A New Power Flow Algorithm for Hybrid AC/DC Power Grid

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Abstract. Aiming at the problem of grid power flow calculation with VSC (Voltage Source Converter) unit in the context of the energy internet, this paper presents a new converter equivalent model. This study introduces a novel unified power flow algorithm for hybrid AC/DC power grids. The method simplifies the converter model by means of equivalent substitution and power conversion. The model better inherits the advantages of traditional AC power flow calculation. Finally, a unified iterative method is used to calculate an IEEE-57 node.

1. Introduction
In recent years, the rapid development of VSC-HVDC technology has obvious advantages compared with the conventional HVDC transmission technology. The fully controlled shutdown device has one more control than the half-controlled device, so the VSC-HVDC technology can simultaneously control the active and reactive variables. It is not necessary to install a reactive power compensation device. Up to now, the VSC-HVDC type inverter has adopted an MMC type structure. Due to the advantages of both active and reactive control, VSC-HVDC transmission technology is widely used in wind power, photovoltaic, DC distribution network and other aspects. In the context of the global energy Internet, more and more landscape renewable energy sources will be connected to the power system. The large-scale application of flexible DC transmission components in the power system will inevitably affect the original grid power flow.

VSC-HVDC is commonly used to build multi-terminal flexible DC networks. If we use the alternating iteration method to separate the AC side and the DC side, the superiority of the AC power flow calculation cannot be inherited. Reasonable equivalence and modeling of the converter enables the processing on the DC side to be closer to AC. On this basis, the unified iterative method can better inherit the advantages of AC power flow calculation.

There have been many studies on the power flow calculation for VSC-HVDC grids. In this paper, a new mathematical modeling is carried out for flexible VSC. The remainder of this study is organized as follows. Section 2 describes the mathematical model of AC/DC networks comprising VSC-HVDC, which includes the DC node classification and VSC control mode instruction. Then, case studies are discussed in section 3.

2. Mathematical model of power flow calculation
This section focuses on the mathematical model of VSC-HVDC for power flow. The VSC converter
station in a hybrid AC/DC power grid interconnects the AC grid and DC grid to form the channel of energy transmission. The model of VSC-HVDC unit is shown in figure 1.

Figure 1. VSC-based converter station (a) schematic representation (b) Equivalent circuit model.

Figure 1(a) shows the converter station, which consists of a coupling transformer, a phase reactor, an AC filter, a VSC block on the AC and DC sides and a DC capacitor. The current VSC-HVDC uses the MMC structure, so the output AC sinusoidal waveform is very neat. The use of this technique (MMC) makes the low pass filter no longer necessary to be installed. In figure 1(a), \( U_{ss} \), \( U_{cc} \) and \( U_{dk} \) indicate the voltage of point of AC bus, converter voltage, and DC bus voltage, respectively. Figure 1(b) is a model for simplifying and equivalent processing for power flow calculation. In figure 1(b), \( s_{ki} P \) is the power delivered by the AC grid to the converter station. \( c_{ki} P \) is the active power delivered to the inverter after passing through the transformer and the line. \( d_{ki} P \) is the active power received by the DC side. \( c_{ki} Y \) represents the impedance that integrates the converter transformer, low-pass filter, and line impedance. In this paper, the loss of the VSC converter is also added to \( c_{ki} Y \) according to the empirical equivalent value of the corresponding magnitude of the impedance. If we take the direction of power in figure 1(b) as positive, the general mathematical model of a converter station can be written as follows:

\[
\begin{align*}
    \begin{bmatrix}
        p_{si} \\
        q_{si} \\
        s_{iU} \\
        s_{i\delta} \\
        d_{ki} P
    \end{bmatrix} &= \begin{bmatrix}
        U_{ss}^2 G_{sk} - U_{ss} U_{ck} \left( G_{sk} \cos(\delta_u - \delta_{sk}) + B_{sk} \sin(\delta_u - \delta_{sk}) \right) \\
        -U_{ss}^2 G_{sk} - U_{ss} U_{ck} \left( G_{sk} \sin(\delta_u - \delta_{sk}) - B_{sk} \cos(\delta_u - \delta_{sk}) \right) \\
        -U_{ss}^2 G_{sk} + U_{ss} U_{ck} \left( G_{sk} \cos(\delta_u - \delta_{sk}) - B_{sk} \sin(\delta_u - \delta_{sk}) \right) \\
        U_{ss}^2 G_{sk} - U_{ss} U_{ck} \left( G_{sk} \sin(\delta_u - \delta_{sk}) + B_{sk} \cos(\delta_u - \delta_{sk}) \right) \\
        \end{bmatrix} \\
    &+ \begin{bmatrix}
        c_{ki} P \\
        d_{ki} P
    \end{bmatrix}
\end{align*}
\]

(1)

In equation (1), the state quantities are \( P_{si}, Q_{si}, s_{iU}, s_{i\delta}, d_{ki} P \). The state variable used directly in the solution process is \( P_{si}, Q_{si}, s_{iU}, s_{i\delta}, d_{ki} P \). The remaining variables are calculated by one variable.

