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Analysis of using MMC topologies for the direct integration of renewable generation with modular electrolyzers

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***Index Terms*—Modular Multilevel Converters (MMC), Renewable energy systems, Converter control, Power-to-X, Hydrogen, Simulation.**

***Abstract*—This paper analyzes the use of MMC topology for integrating directly renewable generation with modular electrolyzers in order to increase the efficiency, and to favor the use of additional energy storage and the increase of capacity factor. The study focuses on the performance of the MMC in different operational scenarios. The results demonstrate the proper behavior of the converter when the consumption of the electrolyzers is equal in each submodule of the MMC.**

I. Introduction

Hydrogen has been identified as a promising energy carrier for a low carbon future. It can be produced through various methods, among them, the electrolysis of water which consists of splitting water molecules into hydrogen and oxygen using an electrical current [1].

Almost 99% of the hydrogen currently produced is obtained through processes from natural gas, which result in large CO2 emissions, approximately 11 tons of CO2 per ton of hydrogen (grey hydrogen) [2]. Therefore, other types of hydrogen production are being investigated and implemented. Blue hydrogen uses carbon capture or compensation technologies in fossil fuel processes to minimize its emissions. Green hydrogen is obtained from renewable sources, with the most common method for its production being water electrolysis [3]. All government efforts are focused on green hydrogen, due to its low environmental impact and close relationship with renewable technologies. A clear example is the EU Hydrogen Strategy with an estimated budget of approximately 180-470 billion euros [4].

Currently, the production cost of grey hydrogen is around 0.8-1.6 €/kg, blue hydrogen ranges from 1.25-2.25 €/kg and green hydrogen is above 3 €/kg [2]. Thus, the current objective of green hydrogen is to reduce production costs to be economically competitive against other production methods.

To reduce the production cost of green hydrogen, it is necessary to decrease the cost of electrolyzers (the device to produce hydrogen from electricity) and power electronics, lower electricity prices, and increase the operating hours of the electrolyzer (hybridization of renewable energies or storage) and its efficiency [5].

Green hydrogen implies the continue searching of the optimal combination of renewable energies with electrolysers. The optimal conversion of renewable energies into hydrogen can be achieved, among others, by means of:

- Connection with the least number of pieces of equipment or interaction with the electric grid between the renewable energy source and the electrolyzer.
- Optimal dimensioning between the electrolyzer and the generation source.
- Production of hydrogen not only in areas with grid connection but isolated from the grid.
- Increase of the capacity factor (understood as the hydrogen produced annually) by means of using energy storage to optimize.
- Use of advanced power electronics topologies and control strategies in order to improve the performance and efficiency.

The paper is focused on the latter measure, analysing a promising topology of power electronics to integrate electrolyzers with renewable energies.

A commercial electrolyzer is usually connected to the grid by means of a three-phase diode rectifier and a

DC/DC converter, in order to control the input current provided to the system. The electrolyzer cells are conventionally placed in series/parallel association in order to reach the voltage in the range of 580V, although the use of a DC/DC converter could lead to the use of a lower voltage if necessary [6]. Nevertheless, the use of lower voltage to get high power implies higher current and, as a consequence, more power losses.

On the one hand, it is well known that the operation at partial load of electrolyzers lead to low efficiencies and more degradation of the materials. On the other hand, the malfunctioning of any cell would lead to stop the operation of the whole system. Thus, it is convenient to use a distribution of different modules of electrolyzer to overcome both drawbacks. One possibility is to connect to the mains through different DC/DC converters, operating at full power a certain number of them depending on the level of renewable power available. Another possibility, keeping the idea of modularity, is to take advantage of a global operation of the modules and to integrate the different modules in a modular multilevel converter (MMC). The MMC would substitute the diode rectifier plus the whole set of independent DC/DC converters taking advantage of the AC/DC conversion and the reduction of DC voltage in the internal submodules of the converter.

The objective of this paper is to develop and present a detailed model, as well as perform simulation and analysis of a novel green hydrogen generation system. The proposed approach involves the direct integration of renewable generation with modular electrolyzers, using MMC as the grid-side converter in the common topology of a full-converter wind turbine or a solar power plant, to generate hydrogen, inject power to the grid or both at the same time.

