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STEADY-STATE POWER FLOW CALCULATION IN A HYBRID HVAC/VSC-HVDC GRID

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Abstract. Voltage source converter high voltage direct current (VSC-HVDC) transmission technology is increasing its share in AC transmission due to important advantages such as independent P and Q control and lower harmonics. Nowadays, this technology is used to connect far-away remote offshore wind-power plants to mainland networks. VSC-HVDC is the main actor in developing the future multi-terminal DC grids and supergrids. This paper proposes a sequential algorithm to calculate the steady state power flow in a specific hybrid HVAC/VSC-HVDC grid which is a solution that is going to be seen in the early stages of the planned supergid.

Key words: HVDC, Power Flow, Sequential Algorithm, VSC Model

1. INTRODUCTION

The future European grid will change its actual structure depending on different scenarios concerning technology, performances and location for using renewable sources of energy, grid expansion or integration of distributed generation. The main challenges for this future European transmission system are:

- Public acceptance and permitting: transmission of bulk energy meets social of environmental problems. As an example, in mid 2012s, the German power grid was extended only in urgent situations and only with 214 km of the 1834 necessary.
- Renewable energy integration that was not done adequately to the existing power grid development. This situation forced unplanned energy exchanges through the interconnections of neighboring power energy systems. According to ENTSO-E scenarios [1], around 80% of the bottlenecks are related to renewable energy integration.
- New technology insertion and coordinated control of intelligent equipment – usage of more and more advanced technologies for the power grid infrastructure (other than conventional high voltage AC). The HVDC transmission lines are already used for long distances transmission and undersea applications in onshore or offshore projects. Phase-shifting transformers (PST) and FACTS devices, for targeted active and/or reactive power control are often used to meet the unplanned power flows. In highly meshed power grids, as the European one, the excessive use of intelligent control devices can bring real benefits only with coordinated operation. If a complex and coordinated system of control is not deployed, the transmission system may not have the expected behavior and the used devices may not deliver their full potential, as all this new technologies are highly influencing one each other.
- International expansion: there is already a trend in Europe and in the whole world to plan power grid extensions only in continental limits. But there are initiatives that focus on interconnecting, as an example, all the transmission networks among the Mediterranean shore, Europe or even from China with the ones from Europe [1].
- Supergrids and smart distribution power grids: for a good, secure and efficient common usage of transmission and distribution grids, there are needed special measures of coordination in their development and operation.

Existing AC power grids are shaken by recent changes, as generated distribution sources and micro-grids to integrate renewable energy sources, energy storage or usage of electrical vehicles. For the wind generators, AC or DC voltage can be used, but for the connection of photovoltaic systems to the grid, inverters must be used as the outputs are all at DC voltage. Also, to control charging and discharging for battery-based storage systems, AC/DC controller voltage should be used.

One of the solutions for these challenges is the deployment of a hybrid HVAC/HVDC grid, at distribution but also transmission level [1-4]. The general rules of an AC transmission grid do not apply also for HVDC grids, in terms of active or reactive power transfers that are independent of phase angle/voltage variations in the second case. The network operators will need to know how to predict the behavior of a hybrid system in order to maintain the grid in secure conditions.

Thus, it is very important for an initial set of operating conditions to determine the actual power flow in a power system. This calculus is utilized from planning and design of a power system to its operation. The steady-state power flow calculation bases on a balanced system who’s parameters are constant, linear and concentrated and a nodal analysis is necessary in order to describe the power grid.

The deployment of a sequential algorithm for power flow in a hybrid HVAC/VSC-HVDC network is not a new issue, but in this case, the calculation is made considering an inner DC slack bus iteration, that will lead to more accurate results. The mathematical process is also simpler, as it just needs to follow the steps for the algorithm. The main contribution of this paper is the converter model. Because the proposed method is a sequential one, the algorithm can be implemented easily for other AC grids power flow calculations.

In this paper steady state power flow analysis for a hybrid HVAC/VSC-HVDC grid is performed. The algorithm used for this purpose is a sequential one, treating separately the AC grid and the DC grid and it is implemented in a MATLAB environment. The paper is organized as follows: section II presents an introduction regarding VSC converter modeling, while in section III it is described a brief analytic basis of the power flow problem. Section IV illustrates the power flow calculation using the proposed algorithm for a specific grid and its results. The conclusion is made in Section V.

2. VSC MODELING

Seen from the PCC of the AC side, the VSC-HVDC station contains the converter transformer, the AC filters and the phase reactor (Figure 1).

