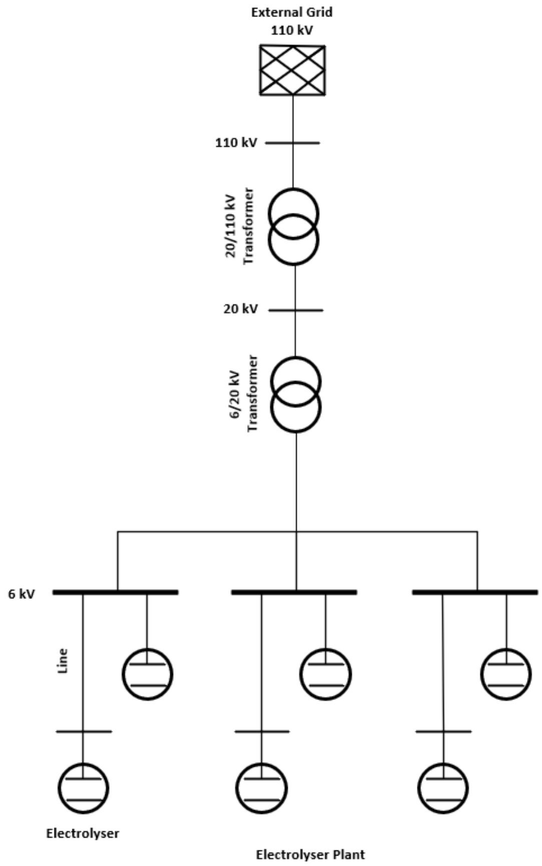

Fig. 4 Overview of the Electrolyser Power Plant (one segment)

As already mentioned, the second approach for modelling the current source of the electrolyser units had been selected using the harmonic current spectrum (magnitudes and phase angels) of a generic 12-pulse bridge rectifier taken from the DIgSILENT PowerFactory library (see Table 1).

Table 1 Harmonic current spectrum of the 12-pulse bridge rectifier

Harmonics order	I_h/I_1 p.u.	Φ_h-hϕ_1 degree
11	9.0909	180
13	7.6923	0
23	4.3478	180
25	4.0000	0
35	2.8571	180
37	2.7027	0
47	2.1277	180
49	2.0408	0

Each unit of the electrolyser plant comprises the identical harmonic current spectrum of this rectifier model. For validating the main findings of this study selected simulation runs were repeated with a generic 6-pulse bridge rectifier model from the library.

Four main simulation scenarios with different series and parallel connections of the electrolyser units have been developed in DIgSILENT PowerFactory to model the electrolyser plant, which has a rated capacity of 80 MW. Scenarios 1 and 2 involve 1 MW rated electrolysers, while Scenarios 3 and 4 comprise 5 MW electrolyser units. Thereto the plant could be composed either with a combination of medium sized 1 MW electrolysers in large numbers or with a smaller number of higher rated 5 MW electrolysers.

In order to adapt the green hydrogen production according to the variable power output of the 120 MW windfarm, four different loading conditions of the electrolyser plant (25%, 50%, 75% and 100%) have been considered. One very important assumption in this context is the fact, that the electrolyser units have a limited operational range between 50 % and 100 % of its rated capacity. Below 50 % the electrolyser units could be taken out of service and disconnected from the hydrogen plant.

Four each of the four different loading conditions there are multiple possibilities for operation. Furthermore, considering as well the four plant scenarios in total 65 simulations had been performed to analyse the optimal hydrogen plant configurations for minimisation of the harmonic current impact at relevant grid elements.

In Scenario 1 80 electrolysers with a total capacity of 80 MW are used, and each electrolyser unit is rated 1 MW. This setup is configured so that five electrolysers are connected in series. Eight of these 16 groups of 5 electrolysers are connected to one 110/20 kV transformer, and the other eight are associated with another 110/20 kV transformer as shown in Fig. 5.

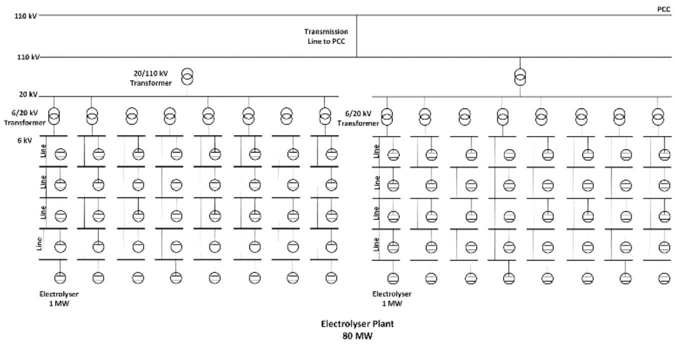

Fig. 5 Scenario 1 of the electrolyser plant with 80 units, divided in 16 groups of each five 1 MW electrolysers.