It is important to note that integrating this configuration into a wind turbine can be a complex process, due to the limited space available in the nacelle or tower for all the equipment required for a hydrogen generation system. Thus, the ideal option for connecting an electrolyzer to a wind farm or wind turbine is at the point of common coupling (PCC) with the grid. For this reason, the optimal solution for implementing this novel configuration would possibly be in a solar power plant, where the hydrogen generation system can be located on the ground with more available space.

The control used in the converter is the standard MMC grid following control. Voltage-oriented control (VOC) is employed, consisting of two regulation loops: one for the voltage of the DC bus and the other for the grid currents control. The control strategy aims to maintain a stable voltage in the DC bus at the reference value despite power fluctuations.

The circulating current control, voltage balancing algorithm of the submodule capacitors, and specific modulation technique of the MMC converter are also implemented. The simulation model does not consider the maximum power point control of the renewable generation or other associated controls. To simulate renewable power generation, a variable current source is used at the input of the MMC converter.

To achieve a modular distribution of the electrolyzers, they are connected to the capacitor of each submodule of the MMC converter, taking advantage of the reduced voltage level in the submodules.

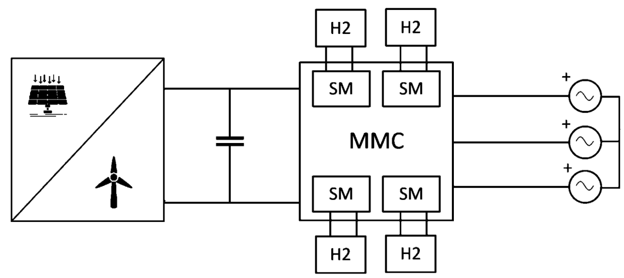

Fig. 1. Proposed green hydrogen generation system

The paper is organized as follows. Section II describes the topology of the MMC and the implemented control. Section III introduces the proposed configuration for green hydrogen generation and the simulated case studies. Finally, the performed simulations and the conclusions derived from them are presented.

II. MMC TOPOLOGY AND CONTROL

The topology of a three-phase MMC converter is presented in Figure 3. The MMC has N submodules (SMs) connected in series. The SMs form chains, and these chains configure the three branches of the converter. Each branch is formed by two arms, an upper arm and a lower arm, both of them composed of SMs and an arm inductor (L_{arm}).

TABLE I
SM STATES

SM State	S_1	S_2	V_{SM}
Inserted	1	0	V_c
Bypass	0	1	0

The SM has a half-bridge topology in parallel with a capacitor (C). The switches can be in two complementary states, when switch S1 is closed and S2 is open, the SM is in an insertion mode and the voltage across the SM terminals will be Vc. In the other case, where S1 is open and S2 is closed, the SM is in bypass and the voltage inserted by the SM is 0. The capacitor acts as a DC source, inserting its voltage when it is in insertion mode, and charging or discharging depending on the direction of the current [7].

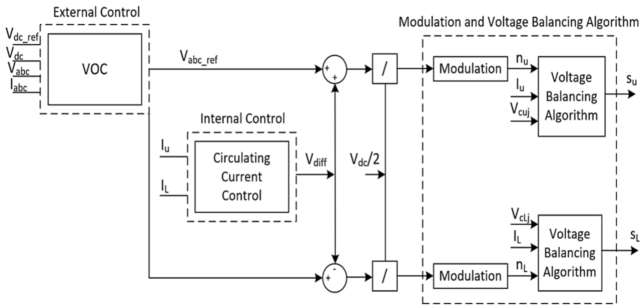

Fig. 2. MMC control scheme

The control of the modular multilevel converter has three stages:

1) An external control loop is used to regulate the voltage on the DC bus of the converter.
2) An internal control loop is implemented to limit the circulating current.
3) A control algorithm is implemented to balance the voltage of the capacitors in each submodule.

Figure 2 provides a basic diagram of the control stages of the MMC converter [8].

