Study on Optimal Operation of AC-DC Hybrid Distribution Network

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Abstract. With the increase of power load and the access of distributed generation, AC/DC hybrid distribution network will become the development trend of urban distribution network in the future. The core of AC/DC distribution and distributed generation are voltage source converters based on full control switches. This paper simply analyzes the operation principle and control mode of voltage source converters, a power flow calculation method of AC/DC hybrid distribution system is proposed, and the optimization model of AC/DC hybrid distribution network with minimum network loss and minimum voltage deviation of DC network is established. The particle swarm swarm (PSO) algorithm is used to solve the calculation. Considering the load disturbance, the droop control is set for each VSC, at the same time this paper compares the advantages and disadvantages of the whole time optimal power calculation and droop control combined with the optimal power calculation method. Then the control mode of the distribution network is proposed. Finally, an example of PG&E 69-node distribution network in the United States is given to verify the correctness of the proposed model and algorithm.

Keywords: AC/DC hybrid distribution network, VSC, Particle Swarm Optimization, Droop control.

1. Introduction

The first paragraph after a heading is not indented (Bodytext style). With the progress of power electronics technology, the performance of VSC has been greatly developed, and gradually applied in the field of distribution network, making the uncontrollable traditional AC distribution network into a mixed AC and DC distribution network with certain power flow control and optimized operation functions. The distribution network has transformed from passive control to active control direction. The change of the distribution network structure also leads to the change of the corresponding power flow algorithm. The traditional distribution network algorithm only involves AC. After the DC part is added, the power flow calculation needs to adopt the mixed AC and DC power flow calculation. After adding the VSC to the distribution network, the control strategy has higher flexibility and complexity. The main control strategy which can be applied are master-slave control, droop control and voltage deviation control. The control reference values such as voltage, power, current will affect the trend of the distribution of the whole system. General reference may consider the load in peak value and experience to select VSC capacity.
In the aspect of AC/DC power flow algorithm, the contents of various literatures are classified. In Literature [1], the nodes in the microgrid were divided into general nodes and converter nodes, then the paper had constructed the current injection iteration equation, which is solved by the alternating iteration method. In literature [2], the unified iteration method and the alternate iteration method were introduced, the paper also analyzed their advantages and disadvantages. Then, an equivalent method combining the advantages of the two methods and considering the AC-DC coupling was proposed to solve the power flow. Literature [3] adjust the output reactive power of the converter station and the charge of the stored energy to ensure the safe operation of the power grid. At the same time, it minimize the power purchase cost of the power supply company. In this paper, the original mixed integer nonlinear programming was changed into mixed integer linear programming by using the linearization technique, and a method was found for solving the model. Literature [4] considered the various connections between nodes in the AC and DC distribution network, it used three matrices to make the power flow correction equation of all nodes have a uniform form so that the AC and DC network can be solved iteratively in a uniform way. However, the transmission loss of converter station was not considered in Literature [1-3], which would affect the calculation result. Moreover, the control mode such as constant power of VSC was not considered in the algorithm in Literature [4], which would bring a little inconvenience to the calculation.

At present, the domestic research on VSC application in distribution network optimization is not very in-depth. In Literature [5], some lines were changed into DC lines to optimize, and the transmission loss of VSC was considered in detail when constructing AC/DC power flow. Literature [7] proposed a two-layer optimization of AC/DC distribution network, in which the upper layer minimizes the total network loss by adjusting back-to-back VSC, while the lower layer adjusts the power of energy storage, controllable DG and flexible load under the constraints of the upper layer, so as to minimize the regional scheduling cost. The DC part of the model is only B2B-VSC, and no network is formed, so it does not involve the calculation of DC power flow. The above literatures consider adding VSC to the distribution network for optimization, but most of them are to transform the lines of the distribution network and the optimization methods are relatively simple.

In view of the traditional distribution network optimal operation problems, this paper presents a AC/DC hybrid power distribution network optimal operation strategy: first in the AC distribution network, this paper selects some areas to establish dc network, the VSC was used for connection between ac and dc, changing some AC load to the DC load. Then using the PSO algorithm to optimize the transmission power of VSC under the dynamic load for the target of minimizing the network loss and the DC voltage deviation. The difference of establishing DC network in different locations is compared, and some suggestions are put forward for the operation of distribution network. At last, this paper verifies the validity of the proposed strategy by the calculation and analysis of PG&EE69 distribution network and symmetrical 138 nodes distribution network.