Scenario 2 also consists of 80 electrolysers same as in Scenario 1. The only difference here is the connection of the electrolysers. This setup here is configured in such a way that there are ten electrolysers connected in series. Each 4 of the total 8 groups are connected in parallel to one 110/20 kV transformer. This configuration has been shown in Fig 6.

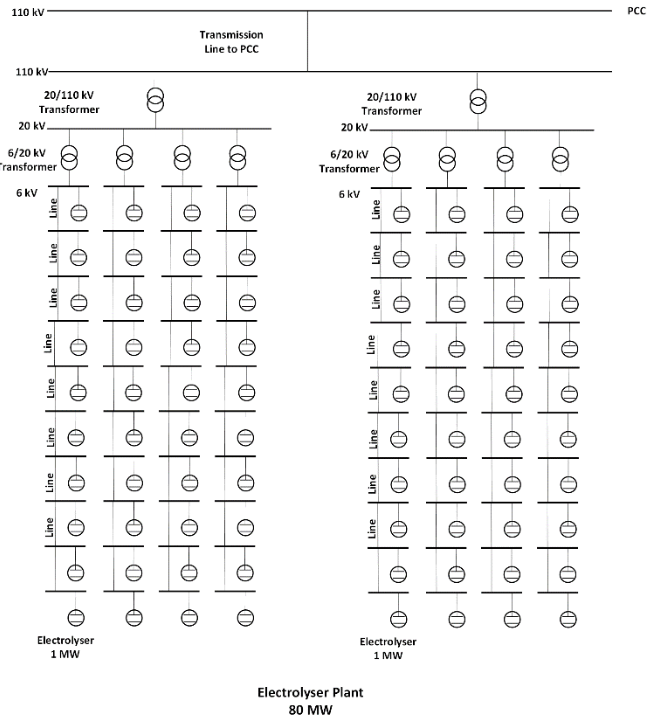

Fig. 6 Scenario 2 of the electrolyser plant with 80 units, divided in 8 groups of each ten 1 MW electrolysers.

In Scenario 3 16 electrolyser units each with a rated capacity of 5 MW are forming the hydrogen plant with a total capacity of 80 MW. This set up is configured in such a way that there are two electrolysers in series. Two groups of two units in series are connected to one 110/20 kV transformer and in total. four 110/20 kV transformers are required. The configuration of these electrolyser plant is shown in Fig. 7.

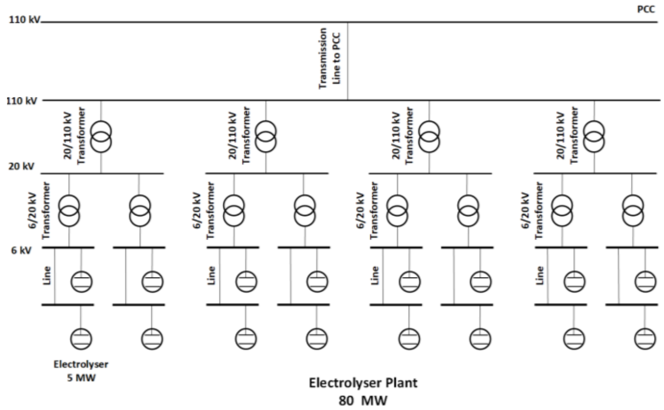

Fig. 7 Scenario 3 of the electrolyser plant with 16 units, divided in 4 groups of each four 5 MW electrolysers

Scenario 4 consists of 16 electrolysers same as in Scenario 3. The only difference here is the connection of these electrolysers. In this setup 8 electrolysers of 5 MW rated capacity are forming a group and connected in parallel to one 20/110 kV transformer. The other group of 8 units is connected is similarly to the HV grid as shown in Fig 8.

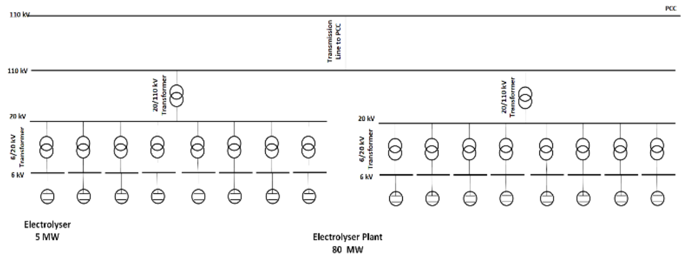

Fig. 8 Scenario 4 of the electrolyser plant with 16 units, divided in two groups of each eight 5 MW electrolysers.