A. External Control

The external control, also known as VOC, is shown in Figure 4. The grid currents (I_{abc}) and voltages (V_{abc}) are measured and transformed into dq following the grid voltage phase. The DC bus voltage (V_{dc}) is also measured.

The idea is to control the DC bus voltage at the reference value (V_{dc_ref}) despite variations of the entering power. There are two regulation loops. The voltage control loop provides the I_{d_ref}, if the power generation increases, the DC bus voltage will increase and the voltage control loop must increase I_{d_ref} to provide more power to the grid and maintain V_{dc} to its reference value.

The current control loop regulate the grid currents at its reference values. I_{d_ref} is provided by the voltage control loop as seen before and I_{q_ref} is set depending on the required power factor. If the required power factor is 1, I_{q_ref} must be set to 0 [9].

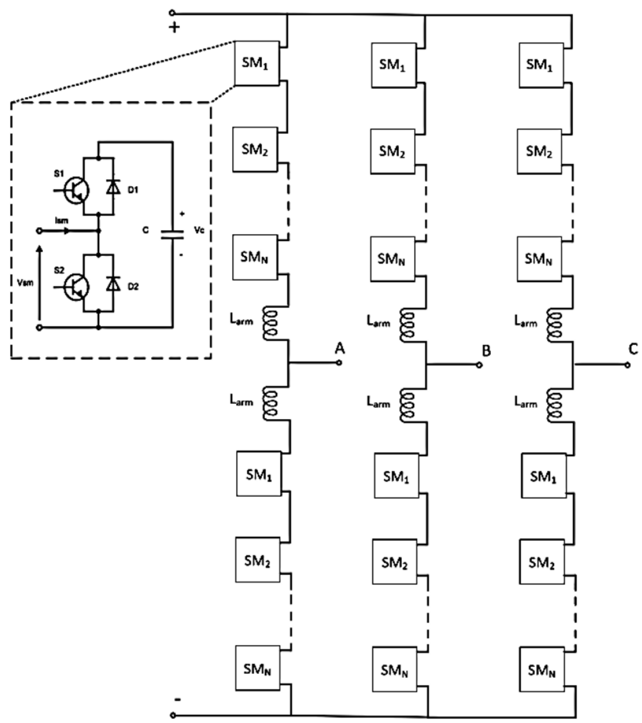

Fig. 3. Three-phase MMC converter

In the case of a solar power plant, the maximum power point tracking (MPPT) algorithm determines the reference voltage of the DC bus on external control. This implies that the system operates within a voltage range based on the MPPT by varying the voltage of the DC bus.

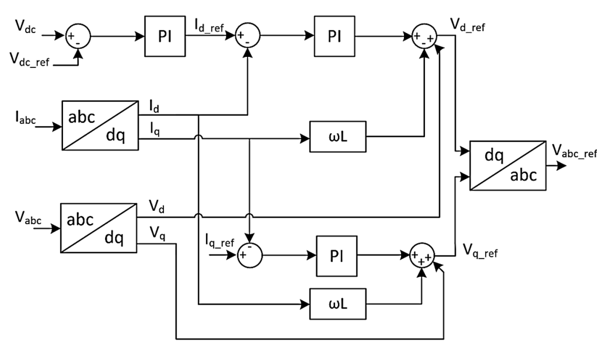

Fig. 4. External control (VOC)

B. Internal Control

The internal control, also known as circulating current control, aims to reduce the second order harmonic of the DC current that flows through the arms of the MMC. The circulating current introduce inefficiency and imbalance inside the converter so it must be eliminated or reduced in order to improve the performance of the MMC [10].

Part of the circulating current is reduced by the inductor of the arms, however, in order to avoid great inductances, the use of an internal control is required.

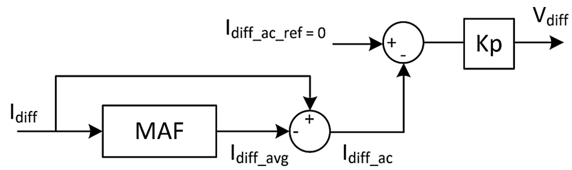

Fig. 5. Circulating current control

The control scheme used to reduce circulating current is shown in Figure 5. This control is applied individually to each branch of the converter.