The role of the converter transformer is to realize an reactance between the AC system and the VSC converter, as it cannot be directly connected. Also, the transformer adapts the system voltage to the VSC and may be designed with adjusting taps.

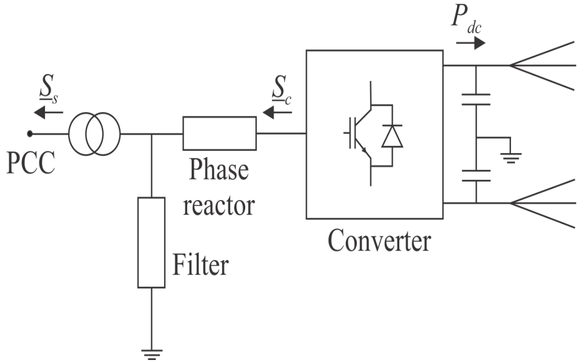

Fig. 1. Model of a VSC-HVDC conversion station [6]

The AC filters depend on the converter configuration and their purpose is to attenuate the harmonics. Only filters with higher tuning frequencies may be required, and such filters are normally cheaper and more compact than those with lower tuning frequencies. But as a drawback, they absorb reactive power on the fundamental frequency and if the AC grid is not able to provide this reactive power, only an adequate VSC control or the use of a shunt reactor may compensate it. The phase reactor can protect the transformer from high frequencies that may appear because of the commutation process and the associated rapid changes of high voltage (dv/dt) and current (di/dt). Harmonic generation can also vary with the VSC topology chosen, the chosen type of controllable switch, and the VSC switching technique. The converter is used for voltage conversion, from AC to DC [3].

The model of the VSC-HVDC station and its components, as seen from the AC side, can be observed in fig.1.

AC Side

The AC side of the converter is depicted in Figure 2. The model assumes a controllable voltage source $\underline{U}_C = U_C \angle \theta_C$ behind the phase reactor that is represented as a complex impedance $\underline{Z}_C = R_C + jX_C$ (Thévenin model). The low pass filter from the figure is represented through susceptance B_f at system frequency. The filter is connected to the AC system through a transformer, represented as a complex impedance $\underline{Z}_{tf} = R_{tf} + jX_{tf}$.

The active and reactive powers from the grid can be written as function of the complex voltages:

$$P_s = -U_s^2 G_{tf} + U_s U_f \left[G_{tf} \cos\left(\theta_s - \theta_f\right) + B_{tf} \sin\left(\theta_s - \theta_f\right) \right]$$

$$Q_s = U_s^2 B_{tf} + U_s U_f \left[G_{tf} \sin\left(\theta_s - \theta_f\right) - B_{tf} \cos\left(\theta_s - \theta_f\right) \right]$$

where $\underline{U}_s = U_s \angle \theta_s$ and $\underline{U}_f = U_f \angle \theta_f$ are the AC system and filter voltages.

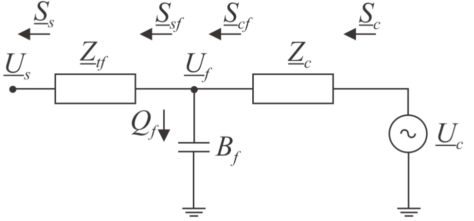

Fig. 2. Equivalent model of a VSC station connected to an AC system for the steady state power flow calculation [6]

At the converter the active and reactive powers are:

$$P_c = U_c^2 G_c - U_f U_c \left[G_c \cos\left(\theta_f - \theta_c\right) - B_c \sin\left(\theta_f - \theta_c\right) \right]$$

$$Q_c = -U_c^2 B_c + U_f U_c \left[G_c \sin\left(\theta_f - \theta_c\right) + B_c \cos\left(\theta_f - \theta_c\right) \right]$$

Converter loss may be considered as $P_{loss} = \beta \times P_c$, where β represents 1.65% of the converter active power [7].

Depending on the topology of the VSC converter, the AC filter can be neglected (as for a modular multi-level one), or not (for two or three level VSCs with PWM modulation). A simplified model of a converter, the transformer's influence can also be neglected [7].

On the AC side, each converter can control either the reactive power or the alternative voltage, so each PCC can be seen as a PQ or PV bus.