2. AC/DC hybrid distribution network model

AC-DC hybrid distribution network is mainly divided into three parts: AC network, DC network and VSC. VSC is the power interaction point between DC network and AC network, and it is also the key equipment to control the flow of the system.

2.1. VSC model

AC system and DC system can exchange power through VSC and its working principle is shown in Figure 1.

![Figure 1. Working principle of VSC.](image-url)
$P_S$ and $Q_S$ are the power injected into the VSC by the AC network, $U_S$ and $\delta_S$ are the voltage and phase angle of the AC network, $P_C$, $Q_C$, $U_C$ and $\delta_C$ are the active power, reactive power, voltage and phase angle of the AC side of the VSC, $R_C$ and $X_C$ are the equivalent reactance of the commutator compressor and the commutator reactor, $U_d$ and $I_d$ are the direct current voltage and current. The voltage drop on the impedance is:

$$\Delta U = \frac{P_C R_C + Q_C X_C}{U_C} = U_S \cos(\delta_S - \delta_C) - U_C$$  \hspace{1cm} (1)$$

$$\delta U = \frac{P_C R_C - Q_C X_C}{U_C} = U_S \sin(\delta_S - \delta_C)$$  \hspace{1cm} (2)$$

Change the impedance to admittance form,

$$G_C + jB_C = \frac{1}{R_C + jX_C}$$  \hspace{1cm} (3)$$

From formula (1)-(3), the formula below can be get,

$$P_S = U_S^2 G_C - U_S U_C \{G_C \cos(\delta_S - \delta_C) + B_C \sin(\delta_S - \delta_C)\}$$  \hspace{1cm} (4)$$

$$Q_S = -U_S^2 B_C - U_S U_C \{G_C \sin(\delta_S - \delta_C) - B_C \cos(\delta_S - \delta_C)\}$$  \hspace{1cm} (5)$$

Set the loss of converter transformer and reactor as $P_{loss}$, and assume that the loss measured on the DC side and AC side of VSC has been included in $P_{loss}$, then the power constraint on both sides of the DC side of converter and AC network is:

$$P_C = P_S - P_{loss}$$  \hspace{1cm} (6)$$

The power of DC side is:

$$P_d = P_c$$  \hspace{1cm} (7)$$

VSC generally uses pulse-width modulation technology, and the relationship between AC side voltage and DC side voltage of the converter is [9]:

$$U_c = \frac{\mu M}{\sqrt{2}} U_d$$  \hspace{1cm} (8)$$

To simplify the calculation, the active power $P_{loss}$ consumed in impedance $Z_C$ is 1.6% of the active power on the side of AC network [10].

$\mu$ is the utilization rate of DC voltage, which is related to the modulation mode of pulse. It is $\sqrt{3}/2$ in sine pulse width modulation and 1 in space vector pulse width modulation. M is modulation. Besides the modulation, VSC also has a control variable named phase-shifting Angle $\delta$ (the
difference value between the voltage Angle of AC side $\delta_s$ and the voltage Angle of AC side of VSC $\delta_c$). By controlling the two quantities above, the VSC can control the export variable $U_c$ and $\delta_c$ of the AC side to control the trend. The active power flow direction of VSC and AC power grid is determined by the magnitude of $\delta_c$ and $\delta_s$. When $\delta_s > \delta_c$, the AC power grid injects active power to VSC, when $\delta_s < \delta_c$, the VSC sends active power to AC power grid. The reactive power mainly depends on voltage, and the flow direction of reactive power can be adjusted by adjusting the outlet voltage of the converter.

VSC can regulate active quantities and reactive quantity by regulating $M$ and the delta [11]. The active class physical quantities including active power $P_s$ of the AC side, voltage $U_{dc}$, frequency $f$ and current $i_d$ of DC side, reactive quantity including reactive power $Q_s$ and voltage $U_s$ of AC side. One of each quantities was chosen to control by VSC, the common control mode of VSC are $P_s - Q_s$, $P_s - U_s$, $U_{dc} - Q_s$ and $U_{dc} - U_s$.