It takes as input the circulating current measured in the branch (I_{diff}) and the reference AC circulating component current ($I_{diff\_ac\_ref}$). Firstly, a moving average filter (MAF) is used, operating at twice the grid nominal frequency, to eliminate the second order harmonic and obtain the average value of the circulating current. The second order component is obtained by subtracting the measured circulating current. Finally, the error respect to the reference value is obtained and controlled by a proportional type regulator. The result is the differential voltage (V_{diff}), which is added to the reference voltages obtained in the external control, as shown in Figure 2.

The simulation results of the circulating current control are shown in Figure 3. At t = 0.5 s, the control is activated, resulting in a significant reduction in the amplitude of the second-order harmonic.

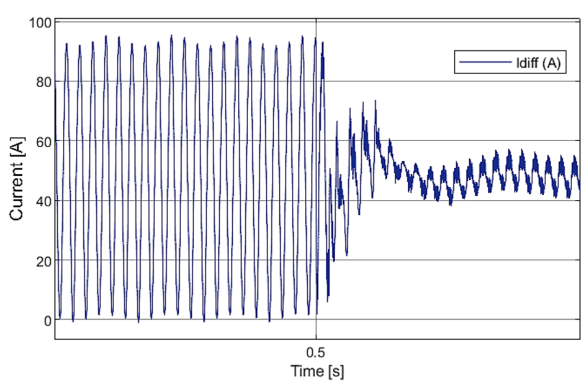

Fig. 6. Simulation of Circulating Current Control

C. Voltage Balancing Algorithm

The capacitors of the MMC experience an imbalance with respect to their average value. To solve this issue, a voltage control algorithm must be integrated. That implies continuously monitoring the capacitor voltage levels and, based on their levels and the direction of the current (to determine if the capacitor is charging or discharging), the algorithm prioritizes the insertion of one submodule over another in order to balance the capacitor voltages [11].

The algorithm is applied separately to the upper and lower arms. Firstly, the capacitor voltages are multiplied by the negative sign of the arm current direction. The negative sign is due to convention, where the positive current is taken as the one that charges the submodule capacitors. Then, two ordering stages are implemented. In the first stage, the capacitor voltages are sorted in descending order to obtain the priority index (j) of each submodule. In the second stage, the previous index is sorted in ascending order to determine the activation order of each submodule. With the activation order and the number of submodules to be inserted (n_{SM}), if the index is less than or equal to n_{SM}, the submodule will be active. The number of submodules required is determined by the modulation technique, which in this case is Phase-Shifted Pulse Width Modulation (PS-PWM) [12].

The algorithm also includes a feedback loop through a delay and gain based on previous switching states. This reduces the switchings frequency, as the change of activation states is restricted.

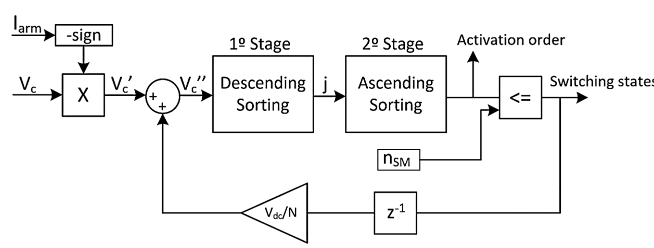

Fig. 7. Voltage Balancing Algorithm

The simulation results of the voltage balancing algorithm are shown in Figure 8. The top of the figure shows the voltages without the algorithm, and the bottom part shows the voltages with the algorithm activated. A remarkable improvement in capacitor voltage behavior is observed with the algorithm, as the voltages are balanced and the amplitude is reduced.

III. Modular Green Hydrogen Production using an MMC

This section presents a study of the performance of the previously described MMC converter, observing its response for a modular green hydrogen production.

