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Protection of MVDC grids for the production of green hydrogen

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Abstract. Green hydrogen production from renewable energy sources has a big potential to reduce energy dependence on fossil fuel, contributing to the global goal set by the international community of net zero emissions by 2050.

Electrolyzers are connected to grid with power stages that can be designed as active devices with high control capability and a remarkably fast operation. Nevertheless, in the present, they must overcome some challenges in order to ensure a reliable operation. This paper addresses the concept of protection of DC grids with electrolyzers fed from renewable energy sources. The topologies of the grid are discussed as well as protection features and fault clearing strategies. A new dynamic model for multi megawatt PEM electrolyzer is introduced. Finally, a case study with a PEM electrolyzer in a MVDC system is included.

Key words. Direct Current, Electrolyzer, Hydrogen, Grid, Protection.

1. Introduction

Hydrogen can play a key role for reducing the challenges of renewable energy sources (RES) integration, such as uncertainty and availability [1]. The hydrogen strategy of the European Union, adopted in 2020, examines the potential for renewable hydrogen to assist in the cost-effective decarbonisation of the EU [2]. It aims to make renewable hydrogen a viable solution by proposing the installation of at least 40 GW of electrolyzers by 2030 in the EU. Therefore, this incipient industry is expected to gain volume in the medium term [3], however, nowadays there are just a few manufacturers [4], [5].

An electrolyzer operates decomposing the water molecule into hydrogen and oxygen using the energy provided by direct current electricity applied to a pair of electrodes (anode and cathode) separated by an electrolyte. There are three main technologies depending on the temperature of operation, as shown in Fig. 1:

- Low temperature: Alkaline and Polymer electrolyzers.
- High temperature: Solid Oxide electrolyzers.

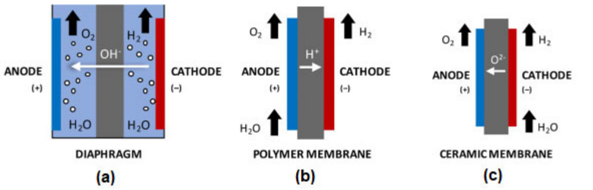

Fig. 1. Electrolyzer technologies [6]. a) Alkaline, b) PEM, c) Solid oxide.

Most conventional electrolyzers make use of power stages based on Line Commutated Converter (LCC) technology, which has a number of limitations, such as low power quality, reduced controllability, low power density, as well as high harmonic content in the supply voltage and current, which reduces their efficiency and useful life [7],[8]. These aspects result in a suboptimal performance and a negative impact on the grid connection, which results in an increased cost per kg of produced hydrogen.

On the other hand, Voltage Source Converter (VSC) based power stages present a much more flexible technology. It brings advantages such as the ability to improve power quality and increase the power density, efficiency and controllability of the electrolyzer [7], [8].

From the point of view of the power system, an electrolyzer is a mere power load [9]. However, one of the fundamental aspects to be considered in the integration of electrolyzers into the grid and their coordination with other equipment is fault response. One of the trends observed in the state of the art is to integrate electrolyzers through direct current (DC) grids [10]. These grids are subject to faults just like AC networks, since pole-to-ground or pole-to-pole faults can occur. Under such conditions, the voltage drops sharply and the current rises rapidly to very high values that can damage the power stages of the electrolyzers. If the fault is not cleared quickly enough, the power stages must self-disconnect in order to protect themselves. Therefore, it is necessary to have very fast and reliable protection systems that are able to prevent component damage [11]. On this way, faults must be detected, located and cleared in a very small time range, which according to the literature is estimated to be in the order of 10 ms [12]. DC protection systems have to ensure safety and minimize the impact of faults and component stress. To this end, they must meet the following requirements [13]: accuracy, speed, sensitivity, selectivity and reliability.

This paper analyses the protection of electrolyzers connected to DC grids. This way, the different feasible topologies are considered as well as their specificities regarding the protection system. Thereafter, the protection of one specific MVDC grid with electrolyzers and RES is addressed.

2. Protection of MVDC grids

This paper just considers electrolyzers connected to DC grids and other possible applications are neglected. This way, depending mainly on the rated power, electrolyzers can be connected to medium voltage DC systems (MVDC) [14],[15] or high voltage DC systems (HVDC) [16]. HVDC systems are a mature technology that has a place in today's power system, due to technical and economical superiority for certain applications, such as bulk transmission systems over long distances, undersea connections and integration of large-scale remote RES [17].