3 Results

In the following section the achieved results using this methodology is described, displayed and discussed in detail.

Based on the operational capacity of the electrolyser plant a large number of operational Cases have been developed, which are shown in the following tables. Each loading capacity (e.g. 25%,50%,75%) has several cases where different electrolyser units could be turned on/off to fulfil the loading criteria. These cases consist of different combinations of electrolysers in working condition to meet the loading demands. (e.g. for 25% loading in 1 MW electrolyser case, 20 electrolyser in full load condition can fulfil the demand or 40 electrolysers on half load can meet the demand).

The following tables 2 to 5 compile the Voltage / Current THD (in %) at different grid components/locations of the hydrogen plant model for four selected loading conditions after performing harmonic load flow simulations.

Scenario 1:
For Scenario 1, 15 different Cases have been mentioned in Table 2. For 25 % loading the least Current THD is for Case 3 which is 6.78% at transmission line to PCC. For 50% loading Case 2 showed less current THD in system and same goes for 75 % loading capacity.

Table 2 Voltage / Current harmonic distortions in Scenario 1

Loading Capacity	Location	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
25%	Busbar PCC (V_{THD})	5.74	5.74	2.86	2.88	2.88	4.13
	Line PCC (I_{THD})	13.42	13.40	6.78	6.80	6.81	9.76
	Line El-Plant (I_{THD})	26.75	26.38	13.39	13.20	13.39	19.67
50%	Busbar PCC (V_{THD})	11.40	5.73	5.73	6.56	N.A.	N.A.
	Line PCC (I_{THD})	29.64	14.55	14.79	18.18	N.A.	N.A.
	Line El-Plant (I_{THD})	26.03	12.54	13.01	18.02	N.A.	N.A.
75%	Busbar PCC (V_{THD})	11.40	7.35	8.57	6.93	N.A.	N.A.
	Line PCC (I_{THD})	29.61	19.55	22.06	20.83	N.A.	N.A.
	Line El-Plant (I_{THD})	17.08	12.07	12.72	14.97	N.A.	N.A.
100%	Busbar PCC (V_{THD})	11.40	N.A.	N.A.	N.A.	N.A.	N.A.
	Line PCC (I_{THD})	26.07	N.A.	N.A.	N.A.	N.A.	N.A.
	Line El-Plant (I_{THD})	12.35	N.A.	N.A.	N.A.	N.A.	N.A.

Scenario 2:
For Scenario 2 there are in total 16 operation points / Cases with different loading conditions. For 25 % loading Case 3 showed promising THD % at PCC compared to the others. For loading capacity 75 % and 100 % Case 2 has recorded less current THD in the system.

Table 3 Voltage / Current harmonic distortions in Scenario 2

Loading Capacity	Location	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
25 %	Busbar PCC (V_{THD})	5.80	5.80	2.30	2.90	5.80	4.10
	Line PCC (I_{THD})	13.21	13.21	5.31	6.72	14.60	9.53
	Line El-Plant (I_{THD})	26.65	26.50	13.26	13.10	13.24	19.42
50%	Busbar PCC (V_{THD})	11.60	5.80	5.80	6.30	N.A.	N.A.
	Line PCC (I_{THD})	29.07	14.30	14.60	17.36	N.A.	N.A.
	Line El-Plant (I_{THD})	26.49	12.62	13.24	18.01	N.A.	N.A.
75%	Busbar PCC (V_{THD})	11.60	7.30	8.70	6.90	N.A.	N.A.
	Line PCC (I_{THD})	29.08	18.98	21.67	20.29	N.A.	N.A.
	Line El-Plant (I_{THD})	17.29	12.16	12.86	15.26	N.A.	N.A.
100%	Busbar PCC (V_{THD})	11.60	N.A.	N.A.	N.A.	N.A.	N.A.
	Line PCC (I_{THD})	25.84	N.A.	N.A.	N.A.	N.A.	N.A.
	Line El-Plant (I_{THD})	12.61	N.A.	N.A.	N.A.	N.A.	N.A.

Scenario 3:
Scenario 3 consists of 16 operational points for different loading capacities. Overall THD (%) for scenario 3 is less compared to all the other Scenarios. Particularly in 25 % loading capacity Case 3 and Case 4 have similar results and which is lesser than the other. Similarly, Case 2 and Case 3 have been recorded with less current THD for 50 % loading condition. Whereas in 75 % loading capacity only Case 2 has less current THD emissions in the system.