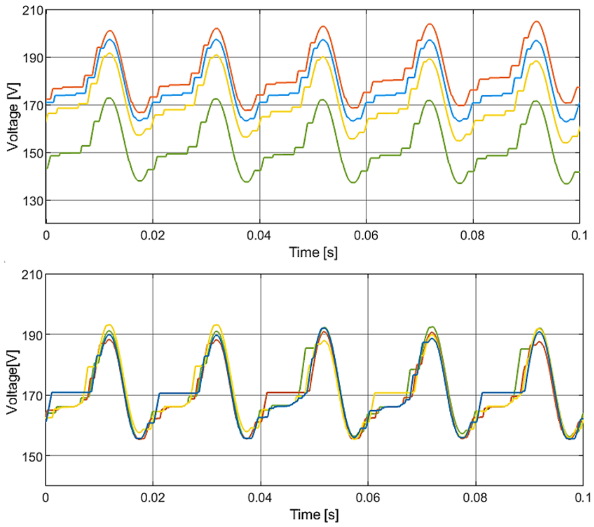

Fig. 8. Simulation of Voltage Balancing Algorithm

The modularity of the MMC converter enables to study different configurations with the aim of integrating renewable energy generation and electrolyzers within the same converter. It is possible to implement energy generation on the DC bus or within the submodules of the MMC.

Thus, the hybridization of the electrolyzers and generation technologies can be studied by including them in different submodules of the converter at the same time.

In this paper, as explained before, the configuration studied involves connecting the renewable generation to the DC bus of the MMC, while the electrolyzers are connected to each converter submodule. To ensure optimal performance, a DC/DC converter might be necessary to regulate the voltage level of the submodule and adjust it to the specific requirements of the electrolyzer for optimal production. Nevertheless, for the purpose of simplification in this study, which is focused on the MMC, the electrolyzers have been considered as current sources in consumption connected to the SMs.

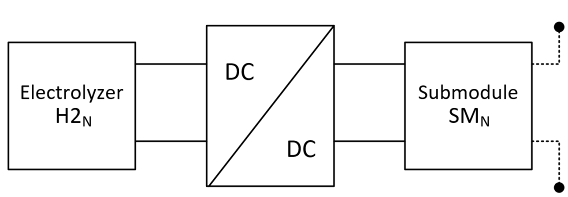

Fig. 9. Electrolyzer connection to SM

To prevent the total power of the electrolyzers from exceeding the power of the converter, the maximum power consumption of each electrolyzer is calculated using Equation 1, where (P_{MMC}) is the total power of the MMC, and (N_{SM}) is the total number of submodules of the converter.

$$P_{elect\_max} = \frac{P_{MMC}}{N_{SM}} \tag{1}$$

However, the sizing of the electrolyzer power relative to the converter power can be determined by various factors. In order to increase the electrolyzer's operating hours at maximum power, its power rating may be lower than the total power of the converter. This strategy allows to export excess power to the grid, when the electrolyzers are unable to consume it.

The performance of the MMC converter will be studied in 3 scenarios. The first scenario considers that the total power consumption of the electrolyzers is equal to the power generation. The second scenario assumes that the consumed power is half of the generated power. Finally, a third one takes into account the response of the converter when several electrolyzers are not operational.

The analysis has been carried out by means of simulations using Matlab/Simulink and the basic parameters of the MMC modeled are included in Table II. These parameters have been based on connecting the MMC converter to the DC bus of a 100 kW wind turbine.

TABLE II
MMC PARAMETERS

Parameter	Value	Units
P_{MMC}	100	kW
V_{dc}	700	Vdc
Capacitor voltage SM (V_c)	175	Vdc
Nº SMs per arm	4	
V_{ab}	400	Vac
Capacitance SM	10	mF

A. *First Simulation Scenario*

In the first scenario, the renewable generation power is fixed at 100 kW and each electrolyzer's power consumption is set at 4.16 kW, ensuring a balanced consumption generation and no power exchange with the grid. That allows visualization of the MMC converter's behavior during peak renewable generation and maximum electrolyzer consumption.

The results of the first simulation scenario are presented in Figure 10. The first graph shows the DC bus voltage of the converter, the second one shows the capacitor voltages of one arm, the third one shows the grid currents, and the bottom graph shows the power generation and consumption of the electrolyzers.

The graphs show that the DC bus voltage remains stable, the capacitor voltages are balanced with an acceptable ripple amplitude, the grid currents are approximately 0, and the power generated is equal to the power consumed by the electrolyzers.