2.2. AC system model
Excluding transformers, the AC system model in the hybrid grid is not much different from that in the traditional grid, and its nodes are divided into PQ nodes, PV nodes and balance nodes. Under the unit system, the correction equation of PQ nodes in the Cartesian coordinate system is:

$$\Delta P_i = P_i e_j - e_i \sum_{j=1}^{n} (G_{ij} e_j - B_{ij} f_j) + f_i \sum_{j=1}^{n} (G_{ij} f_j + B_{ij} e_j) = 0$$  \hspace{1cm} (9)$$

$$\Delta Q_i = Q_i e_j - f_i \sum_{j=1}^{n} (G_{ij} e_j - B_{ij} f_j) - e_i \sum_{j=1}^{n} (G_{ij} f_j + B_{ij} e_j) = 0$$ \hspace{1cm} (10)$$

The revision equation of PV nodes is

$$\Delta P_i = P_i e_j - e_i \sum_{j=1}^{n} (G_{ij} e_j - B_{ij} f_j) + f_i \sum_{j=1}^{n} (G_{ij} f_j + B_{ij} e_j) = 0$$ \hspace{1cm} (11)$$

$$\Delta V^2 = V_i^2 - (e_i^2 + f_i^2) = 0$$ \hspace{1cm} (12)$$

Where $P_i$, $Q_i$ and $V_i$ are active power, reactive power and voltage of the given nodes respectively, $G_{ij}$ and $B_{ij}$ are the real and imaginary parts of the network admittance matrix of the AC system respectively and N is the total number of nodes of the AC system.

For AC nodes connected to VSC, the nodes can be regarded as PV node or PQ node according to the type of VSC control mode. When the control mode is $P_s - Q_s$ and $U_{dc} - Q_s$, the nodes can be regarded as PQ nodes. When the control mode is $P_s - U_s$ and $U_{dc} - U_s$, the nodes can be regarded as PV nodes.

2.3. DC system model
Suppose there is a DC network with N nodes, the relationship between node voltage and injected power is as follows:
\[ P_i = V \sum_{j=1}^{n} G_{ij} V_j \] (13)

If the power \( P_{is} \) of nodes from 1 to \( n-1 \) is known, the power correction equation can be written for \( n-1 \) nodes:

\[ \Delta P_i = P_{is} - V \sum_{j=1}^{n} G_{ij} V_j = 0 \] (14)

The \( n \)th node is the balance node and does not need to participate in iteration. If DC network is connected to an AC network through a VSC, at least one VSC should be in the state that controlling DC voltage remain constant. The DC nodes connected to the VSC are regarded as the balance nodes of the DC network.

References are cited in the text just by square brackets \([1]\). Two or more references at a time may be put in one set of brackets \([3, 4]\). The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

3. Control model between VSC converter stations

In daily life, the load is not invariable, so it is necessary to set control strategies for multiple VSCs to deal with load fluctuations. The commonly used control strategies include master-slave control, voltage deviation control and droop control.

3.1. Master-slave control

In the master-slave control mode, a main converter station is set to maintain constant voltage on the DC side, and power changes on the DC side are all undertaken by the converter station. The other converter stations are in the active power and reactive power control mode or active power and AC voltage control mode. The control formula is as follows:

Main converter station:

\[ U_d - U_{dref} = 0 \] (15)

\( U_d \) and \( U_{dref} \) are the measured value and the given value of the voltage on the DC side respectively.

Subordinate converter station:

Active power control quantities control the constant of active power on AC side:

\[ P_s - P_{sref} = 0 \] (16)

Reactive power control quantities control the constant of reactive power or voltage on AC side:

\[ Q_s - Q_{sref} = 0 \text{ or } U_s - U_{sref} = 0 \] (17)

Where \( P_s, P_{sref}, Q_s, Q_{sref}, U_s \) and \( U_{sref} \) are respectively the active power measured value and the set value of AC side, reactive power measured value and the set value of AC side, the voltage measured value and the set value of AC side.
3.2. Voltage deviation control
Although the structure of the master-slave control mode is simple, but the fluctuation of load on the DC side can only be borne by the main converter station, so the capacity of the VSC is higher. In voltage deviation control method, the value of voltage on the DC side is not only related to the reference value of voltage, but also associated with the limit of voltage. The DC voltage at the outlet of the converter station controlled by deviation must meet a certain constraint relationship with the DC voltage of the other converter stations, so the voltage deviation control station and the other converter stations have the ability to regulate the voltage together.