MVDC systems cover the step within HVDC and low voltage DC (LVDC) systems. Moreover, they provide added values for AC distribution, including power flow controllability, operation, power quality and power management facilities. Nowadays, MVDC systems are mainly employed in motor drive systems such as marine applications and aircrafts, and to an extent with RES. Nevertheless, up to the present, there are just a few MVDC projects connected to the power system, which are mostly located in China. For instance, the ±27 kV ANGLE-DC project (UK) [18], the ±10 kV three-terminal Jiangdong MVDC Project [19], Zhuhai Tangjia Bay Project [20], ±10 kV three-terminal Zhangbei and AC/DC distribution grid project [21] and the ± 20 kV four-terminal MVDC project in Suzhou [22].

The number of MVDC systems is foreseen to increase over the next years due to the rising number of DC loads and RES, which are overall DC sources. This way, MVDC systems have been proposed to transfer renewable power to DC loads, including storage systems and power-to-gas (P2G), where hydrogen is obtained from an electrolysis process. In consequence, hydrogen is expected to be a major application of MVDC grids.

MVDC systems can be considered as a small scale HVDC system [23], with lower voltage level and shorter transmission lines. Nevertheless, comparing with conventional AC grids, DC grids stand for active systems, with different characteristics that will contribute to a more efficient use of existing infrastructures. In brief, the operation in steady state and fault management will be the main differences.

Fault management in AC systems consists mainly in supporting grid protection or maintaining the operation by supporting the grid. In case of MVDC faults, the goal is to isolate the affected system and keep the operation of the healthy system. The consequences are dependent on the particular fault case scenario.

A. Fault management strategy

Fault management strategies for DC distribution grids can be classified according to the employed interrupting devices:

- AC circuit breaker. AC circuit breaker (ACCB) based protection strategy employs the converter AC side ACCBs to isolate DC faults. This is a low cost practical solution. Nevertheless, it lacks selectivity as it entails the interruption of the entire DC grid. This strategy has been applied in Suzhou [22] and ANGLE-DC projects [18].
- Converters with fault blocking capability. This strategy employs converter topologies with capability to isolate faults. One major drawback is the higher complexity and expense that includes the initial investment as well as the losses in the useful life. This strategy has been selected in the Zhangbei Project, with double clamp modular multilevel converters [21].
- DC circuit breaker: DC circuit breakers (DCCBs) are employed to isolate the faulted part of the system. This is a selective strategy with the required fast response. Nevertheless, in order to achieve a widespread use of DCCBs, the manufacturing industry should be developed and the cost reduced. This strategy has been employed in the Tangjia Bay project [21].

B. Protection

At present, the protection of MVDC systems is still at a developing stage, as there are still no standards or regulations. The protection of the DC system mainly depends on the selected fault clearing strategy, the protection devices and the fault detection algorithms.

Regarding the configuration of the protection system, there are some additional issues, comparing with AC grids that must be addressed [23]:

- The setting of control mode of the converters must be considered. The leading converter sets the control mode and the underling converters have to comply with the variations. This way, any change in the operating control mode of the leading converter must spread through the converters line.
- Galvanic isolation between DC grids. Protection with clear fault indications demands galvanic isolation between DC grids. In point-to-point DC links, the transformers located at the AC side of the converters, provide galvanic isolation. Nevertheless, this solution is not valid for DC grids and a proper converter type must be considered.
- Converters can be used to isolate circuits avoiding the use of DCCBs, as aforementioned. Nevertheless, for the appropriate protection of feeders in DC grids, DCCBs are required.

C. *Fault detection algorithms*

From the point of view of fault response, protection algorithms that are responsible for locating and detecting fault conditions, are classified into local measurement-based or communication-based algorithms. Algorithms based on local measurements are very fast, but lack selectivity and are sensitive to misdetection of external faults [24], [25]. They can be based on overcurrent [26] and undervoltage [27] principles, which use current and voltage magnitudes, respectively, as well as rate of change of current (ROCOC) [28] and rate of change of voltage (ROCOV) [29].

Communication-based algorithms use the exchange of data information between both ends of the protection zone [30]. They are inherently selective [31], but depend on the communication channel. The communication time delay may render the protection system unable to meet the rate requirement [32], even when using optical fibre [33].

Consequently, the communication delay is the most limiting parameter for these algorithms [34]. Hence, they are mostly used as back-up protection systems [35], when transmission distances are relatively short [33] or to protect against high impedance fault conditions when speed requirements are not so critical.