Table 4 Voltage / Current harmonic distortions in Scenario 3

Loading Capacity	Location	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
25 %	Busbar PCC (V_{THD})	3.80	3.80	1.90	1.90	2.00	1.90
	Line PCC (I_{THD})	5.21	5.21	2.69	2.69	2.97	2.90
	Line El-Plant (I_{THD})	3.71	3.71	1.86	1.86	2.18	2.15
50%	Busbar PCC (V_{THD})	7.60	3.80	3.80	4.50	5.90	N.A.
	Line PCC (I_{THD})	10.33	5.21	5.21	6.24	8.20	N.A.
	Line El-Plant (I_{THD})	7.42	3.71	3.71	4.54	5.95	N.A.
75%	Busbar PCC (V_{THD})	7.60	4.80	5.70	6.90	6.20	N.A.
	Line PCC (I_{THD})	10.33	8.10	7.77	9.48	9.20	N.A.
	Line El-Plant (I_{THD})	7.42	6.57	5.57	6.88	6.99	N.A.
100%	Busbar PCC (V_{THD})	7.60	N.A.	N.A.	N.A.	N.A.	N.A.
	Line PCC (I_{THD})	10.33	N.A.	N.A.	N.A.	N.A.	N.A.
	Line El-Plant (I_{THD})	7.42	N.A.	N.A.	N.A.	N.A.	N.A.

Scenario 4:
17 operational points have been defined for Scenario 4 in total. For 25 % loading capacity Case 4 has shown less current THD in the system. For 50 % loading capacity Case 2 has shown less current THD and 75 % loading capacity Case 3 has shown less current THD compared to the other.

Table 5 Voltage / Current harmonic distortions in Scenario 4

Loading Capacity	Location	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
25 %	Busbar PCC (V_{THD})	3.80	3.80	1.90	1.90	2.40	2.40
	Line PCC (I_{THD})	10.23	10.21	5.28	5.27	6.47	6.49
	Line El-Plant (I_{THD})	27.30	26.94	13.40	13.21	16.62	16.65
50%	Busbar PCC (V_{THD})	7.60	3.80	3.80	4.10	6.10	N.A.
	Line PCC (I_{THD})	22.53	11.07	11.26	12.96	18.07	N.A.
	Line El-Plant (I_{THD})	29.71	14.05	14.56	17.19	23.81	N.A.
75%	Busbar PCC (V_{THD})	7.10	4.70	4.90	7.10	6.40	7.60
	Line PCC (I_{THD})	21.69	17.39	15.23	21.06	20.30	22.59
	Line El-Plant (I_{THD})	17.08	15.25	12.27	16.32	16.49	17.49
100%	Busbar PCC (V_{THD})	7.60	N.A.	N.A.	N.A.	N.A.	N.A.
	Line PCC (I_{THD})	20.08	N.A.	N.A.	N.A.	N.A.	N.A.
	Line El-Plant (I_{THD})	12.72	N.A.	N.A.	N.A.	N.A.	N.A.

A comparison of the different scenarios and operational cases with respect to the four different loading capacities (25%, 50%, 75% and 100%) indicates, that cases with less harmonic currents occur when the required number of electrolyser units to meet the loading condition are operating at full load. This mode of operation results in partly shutdown or exclusion of electrolysers and their network infrastructure from the simulation, which seems to have a reducing impact on current harmonics emission.

For 25 % loading condition, in Scenario 1 the cases 2, 3 and 4 have 20 electrolyser units each working on full load, so only the network infrastructure of these electrolysers will impact harmonics emissions. The same situation was observed in Scenario 2, Scenario 3, and Scenario 4 for 25 % loading.

For 50% loading the results follow a similar trend as for the 25% loading cases. In Scenario 1, case 2 and 3 40 electrolysers have been working on full load where the other 40 have been out of the service with their entire infrastructure.

For the 75% loading condition it is also advised to operate the required number of electrolyser units on full load, because while operating all electrolysers on partial load it seems that they would emit more harmonics in the system than for the other modes of operation.

When operating the hydrogen plant at full load, all electrolyser units must run at their full capacity. Harmonic load flow analysis was conducted for all four scenarios at 100% loading. When operating the hydrogen plant at 100% the entire network infrastructure will be used, so only the effect of superposition principle has an impact on harmonic emissions. However, a small number of electrolysers with a larger rated capacity (Scenario 3 and 4) will require a different network infrastructure compared to Scenario 1 and 2, which will result in less harmonics at PCC.
The large number of simulations run for the four different scenarios and in total 65 operational cases using 12-pulse bridge rectifiers have clearly identified the configuration for each scenario with minimal harmonic current emissions on the transmission line to the PCC. This configuration seems to be also optimal using another rectifier technology with different harmonic current spectrum.