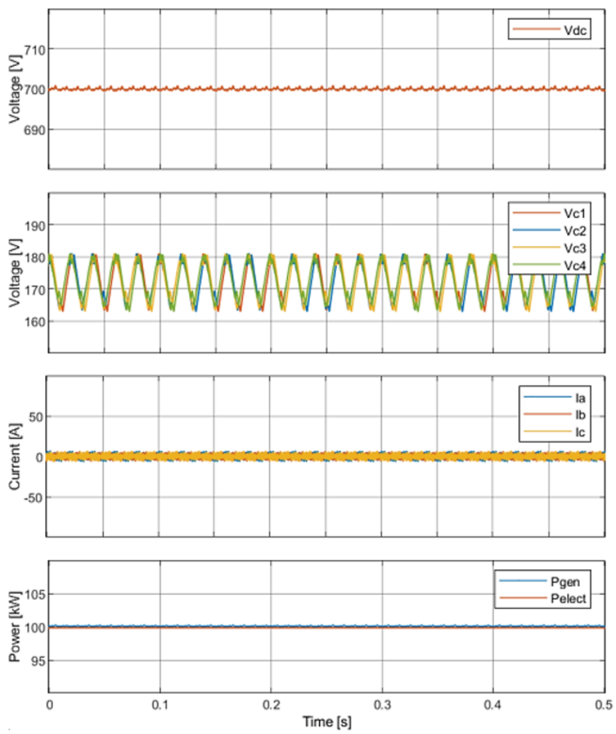

Fig. 10. Simulation of 1º Scenario

Therefore in this scenario where generation is maximum and stable, and consumption is equal to generation, a correct behavior of the MMC converter is observed.

B. Second Simulation Scenario

In the second scenario, the power of the electrolyzers is set to half of the maximum power of the generation (50 kW). As a result, there are times when the generation exceeds the consumption of the electrolyzers, and power is exported to the grid.

This simulation allows to observe the behavior of the MMC converter when the power sizing of the electrolyzers is lower than the maximum power of generation or when the electrolyzers operate in a different power range than their maximum. The simulation also includes a variation of the generation power to get how the exported power to the grid changes.

The results are presented in Figure 11. At the start of the simulation, the generated power is at its maximum, and the electrolyzer power is set to 50 kW. At t = 0.25 s, the generation power is ramped up to 75 kW, causing a decrease in the grid current and power exported.

The graphs show that the DC bus voltage remains stable and the control regulates it when there is a power fluctuation. The capacitor voltages are balanced with an acceptable amplitude and the grid currents vary with respect to the change in generation power generation.

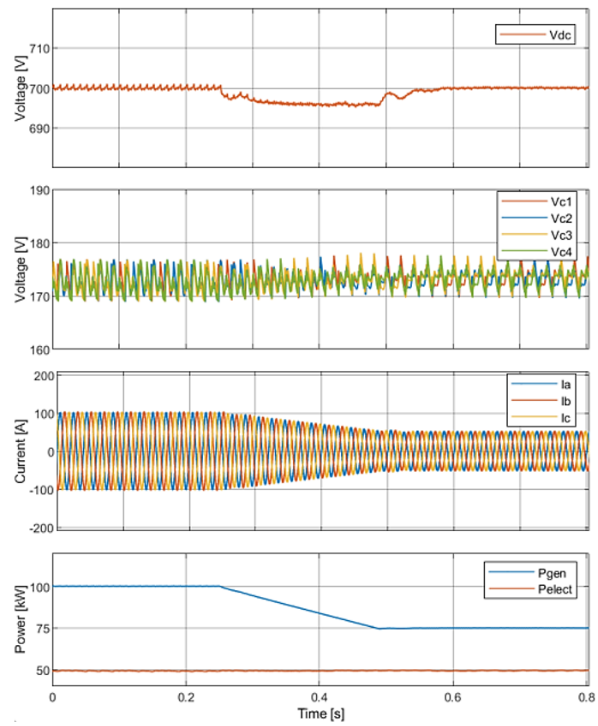

Fig. 11. Simulation of 2º Scenario

In this scenario where the generation power varies and the consumption is half of the generation power, a correct performance of the converter is observed.