3. MVDC grid topologies

The feasible MVDC system topologies are foreseen to be point-to-point links with two substations at first and later on, presumably, multiterminal configurations with three or more VSC based substations. The last one is highly suitable for the integration of RES and DC loads into the grid [23][36].
The practical multiterminal topologies are hereinafter presented:

- Radial Topology: there is a single path for connecting the existing AC grid with the MVDC system, as shown in Fig. 2. The MVDC system can comprise RES, storage systems, DC loads as well as AC loads. This topology is rather simple, reduces distribution losses and easily enables different voltage levels. The main limitation is that in case of failure, service is interrupted downstream the faulted point.
  The unidirectional power flow facilitates the operation of the protection system. In this regard, overcurrent based algorithms are a good option.
- Ring Topology: there are two or more paths between the AC grid and MVDC system, Fig. 3. This topology requires high speed DC switches located at both ends of each DC bus to isolate faults. In case of failure, just the faulted line is isolated while the remaining systems keep on operating. Ring topology is fully dependant on the AC grid, as any failure will result in the loss of the MVDC system. More reliable than radial topology but the protection system is more demanding.
- Mesh Topology: there are two or more AC grids connected to the MVDC system, which is interconnected by several paths, Fig. 4. This way, the redundancy results in a higher reliability. Moreover, in case of failure, the mesh topology just isolates the faulted DC bus.
  Besides, meshed topologies are the most challenging ones for a selective operation of the protection system. In MVDC meshed systems communication-based algorithms can improve the selectivity, considering that the length of MVDC lines will not commonly cause large time delays.

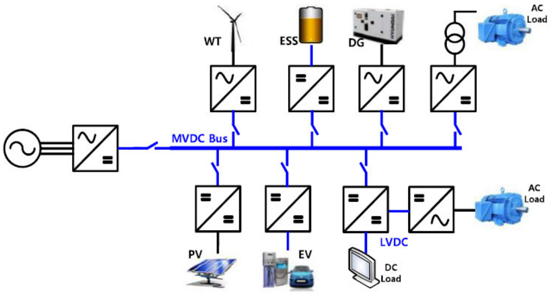

Fig. 2. MVDC Radial Topology [36].

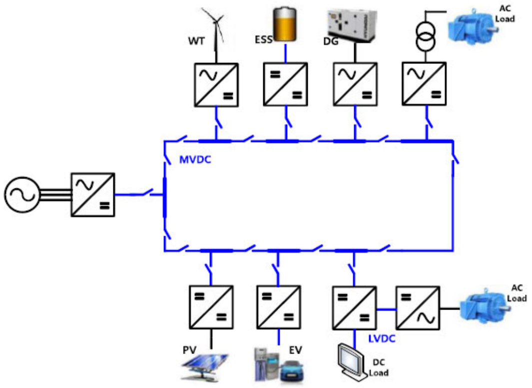

Fig. 3. MVDC Ring Topology [36].

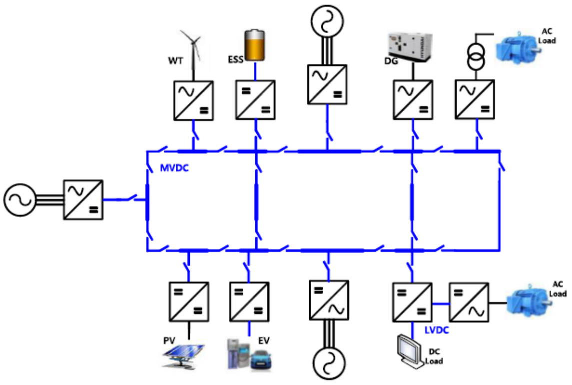

Fig. 4. MVDC Mesh Topology [36].