DC Side

From the DC side, the VSC-HVDC system can be operated in three different modes of control:

- A converter (called slack converter) has the role of direct voltage (U_{dc}) control. This converter must maintain the power balance in the DC system:

$$P_{dc,1} + P_{dc,2} + \ldots + P_{dc,N} - P_{loss,DC} = 0$$

where $P_{dc,i}$ is the DC power injected by each terminal of the DC grid, and $P_{loss,DC}$ is the power loss in the whole DC grid.

- The other converters control the active power.
- The voltage droop control, which represents a combination of the two modes of control presented above.

The VSC converter controls the DC voltage U_{dc} at a set value $U_{dc,set}$, keeping in the same time the DC power P_{dc} at a desired value $P_{dc,set}$. By this control mode, converters can contribute at the DC power balance, together with the slack converter [8].

3. POWER FLOW CALCULATION

The power flow calculus can be done by knowing the power grid data, as longitudinal impedances and shunt admittances for branches and apparent complex powers for buses. Such a calculus establishes the power flow, the power losses and the voltage drops on different component elements of the electric network.

For the calculation of the power flow in a hybrid HVAC/VSC-HVDC grid, it can be used a sequential or an unified method. In a sequential method, the equations for the AC and DC grids are solved separately, while for an unified method, both grids are solved simultaneously, in the same iteration.

The power flow calculation in this paper is performed through a sequential method. The used algorithm calculates in turns the steady state power flow for both AC and DC systems. Figure 3 presents the flow chart for such an algorithm. A similar algorithm is presented in literature [6]-[9].

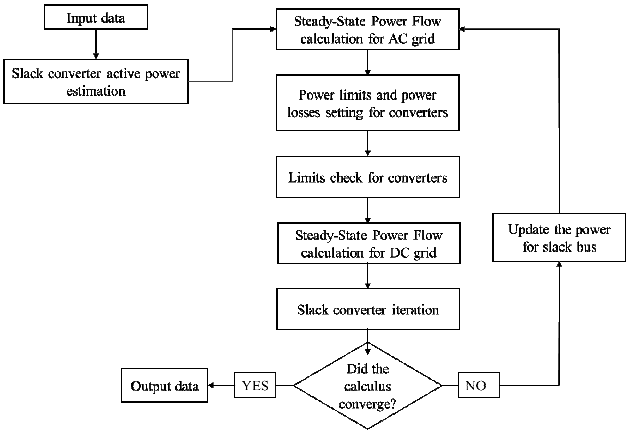

Fig. 3. Flow chart for the power flow in sequential algorithm for a HVAC/VSC-HVDC grid

The steps for a sequential method [9] are: firstly, we estimate the DC grid parameters, then we solve the system equations and we modify the DC grid parameters according to the founded solution. The solution is cyclic and the calculation continues until a convergence test is achieved. The AC grid must be solved after each update of the DC parameters. The advantage of the sequential algorithm is the possibility to add easily the MTDC grid in the used software that does the power flow calculation for the AC grid. The program used for an unified algorithm should be rewritten in order to solve both DC and AC systems.

3.1. AC Network

The power flow through AC grid can be described by the equations for bus i:

$$P_i = \sum_{k=1}^{n} U_i U_k \left[G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k) \right]$$

$$Q_i = -\sum_{k=1}^{n} U_i U_k \left[B_{ik} \cos(\theta_i - \theta_k) - G_{ik} \sin(\theta_i - \theta_k) \right]$$

and the power mismatch vector that can be solved by using Newton Raphson algorithm are:

$$\Delta P_i = -\Delta P_i^{'} = P_i^{imp} - P_i = \sum_{k=1}^{n} \frac{\partial P_i}{\partial x_k} \cdot \Delta x_k$$

$$\Delta Q_i = -\Delta Q_i^{'} = Q_i^{imp} - Q_i = \sum_{k=1}^{n} \frac{\partial Q_i}{\partial x_k} \cdot \Delta x_k$$

Voltage controlling converters are represented as dummy AC generators and their AC busses change from PQ nodes to PV nodes. The active power injections of slack converters are also modified in order to realize the voltage control. For first iteration, the DC system is assumed to be lossless:

$$P_{s_{slack}} = - \sum_{j=1;\, j\neq slack}^{N} P_{s_j}$$

With the AC voltages U_s and the power injections on AC side, S_s known, the values for voltage and current can be calculated at converter. When the converter is modeled on AC side, the influence of the transformer is neglected.