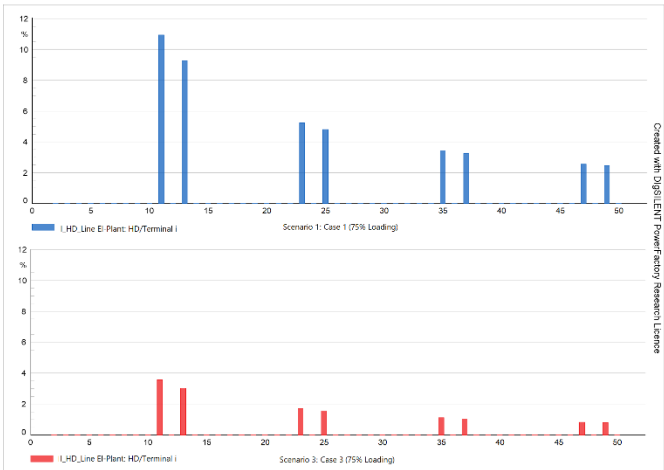

Fig. 9 Harmonic current spectra on the Line "El-Plant" for 75% loading in Scenario 1, Case 1 (blue) as well as in Scenario 3, Case 3 (red).

Fig. 9 presents the current harmonic spectra for two different simulation scenarios, both for 75% loading. The upper diagram shows the result for a hydrogen plant using 1 MW electrolysers and the lower for a plant configuration with 5 MW rated units. The used 12-pulse-bridge rectifier itself generates only harmonic currents with the orders ($n * 12 \pm 1$), i.e. 11, 13, 23, 25, 35, 37, 47 and 49. These harmonic currents are clearly visible in both diagrams, and with optimised hydrogen plant design (Scenario 3, Case 3) they could be reduced remarkably.

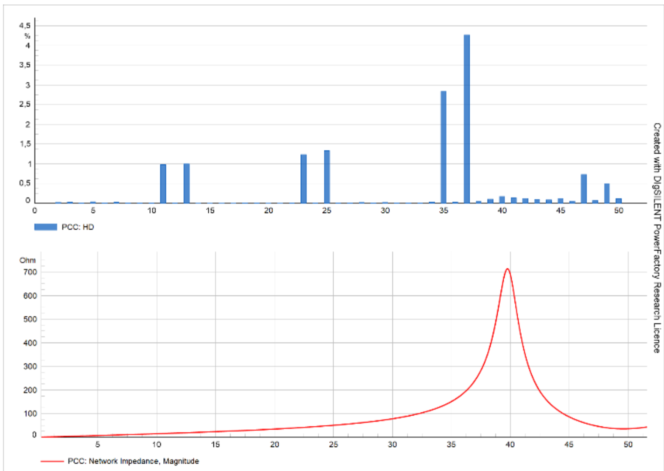

Fig.10 Harmonic voltage spectrum and network impedance for 75% loading at PCC for Scenario 3, Case 1

Although the harmonic current emission of electrolyser units using 12-pulse rectifiers are decreasing with higher orders (Fig. 9), the voltage harmonics at PCC are increasing because of the network impedance course at this network component, which acts as a large series resonance impedance around the 40th order (2.0 kHz), as can be seen in Fig. 10.

4 Conclusion

The large number of simulations run for the different scenarios and operational cases using 12-pulse bridge rectifiers have clearly identified the configuration of each scenario with minimal harmonic current emissions on the transmission lines to the PCC.
By analysing the results, it can be concluded that Scenario 3 has lowest harmonic current emissions for electrolyser plant in the system for all loading capacities.
This configuration seems to be also optimal using another rectifier technology with different harmonic current spectrum.

Furthermore, it can be stated that the network harmonic impedance depends strongly on layout of the electrolyser plant and it will have significant impact on voltage harmonics of the system. Lower harmonic currents may lead to higher harmonic voltages if the network impedances are high and vice versa.

This investigation demonstrated that the harmonic current emissions of Electrolyser plants could be strongly reduced using an optimal design, layout and modes of operation for the entire hydrogen plant including its electrolyser units and grid components. This may lead to better performance, less losses as well to easier connection to the public grid.

Further research topics seems reasonable by:

- Modification of semiconductor technology and type used in the rectifiers of the electrolyser units.
- Implementing measured current harmonic spectra of real electrolyser units.
- Improving the electrolyser model by adding its auxiliary equipment.
- Utilization of a dynamic instead of a static electrolyser model.

5 Acknowledgements

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