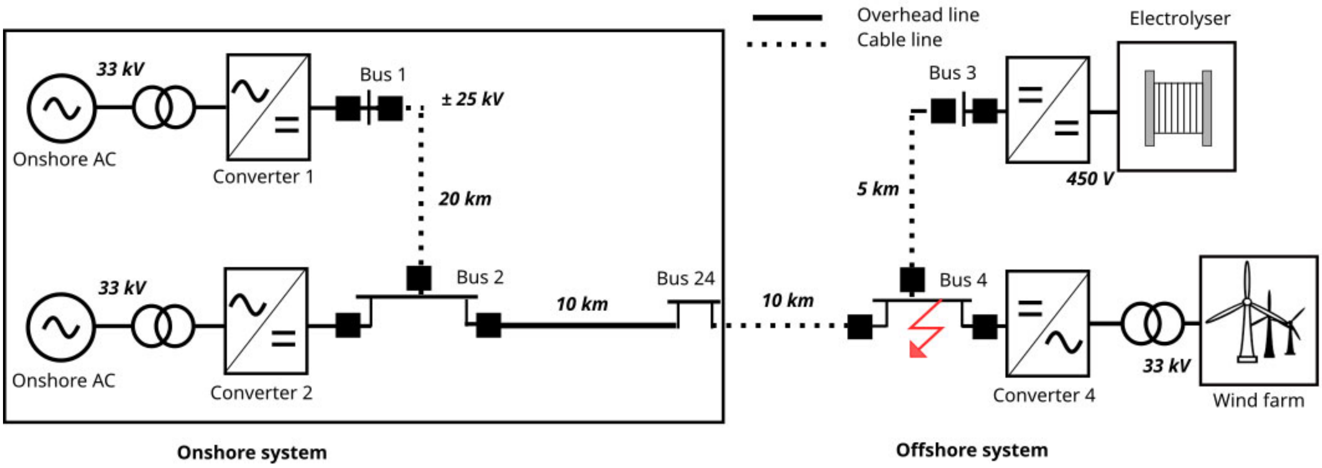

Fig. 5. Radial MVDC system.

4. Case study

The performance of one MVDC system with RES and an electrolyzers is studied with PSCAD/EMTDC software. Fig. 5 shows the MTDC system under analysis, which is a symmetric monopole composed of three MMC half-bridge converters and one DC-DC converter. Converters 1 and 2 are connected with AC grids, converter 4 is a 500 MW offshore wind power plant and converter 3 is a 1 MW electrolyzer. All AC voltages are 33 kV, the voltage of the MVDC system is ± 25 kV and at the electrolyzer is 450 Vdc. This way, the electrolyzer is connected to grid with a power electronic interface. This converter must provide the required DC power to the electrolyzer stack, thus, it must perform a voltage step-down. Moreover, galvanic isolation is required for protecting the electrolyzer from stray currents. Additionally, the power conversion should not present an adverse impact on the grid, according to grid codes [37].

Regarding fault management strategies, employing AC CBs for clearing DC side faults requires large operation times and lacks selectivity. Besides, the critical point in this study case is that the electrolyzer won´t be properly protected, as it has no AC CB. Fault blocking capability converters are overly complex and costly. Finally, the selected strategy is the based on employing DCCBs, which is the most feasible one for the considered study case.

The protection algorithm is based on simple undervoltage and overcurrent algorithms. Moreover, converter valves are protected against overcurrent with a maximum IGBT’s current limit of 2 p.u. Each pole of every DC link includes a mechanical DCCB, which is represented by a black square in Fig. 5. This constitutes a selective scheme, where in case of fault just the affected part is disconnected by the corresponding DCCBs.

A. Dynamic model of the PEM electrolyzer

The dynamic model of a single cell PEM electrolyzer [38] is shown in Fig. 6. The RC branch emulates the losses in the anode and represents the transient operation of the anode reaction while R_{int} is the membrane resistor. The open cell voltage V_{oc} is a DC voltage which represents the reversible voltage that must be overcome in order to lead to the chemical reaction of water splitting into oxygen and hydrogen.

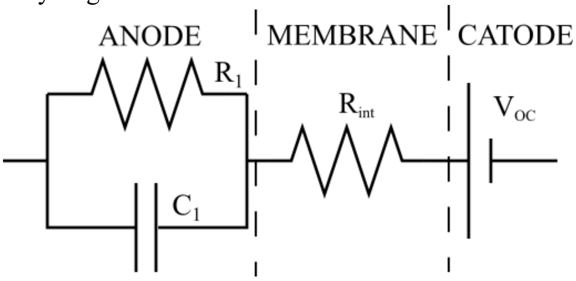

Fig. 6. Dynamic model of a single cell PEM electrolyzer.

The model used in this paper is based on the laboratory characterization of a commercial single cell PEM electrolyzer. The parameters of the cell equivalent circuit have been obtained by adjusting the model response to the measured values of the cell current (orange) and voltage (green) to a step change in the cell current, as shown in Fig. 7.

Fig. 7. Commercial PEM electrolyzer measured response to a current step test.

In order to increase the voltage rating of the electrolyzer used in the MVDC model, the individual cells are connected in series forming one string and several strings are connected in parallel to increase the current rating. Fig. 8 introduces the dynamic model of an equivalent electrolyzer, where N_s is the number of individual cells in series and N_p is the number of strings in parallel.