3.2. DC Network

After the AC power flow, the input data for the DC power flow can be calculated. The unknown quantities are the voltages for the DC buses $U_{dc,i}$ and the power injection of DC slack converter $P_{dcslack}$. DC voltages can be determined using another Newton Raphson algorithm and solving the next set of power flow equations [6]:

$$\left(\mathbf{U_{dc}} \frac{\partial \mathbf{P}^{'}_{\mathbf{dc}}}{\partial \mathbf{U_{dc}}} \right)^{(k)} \cdot \frac{\Delta \mathbf{U_{dc}}}{\mathbf{U_{dc}}}^{(k)} = \Delta \mathbf{P}^{'}_{\mathbf{dc}}{}^{(k)}$$

The power injection of DC slack converter has to be determined iteratively, by calculating the injected active power in the AC grid from the DC slack converter. This power, $P_{s,slack}$, can be solved as it depends on DC grid power loss that also depends on the current at the DC slack converter, yet unknown.

Because of the neglecting hypothesis (no AC transformer and no AC filters), the Jacobian Matrix is simplified, and the system that has to be solved [6] becomes:

$$\begin{bmatrix} \left(\frac{\partial P_c}{\partial \theta_c} \right)^{(k)} & \left(U_c \frac{\partial P_c}{\partial U_c} \right)^{(k)} \\ \left(\frac{\partial Q_s}{\partial \theta_f} \right)^{(k)} & \left(U_c \frac{\partial Q_s}{\partial U_c} \right)^{(k)} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_c{}^{(k)} \\ \frac{\Delta U_c}{U_c}^{(k)} \end{bmatrix} = \begin{bmatrix} \Delta P_c^{(k)} \\ \Delta Q_s^{(k)} \end{bmatrix}$$

where

$$\left(\frac{\partial P_c}{\partial \theta_c}\right)^{(k)} = -Q_c^{(k)} - U_c^{(k)^2} B_c$$

$$\left(U_c \frac{\partial P_c}{\partial U_c}\right)^{(k)} = P_c^{(k)} + U_c^{(k)^2} B_c$$

$$\left(\frac{\partial Q_s}{\partial \theta_f}\right)^{(k)} = -P_s^{(k)} - U_s^{(k)^2} G_c$$

$$\left(U_c \frac{\partial Q_s}{\partial U_c}\right)^{(k)} = Q_s^{(k)} - U_s^{(k)^2} B_{cf}$$

The mismatch vectors, $\Delta P_c^{(k)}$ and $\Delta Q_s^{(k)}$ can be calculated as:

$$\Delta P_c^{(k)} = P_c - P_c\left(\underline{U}_s, \underline{U}_c^{(k)}\right)$$

and

$$\Delta Q_s^{(k)} = Q_s - Q_s\left(\underline{U}_s, \underline{U}_c^{(k)}\right)$$

In these equations, the *k* superscript refers to the DC slack converter iteration. The flow chart for the slack converter iteration is presented in Figure 4.

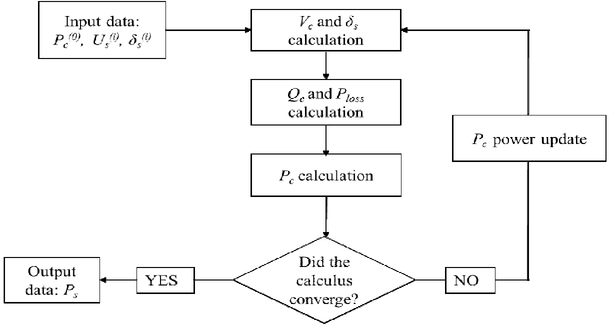

Fig. 4. Flow chart for DC slack bus iteration

The test for convergence is verified for the power injection in the AC grid of the slack converter, $P_{c,slack}$ and then is verified the test for convergence for the entire iteration loop.

4. CASE STUDY AND RESULTS

Figure 5 shows the hybrid HVAC/VSC-HVDC grid analyzed in this paper. The AC grid is represented with normal lines, while the DC grid is represented with thicker lines.

The AC power grid is proposed in [5] and has 5 busses and 2 generators. The meshed DC network is represented by three branches, A-B, B-C and A-C. There are, thus, 3 converters and their topology is modular multilevel (VSC-MMC). The DC voltage is ± 150 kV.