C. Third Simulation Scenario

In this last scenario, the power generation is set to 100 kW, and the power of each electrolyzer is set to 4.16 kW. Unlike the previous scenarios, in this simulation, one electrolyzer from each phase of the converter is not operational, resulting in an imbalance inside the converter.

This simulation allows to observe the behavior of the MMC converter when the power of the electrolyzer is not equal in each SM or when an electrolyzer operation fails.

The simulation results are presented in Figure 12. The graphs show how the DC bus voltage oscillates due to the unbalanced voltage across the capacitors of the SMs. The capacitor in which the electrolyzer is not operational presents an overvoltage compared to the others. The voltage balancing algorithm is unable to control it due to the required inserted modules at each instant. This issue also generates unbalanced currents in the grid and fluctuating generation and consumption power.

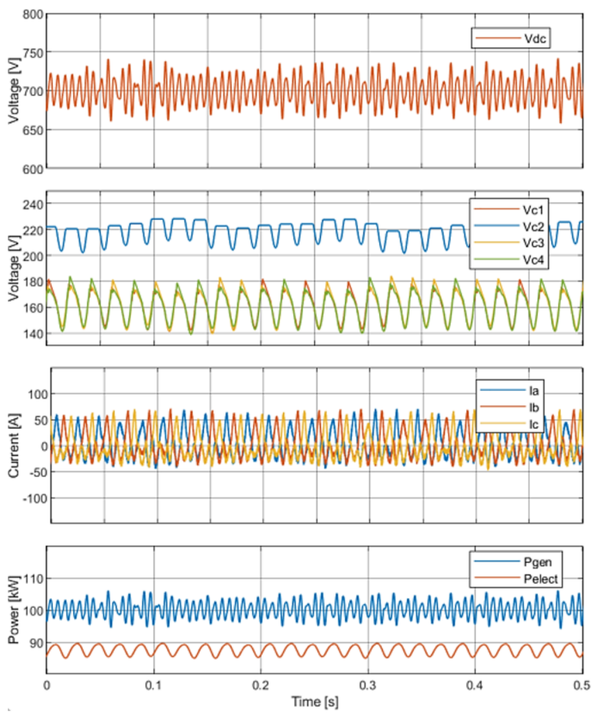

Fig. 12. Simulation of 3º Scenario

In this scenario, where an electrolyzer is not operational in each phase of the converter, the performance of the system is not acceptable due to the imbalance of the SMs in the MMC.

IV. Conclusion

This paper presents a novel approach to integrating renewable energy sources with modular electrolyzers using an MMC topology. The proposed configuration integrates renewable generation at the DC bus of the MMC, with each of the SMs connected to an electrolyzer and the MMC connected also to the grid.

The use of the MMC converter, particularly in this specific configuration, enables the implementation of a modular distribution of electrolyzers, eliminating the need for a single high power electrolyzer, increasing the reliability of the system. Additionally, this approach allows for the reduction or elimination of grid filters due to the capability of the MMC to decrease harmonic distortion and improve power quality compared to other power converter topologies. Furthermore, the MMC facilitates the increase of DC bus voltage levels and the use of different voltage levels in the SMs. The presented simulation results demonstrate the effective performance of the MMC converter connecting electrolyzers to the SMs.

Additionally, the converter shows good performance when the generation power varies and can export power to the grid when the electrolyzers cannot consume all the generated power. The results also demonstrate the importance of maintaining equal consumption among all electrolyzers to prevent imbalances in the MMC and ensure optimal system performance.

The addition of energy storage systems, able to compensate consumption and generation power, would provide additional advantages to the system reducing the interaction with the electric grid or even permitting the isolated operation of the system. Additionally, this topology introduces the possibility to integrate the renewable generation sources not only at the DC bus of the MMC but in the SMs, as in the case of PV-solar modules, maintaining the electrolyzers connected to the same DC bus through different DC/DC converters.

These studies and conclusions demonstrate the high potential of the MMC converter for both grid connected and off-grid hydrogen production from renewable energy sources, offering promising possibilities for future research and development.

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