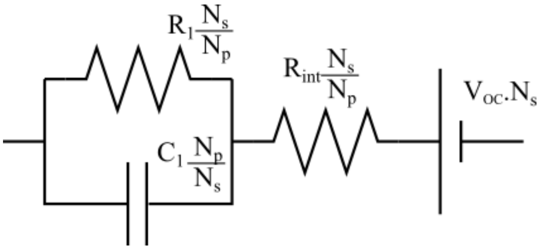

Fig. 8. Dynamic model of a multi megawatt PEM electrolyzer.

The 1 MW and 450 Vdc electrolyzer in the MVDC model is composed by 70 cells in series and 275 strings in parallel and has been implemented in PSCAD. Fig. 9 shows the response of the model to a step change in the current from 0 to nominal value, which is similar to the response measured in the lab for the individual PEM cell.

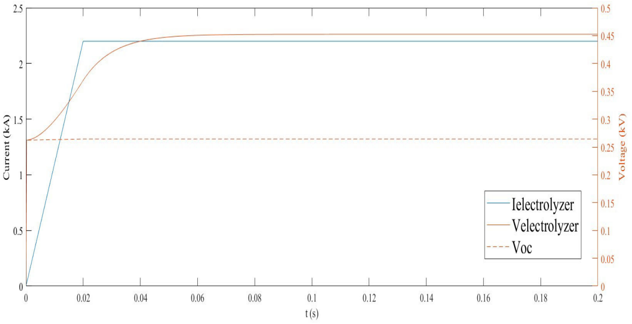

Fig. 9. Simulated response of the dynamic model of a 1MW 450Vdc electrolyzer.

B. *Response to DC faults*

Pole-to-pole faults in MVDC systems are the most severe events. On account of this, a permanent solid pole-to-pole fault is simulated at bus 4 at 1.99 s. Fig. 10 shows the evolution of the currents in the four converters. Protection algorithms detect the fault when the currents and voltages cross respective thresholds. As a result, they send tripping signals to all DCCBs connected to bus 4. DCCBs interrupt fault currents at converter 4, which is the most affected one, in 9 ms. Travelling waves attenuate fault currents in the remaining converters.

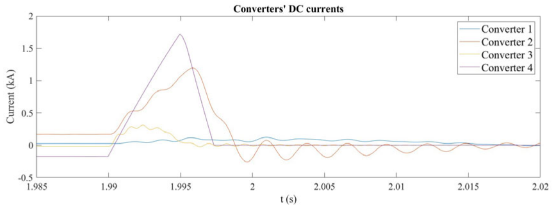

Fig. 10. Power converter currents.

Fig. 11 shows the positive pole current of the electrolyzer at the 25 kV dc bus. The fault causes a reversal of the current that changes from the nominal to 15 times that value at the peak, after then it is reduced due to the action of the DCCB. Finally, after some oscillations, the current is interrupted.

Finally, in case of permanent faults, DCCBs are not reclosed and converters 3 and 4 will be disconnected while grid connected converters will continue their operation after a transient period. This way, a selective and reliable protection is assured. Nevertheless, the constraints of radial meshes arise, as the power supply to the electrolyzer cannot be maintained

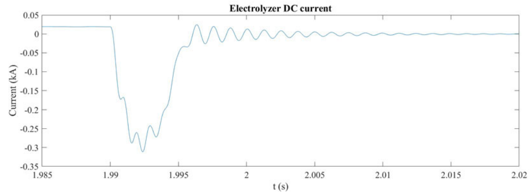

Fig. 11. Positive pole current of the electrolyzer.

5. Conclusions

This paper addresses the protection of MVDC grids with electrolyzers and RES. This way, in the paper, fault management strategies, protection specifications, fault detection algorithms for MVDC systems as well as grid topologies have been discussed.

A case study with RES and one electrolyzer has been analyzed. A single cell PEM electrolyzer has been dynamically modelled and the equivalent model of an electrolyzer with N_s series cells and N_p parallel strings has been presented. The response of the MVDC system for a pole to pole fault has been analysed and the current from the electrolyzer converter has been characterized. As a future research work, the response of the PEM single cell under short circuit in the supply source has to be compared with laboratory measurements.

Finally, the protection with DCCBs has been considered as the most feasible fault management strategy for the analysed case study, providing selectivity and fast operation. Therefore, it can be concluded that electrolyzers can be properly protected in MVDC systems, meeting the protection requirements: sensitivity, selectivity, speed and reliability

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