The steady state power flow algorithm for the AC grid converged after 3 iterations, with a maximum setting of 10 iterations and an accepted error for the convergence of 10^{-8}. The proposed sequential algorithm converged very fast, in 0.36 seconds and after 3 iterations. For this algorithm, the error setting was the same as for the one used in AC power flow, a maximum number of 10 iterations and the accepted error of 10^{-8}.`

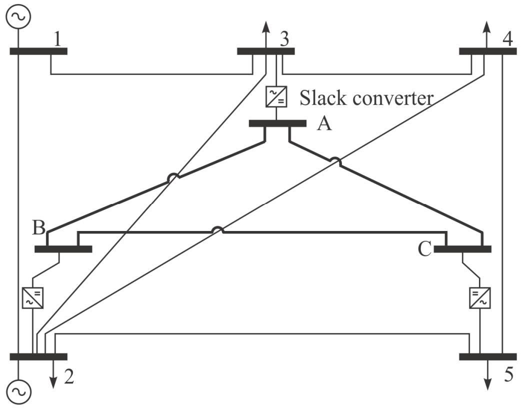

Fig. 5. Hybrid HVAC/VSC-HVDC power grid

For more clarity, because the figure of the complete grid with the active and reactive power flow would be too complex, it was represented in two figures. Thus, the results for the power flow in the hybrid HVAC/VSC-HVDC grid can be depicted in Figures 6 and 7. Figure 6 presents the active and reactive power flow only in the HVAC grid, but with the DC grid connected between busses 2, 3 and 5.

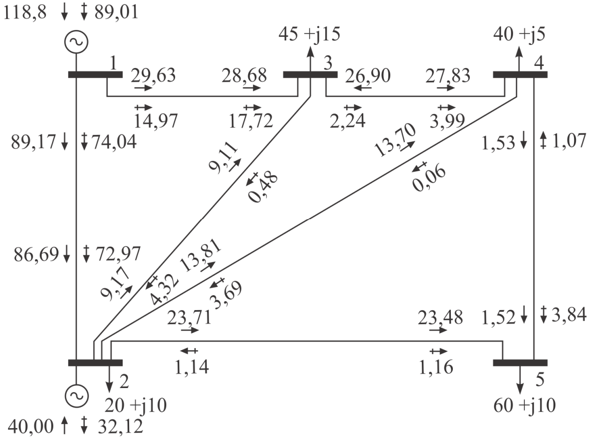

Fig. 6. Power flow in the AC grid with the DC grid connected between busses 2, 3 and 5

In Figure 7 are shown the power flow results of the proposed sequential algorithm only for the DC grid, with the active/reactive injections of the three converters A, B and C. As noted before, converter A (the slack converter) maintains the power balance in the DC system, counting the DC active power losses of 0,5 MW.

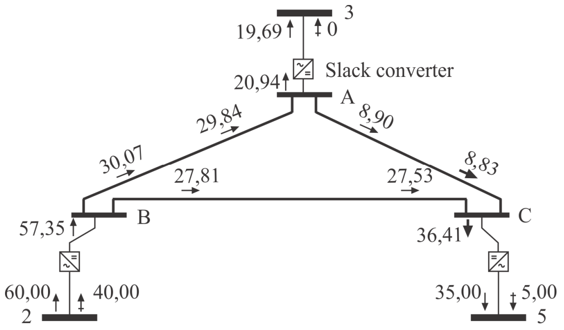

Fig. 7. Power flow and converter's injections in the AC grid for the DC grid

In both Figures 6 and 7, the active power flow (MW) is represented with an arrow (→), while the reactive power flow (MVAr) is represented with a cut arrow ( ). The AC grid is represented with normal lines and the DC grid is represented with thicker lines, as before.

The total active power loss for this hybrid HVAC/VSC-HVDC grid is 4,77 MW. In paper [10] it is performed a power flow calculation for the same hybrid power grid. Although our results are not identical, the differences can be justified by the models of the three converters. In this case, the converter transformer and the AC filter were neglected in order to simplify the mathematical calculations.

5. CONCLUSION

This paper proposes a sequential approach for calculating power flow in a hybrid HVAC/VSC-HVDC transmission grid.

In a hybrid HVAC/VSC-HVDC power grid, converters should be modeled in both AC and DC grids. On AC side, converters are represented as controllable sources of voltage behind a complex impedance. Looking from the AC grid, the converter can be a PV or a PQ bus. On DC side, the converter can have three modes of control: direct voltage control, active power control or voltage droop control. Only the direct voltage control and power control are used for the VSCs in this sequential algorithm. For power flow calculation, the DC grid is represented as a resistive network, with active power injections and continuous voltages.

The sequential algorithm in this paper was implemented in the MATLAB environment.

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