Now we use the voltage source and current source to make an equivalent replacement for the converter station. Ensure that the voltage and current on both sides of the inverter before and after replacement are the same. The admittance \( Y_{sk} \) is then transformed together with the voltage source. The voltage source is eventually turned into a current source. The final result is shown in figure 3.
Only admittance is left between the AC and DC nodes. The calculation form is consistent with the AC flow calculation. Other power variations are expressed in terms of the power of the equivalent injection node. $P_c$ and $Q_c$ are the equivalent active power and reactive power injected into the converter station respectively. The node injection power expressions under different control modes are shown in Table 1.

**Table 1. Equivalent power expression.**

| Control mode | $P_c$ | $Q_c$ |
|--------------|-------|-------|
| $P_a^e$, $Q_a^e$ | $P_a^e$ | $Q_a^e$ |
| $P_a^e$, $U_a^e$ | $P_a^e$ | $Q_a^e$ - $U_a^e (G_a \sin \delta_a - B_a \cos \delta_a)$ |
| $U_a^e$, $Q_a^e$ | $P_a^e - U_a^e (G_a \cos \delta_a + B_a \sin \delta_a)$ | $Q_a^e$ |
| $U_a^e$, $U_a^e$ | $P_a^e - U_a^e (G_a \cos \delta_a + B_a \sin \delta_a)$ | $Q_a^e - U_a^e (G_a \sin \delta_a - B_a \cos \delta_a)$ |

In order to prevent the occurrence of pathological problems, the mathematical essence of power system power flow calculation is the numerical solution of nonlinear equations. The optimal multiplier method is to increase the one-step calculation when the variable increment is obtained in each iteration, and obtain the most satisfactory iteration step. Add calculation steps after each iteration:

$$\mu^k = \text{arg min}_{\mu} \left\| f(\alpha^k + \mu^k \cdot \Delta \alpha^k) \right\|$$

In equation (3), $\alpha^k$ includes the state variable $U_a$, $\delta_a$, $f(\alpha^k + \mu^k \cdot \Delta \alpha^k)$ corresponds to the mathematical model in equation (1).

### 3. Simulation and result analysis

The test case in this section relates a 7-terminal DC grid with the IEEE 57-bus power distribution system to demonstrate the effectiveness and reliability of the proposed unified power flow algorithm for the hybrid AC/DC power grid. The DC nodes are numbered 58 to 64 in Figure 3.
Figure 3. Modified IEEE 57-bus system embedded with a 7-terminal VSC-based DC grid. The control mode and control parameters of the converter station are shown in table 2.

Table 2. Parameters of the converter stations.

| Converter Station | $Z_c$/p.u. | $P_{ref}^m$ / p.u. | $U_{ref}^m$ / p.u. | $Q_{ref}^m$ / p.u. | $U_u^m$ / p.u. |
|-------------------|-----------|---------------------|-------------------|-------------------|----------------|
| 58                | 0.001+j0.083 | 0.5960              | 0                 | 0                 |
| 59                | 0.0015+j0.20 | -0.5                | 0                 | 0                 |
| 60                | 0.003+j0.25  | -0.4                | -0.1              | -0.48             |
| 61                | 0.003+j0.25  | -0.6                | -0.48             |                   |
| 62                | 0.003+j0.175 | -0.5                | 0.99              |                   |

The calculated maximum error of the power flow results of the algorithms is $1 \times 10^{-5}$. The power base values of both the AC grid and DC grid are 100 MVA, and the voltage base value of the DC grid is $400\sqrt{6}/3$ kV. There are no special changes to the communication network. The result focuses on the AC side nodes to which the DC node and the converter station are connected. The number of iterations in the calculation process of this study is 5 times. The calculation results of the AC side node of the converter station and all DC nodes are shown in table 3.

Table 3. Case result.

| Node | Voltage amplitude(kV) | Voltage phase |
|------|------------------------|--------------|
| 1    | 208.000                | 0.000        |
| 12   | 203.000                | -5.327       |
| 15   | 198.000                | -3.998       |
| 16   | 205.413                | -3.971       |
| 17   | 212.058                | -1.685       |
| 58   | 194.660                | 0.000        |
| 59   | 190.335                | 0.000        |
| 60   | 191.483                | 0.000        |
| 61   | 190.764                | 0.000        |
| 62   | 192.471                | 0.000        |
| 63   | 194.032                | 0.000        |
| 64   | 193.085                | 0.000        |

The results are in good agreement with the existing algorithms.

4. Conclusions

A new unified power flow algorithm for hybrid AC/DC power grids is presented in this study. This study uses the equivalent substitution principle to mathematically model the converter station. These studies illustrate the validity and computational performance of the proposed algorithm. This power
flow algorithms can inherit the sparse technology in AC power flow calculation. With the development of distributed renewable energy and the development of DC distribution networks, more and more VSCs will appear in the grid. The superiority of the algorithm in this study will be further demonstrated.

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