3.3. Droop control
The droop control is realized by using the linear relationship between the voltage and active power of the converter station and it has the function of automatically adjusting power. Its control formula is as follows:

\[ P_s = -K(U_{dc} - U_{dcref}) + P_{ref} \]  

(18)

Where, \( P_s \), \( P_{ref} \), \( U_{dc} \), \( U_{dcref} \) and \( K \) are respectively the active power transmission value, the reference value on the AC side, the measured voltage value and reference value on the DC side, the droop coefficient. After setting the relevant reference value at each converter station, the power flow can be adjusted together according to the droop curve.

3.4. Comparison of control modes
It can be seen from the above control modes between various VSCs that the master-slave mode has higher requirements on the stability and capacity of the main converter, because all load fluctuations are borne by the main converter station. If the capacity of the main converter station is insufficient or an accident occurs, the whole system will be affected. The voltage deviation control is similar to the droop control, which adjusts the power with the fluctuation of the load and has high flexibility.

4. Optimal power flow model of AC/DC distribution network
The optimization idea of this paper is to establish a certain number of DC power grids on the basic of AC distribution network. The AC network and DC network are connected by VSC and the load of some nodes is transferred to the DC network to ensure the load of the whole network remains unchanged. Set one of the VSCs to balance the converter station, the control mode of which is constant \( U_{dc} - Q_s \). The rest of the VSCs is set to a constant \( P_s - Q_s \) control mode. Minimizing the sum of four physical quantities as the target: the active power and reactive power that VSC controlled as the variable of optimization. Setting the loss of AC net, the loss of converter, the loss of DC net and the voltage deviation of DC net to select the optimal scheme of dc power grid construction.

4.1. AC and DC power flow algorithm
The calculation process is shown below:

Step1: Set initial iteration values for AC and DC networks.
Step2: Calculate the injected power value of the DC network. The injected power value of the DC network refers to the power injected into the DC network by the non-balanced converter station. The transmission active power controlled by the VSC can be calculated according to Equation (6).
Step3: Solve the DC network correction equation until converging, get the voltage of each node of the DC network and calculate the active power injected into the DC network by the balance converter station.
Step4: According to the active power injected by the balanced converter station into the DC network, the active power injected by the AC side into the VSC can be calculated by equation (6).
Step 5: Solve the AC power flow to obtain the voltage and phase angle of the AC network nodes. Complete the calculation of the AC and DC power flow.

4.2. The optimization model

1) The objective function is:

\[ f(X) = ACloss + VSCloss + DCloss + 8DCvd \]  \hspace{1cm} (19)

All losses and voltages are adopted as standard values. \( ACloss \) is the total loss of AC network lines, the calculation formula is:

\[ ACloss = \sum_{i=1}^{n} \sum_{j=1}^{n} |\hat{V}_i - \hat{V}_j|^2 \cdot y_{ij} \] \hspace{1cm} (20)

Where, \( n \) is the number of nodes on AC network, \( \hat{V}_i \) and \( \hat{V}_j \) are the voltage vectors for nodes \( i \) and \( j \).

\( VSCloss \) is the total loss of converters:

\[ VSCloss = \sum P \cdot 1.6\% \] \hspace{1cm} (21)

\( DCloss \) is the loss of DC network, which is calculated as:

\[ DCloss = \sum_{i=1}^{m} \sum_{j=1}^{m} |V_{dci} - V_{dcj}|^2 \cdot g_{ij} \] \hspace{1cm} (22)

\( DCvd \) is DC voltage deviation of unbalanced nodes, which is calculated by taking the unit value of 1.0 as the benchmark:

\[ DCvd = \sum_{i=1}^{m} (V_{dci} - 1) \] \hspace{1cm} (23)

2) Optimize variables and constraints

The optimization variable is:

\[ X = [P_1, ..., P_k, Q_1, ..., Q_l] \] \hspace{1cm} (24)

Where, \( P_1, ..., P_k \) are the active power values of the VSC which are set as the constant active power control model; \( Q_1, ..., Q_l \) are the reactive power values of the VSC which are set as the constant reactive power control model. The constraint conditions to be satisfied are:

\[ P_{m \text{min}} \leq P_m \leq P_{m \text{max}} \text{ and } Q_{n \text{min}} \leq Q_n \leq Q_{n \text{max}} \] \hspace{1cm} (25)

