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COUNTRY: FR PREF. SUBJECT: PS1
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Need of power flow controllers

Multi-terminal HVDC (MTDC) systems may provide a more efficient solution than conventional point-to-point HVDC links to integrate large scale renewable power sources. Several MTDC projects are in operation in China and others are likely to be developed in Europe. Those projects are subject to evolution during their lifetime: adding new terminals, new conductors, etc., something that can potentially change the system configuration, for instance from radial to meshed. Fig. 1 presents an example of a 4-terminal radial HVDC system. By adding an additional conductor between Station 1 and Station 2, the system evolves to a meshed HVDC system, also called HVDC grid (see Fig. 2).

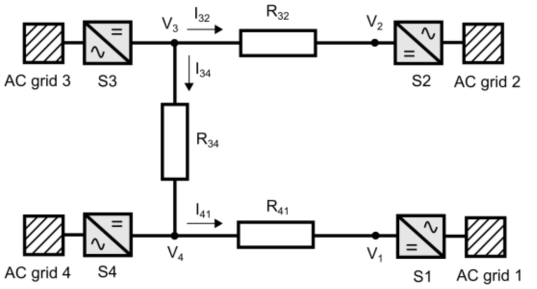

Fig. 1. Radial HVDC system.

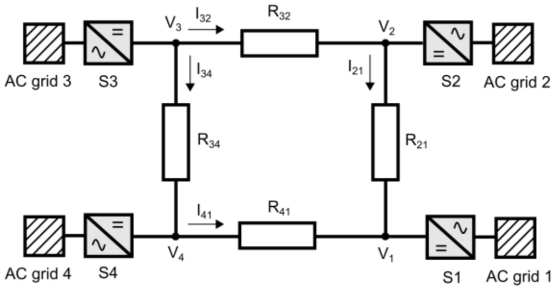

Fig. 2. Meshed HVDC system or HVDC grid.

In a radial system like the one in Fig. 1, there is only one path to transmit the power from one station to another and the currents circulating through the conductors can be directly regulated. By setting V_4 and V_1, I_{41} is controlled; by setting then V_3, I_{34} is controlled; and by setting V_2, I_{32} is also controlled. Thus, the converter stations have enough degrees of freedom to regulate all the currents circulating through the conductors of the system. However, the situation is different in a meshed HVDC system like the one in Fig. 2. In that case, there is more than one path to transmit power from one station to another. Following the same approach as before: by setting V_4 and V_1, I_{41} is controlled; by setting then V_2, I_{21} is controlled; by setting V_3, I_{34} is controlled. Then, I_{32} is imposed by the values of V_3 and V_2, which are already fixed. This means that all the currents cannot be controlled at the same time, since there are not enough degrees of freedom (voltages of the converter stations). This can lead to overloads in some of the conductors, while other conductors remain underused. Since it cannot be solved by the converter stations, power curtailments or the upgrade of conductor cross-sections may be required.

Another solution is to add additional power electronic devices into the system, to provide those extra degrees of freedom. Those devices are called power flow controllers (PFC) or current flow controllers (CFC). They can be understood as the equivalent of flexible AC transmission systems (FACTS) but applied to HVDC grids. Fig. 3 presents the meshed HVDC system of Fig. 2 with a PFC installed in conductor 32.

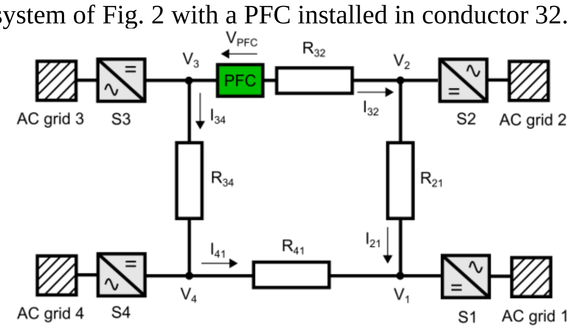

Fig. 3. Meshed HVDC system with a PFC installed in conductor 32.

In Fig. 3, the PFC device inserts a voltage in series with the conductor V_{PFC}, that provides an additional degree of freedom. By setting V_4 and V_1, I_{41} is controlled; by setting then V_2, I_{21} is controlled; by setting V_3, I_{34} is controlled. Then, by setting V_{PFC}, the current I_{32} can be controlled (V_3 and V_2 are already fixed). Thus, all the currents can be regulated at the same time.