Where, \( 1 \leq m \leq k, 1 \leq n \leq l \). The voltage of nodes on AC and DC network can not exceed the limit:
\[0.94 \leq U_{si} \leq 1.06 \quad \text{and} \quad 0.94 \leq U_{di} \leq 1.06\]  \hfill (26) 

3) Solving method. The optimization model was programmed and solved by PSO algorithm on Matlab, the solution process was as follows:

![Flow chart of optimization of AC/DC distribution network.](image)

**Figure 2.** Flow chart of optimization of AC/DC distribution network.

5. The simulation verification

In order to verify the effectiveness of the optimization operation strategy proposed in this paper, two examples are constructed with PG&E69-node distribution network as the model.

5.1. PG&E69 node example test

![Modified PG&E69 node distribution network structure.](image)

**Figure 3.** Modified PG&E69 node distribution network structure.
As shown in the figure, it is planned to set DC networks in three areas with large loads. Each DC network contains three nodes, two of which contain loads, and the VSC connected to the other node is responsible for maintaining voltage stability on the DC side. The load size is the load of the corresponding node in the original network. This example optimizes the pairwise combination of DC network. The dimension of optimization variables is 10, which are the active and reactive power values of VSC controlled by 4 fixed active power $P_i$ and fixed reactive power $Q_i$, the reactive power control values of VSC controlled by 2 fixed voltages on the DC side $U_{DC}$ and fixed reactive power $Q_i$, that means the optimization variables are 4 fixed active power values and 6 fixed reactive power values.

**Table 1.** The AC nodes connected by each VSC in the DC network of the 69-node distribution network.

| DC network   | one | two | three |
|--------------|-----|-----|-------|
| the AC node connected by VSC | 11  | 50  | 39    |
|              | 12  | 53  | 48    |
|              | 67  | 36  | 46    |

The three optimization scheme combinations are as follows: the first scheme is a combination of DC network 1 and 2, the second scheme is a combination of DC network 1 and 3, the third scheme is a combination of DC network 2 and 3. The influence of the three schemes on the network loss is shown in Figure 4.

**Figure 4.** Influence curve of three optimization schemes on 69 nodes distribution network loss.

It can be seen that the loss reduction effect of the first and second schemes on the original AC network is relatively obvious. Then compare the system loss and converter loss under the three schemes, as shown in Table 2:

**Table 2.** Comparison of 69 nodes distribution network loss under three schemes.

|                     | Total average loss of network /kW | Average loss of converter /kW | Loss reduction rate/% |
|---------------------|-----------------------------------|-------------------------------|-----------------------|
| The first scheme    | 104.4                             | 37.3                          | 70.63                 |
| The second scheme   | 280.0                             | 16.2                          | 21.24                 |
| The third scheme    | 141.6                             | 41.4                          | 60.17                 |
| The original net    | 355.5                             | -                             | -                     |
It can be seen that the reduction effect of scheme 1 and scheme 3 on network loss is relatively obvious. Both schemes include DC network 2, and the load of DC network 2 is heavy, so the optimization results of both schemes are relatively good. The other difference between the two schemes is that the network in Scheme 1 is far away from each other. Although the total load of Scheme 3 is heavier than that of Scheme 1, the DC network in Scheme 3 is closer to each other, and most of its corresponding AC nodes are on the same feeder, so the overall improvement effect on the whole distribution network is not as obvious as that of Scheme 1.

6. Conclusions
Based on the traditional distribution network, this paper proposes an optimization scheme of AC/DC distribution network based on PSO algorithm. In the meantime this paper discusses the control mode and parameters of the DC network. The results are as follows:

(1) Establishing a DC network in some areas of the distribution network, connecting the AC and DC parts with VSC. By regulating the power function of VSC, the system network loss can be reduced and the voltage level of AC side can be improved. The total loss reduction rate of the network depends on the network size and load distribution level.

(2) In the above optimization example, the minimum load of PG&E69 nodes distribution network is 3.8022MW, under various optimization schemes, the average 24h network loss of a feeder can be reduced by up to 70.63%. For the distribution network with fewer feeders and uneven load distribution, the construction of DC network can be adopted to optimize the operation of the distribution network, while for the load balanced distribution network, other ways should be considered to optimize the operation of the distribution network.

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