Interline power flow controllers

Those PFCs are a research topic for both industry and academia, with papers and patents describing power electronic circuits to be used to regulate the current flows. They can be classified in different categories: series switching resistors, full power converters connected between poles and variable voltage sources inserted in series with one line or with several lines. Most of the works are supported by simulations of the power electronic circuits and some down-scaled converters have been built in laboratories to test the concepts. Nevertheless, no commercial product exists at the moment.

Among the PFC proposals, the variable voltage sources inserted in series with several lines (also known as interline PFCs) seem to bring more advantages than the other solutions. Fig. 4 presents the model of an interline PFC, composed of two voltage sources. The voltages are inserted in series with the conductors and the power that is extracted from one conductor is injected into the other one, as illustrated in (1).

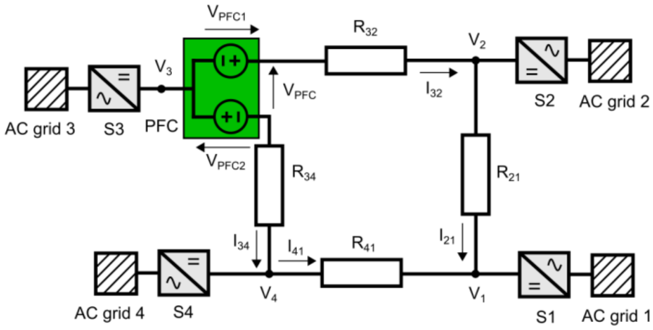

Fig. 4. Meshed HVDC system with the model of an interline PFC in node 3.

$$V_{PFC1} I_{32} = V_{PFC2} I_{34} \tag{1}$$

The power exchange is done between the two conductors, meaning that they do not need to exchange power with external sources (e.g., AC grid, MMC submodules, etc.), avoiding transformers and other interface elements. Interline PFCs do not need to withstand the pole-to-ground voltage (hundreds of kV), only the inserted series voltage (few kV). However, the insulation of the device must be for the pole-to-ground voltage and they must be rated for the nominal current circulating through the HVDC conductors. Fig. 5 and Fig. 6 show two different topologies of interline PFCs.

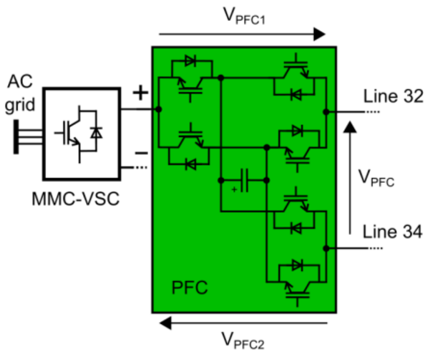

Fig. 5. Interline PFC based on a simplified double H-bridge (bidirectional in voltage and current).

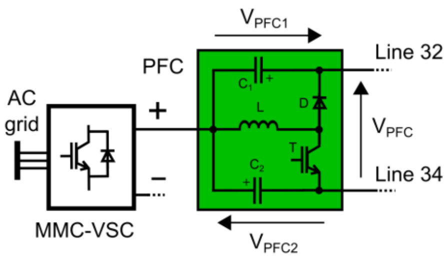

Fig. 6. Interline PFC proposed by SuperGrid Institute (unidirectional in voltage and current).

Challenges and perspectives

Some works have started to analyze the sizing of the power electronic elements and passive components of a PFC, showing a reasonable footprint. The integration of the PFC has also been studied, validating the insertion, bypass and grounding of the device during normal operation, focusing on the required switches to bypass the converter. Those switches have significant constraints but lower than already used switches in HVDC systems, meaning that their feasibility is not questionable.

The remaining challenges include the following.

- PFC protection to ensure the integrity of the device during different kinds of faults.
- Demonstration that operation of the PFC during normal and abnormal conditions does not disturb the stability of the HVDC grid. This includes interoperability aspects between the PFC and the other converters in the system.

- Powering of the PFC elements (gate-driver boards, control equipment, cooling system, etc.). This is needed because the PFC is expected to be installed on an insulated platform and will not be able to harvest power form the lines when it will be by-passed.

Finally, it is needed to consider PFCs in dc grid studies from the planning phase as alternatives to conductor reinforcement and power curtailment. Models for cost benefit analysis (CBA) are then needed.