Power Flow Analysis on AC And DC Transmitting Concurrently Along the Same Feeder Line in Distribution Network

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ABSTRACT: In this paper, the idea that the DC generated by distributed generation (DG) transmits concurrently with AC in the same feeder line in distribution network is presented. The basic concept and the circuit topology are also expressed. For the low capacity DG, it is proposed a concept of “suppositional stack bus” which is useful and convenient for AC and DC power flow computation. After decoupling AC and DC network at the place of “suppositional stack bus”, the computation turns to be simple and rapid. Case study shows that network loss is smaller and voltage is more balanced under this way. So the advantage of the operation as well as the availability of the calculation method is proved.

Keywords: distribution network; power flow; distributed generation; AC and DC

1 INTRODUCTION

In recent years, poor supply of electric power leads to rapid development of power supply and power grid. But current development is a type of rugged investment. In order to make the development of electric power more suitable for the development of economizing type society, more efficient and reasonable utilization mechanism of power supply and power grid should be established. Nowadays, new type of distributed power generation technology which is clean and renewable has been faced with rapid development. It has many advantages, and will lead to the appearance of new specific technique and economic market. On the one hand, it will slow down the construction of power supply; on the other hand, it will make the power grid more flexible and reliable. Relevant laws and regulations have been formulated in China to encourage the development of distributed generation. We can see that the power system will be faced with a new situation in the future.

AC and DC transmitting simultaneously along the same feeder line in distribution network is a new kind of transmitting method to solve the development of distributed generation. In contrast with traditional AC transmitting method of distributed generation, the new method reduces the effect on AC power system which is caused by the method of transmitting. In contrast with DC transmitting method of distributed generation, the new method reduces the cost of feeding circuit and transmission corridor. Concerning the safety margin of DC voltage and DC current, this method can reduce the network loss compared with AC transmitting method, also, it can offer more balanced distribution of voltage. The basic idea is that add the DC current to AC feeding circuit on particular range of primary AC distribution network by using specific device, make DC current and AC current transmit on relevant lines of distribution network together on the premise of electrical characteristics about feeding circuit. When there is DC load, provide the load with power directly, the active power of DC part can exchange with AC distribution network, then the balance of power can be realized. Power adjustment of DC network and AC network can be realized by adopting converter equipment and controlling methods. In this paper, the network topology was raised according to the characteristics of AC and DC transmitting methods along the same feeder line in distribution network. In addition, rapid analysis of power flow analysis of AC and DC transmitting simultaneously along the same feeder line in distribution network can be realized with “virtual balancing machine”.

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2 AC AND DC TRANSMITTING SIMULTANEOUSLY ALONG THE SAME FEEDER LINE

Under the way of AC and DC transmitting simultaneously along the same feeder line in distribution network, AC transmitting method remains unchanged, while the DC current transmits under a certain range with some technical means, also the AC current should be cut off before the DC current given to DC loads. The DC current provided by distributed generation can be added to the distribution circuit with two methods. Firstly, single-stage system can be made up of DC distribution line and AC distribution line. Secondly, bipolar system can be made up of DC distribution line and AC distribution line. About the first method, the DC current and the distribution make up the loop through the ground, which is shown in Figure 1, which is added to the AC distribution line, about the second method, the DC current is added to two three-phase AC distribution line with positive and negative electrode.

![Figure 1. Topology of monopole earth return operation of AC and DC transmitting simultaneously in a same feeder line.](image)

Regardless of single-stage system or bipolar system, the DC current can be added to the AC distribution line by using special insulated transformer or additional transformer, also, the DC transmitting line will be limited with insulated transformer and DC capacitor, and the AC current of distribution will be cut off with inductance coil. In this way, AC and DC transmitting simultaneously along the same feeder line can be realized, in addition, DC current can AC current can be separated, and requirements of operation can be met.

DC current is added to the AC distribution line with symmetrical voltage, and the line voltage remains unchanged, so it makes no difference to the insulation between lines. In comparison of DC transmitting and AC transmitting, when they have the same active power, concerning that there is no inductance in DC transmitting lines, the active loss is little, and there is no reactive loss, so distribution loss reduces in DC transmitting lines and the distribution of voltage is more balanced. When the two methods have the same transmitting power, the higher of DC voltage is, the less of distribution loss is. The DC voltage added to distribution line should be limited to insulation safety margin, when increasing the DC voltage to reduce active loss of distribution line. Usually, concerning that the level of voltage changes little after adding DC voltage to the distribution line, so requirements of insulation safety margin can be limited with design and optimization of DC current. At the same time, it makes little difference to the environment because that the DC current flowing into the ground is small. So, the method of AC and DC transmitting simultaneously along the same feeder line in distribution network is feasible from the perspective of technique and economy, which can benefit much in the future.

3 THE IDEA OF VIRTUAL BALANCING MACHINE IN POWER FLOW CALCULATION

In this paper, power flow calculation can be solved by the “virtual balancing machine” established. Virtual balancing machine means a bidirectional converter on the special location between AC network and DC network. When the DC network is in short of power, AC power is changed into DC power for DC network. When the DC network has surplus power, the rest active power will be reversed into AC network. The virtual balancing machine is a type of transferring the balanced spot of DC network to AC network, AC balancing machine burdens the active unbalance of DC network, then balance of power between DC network and AC network can be realized.

![Figure 2. Suppositional stack bus.](image)

As shown in Figure 2, assume that there two areas MN and PQ of different voltage levels, in which the voltage level of MN is suitable for operation under AC voltage level, such as 10kV and 35kV, there are several feeder lines, also, the distributed generation flows into one side of the network from several lines of the feeder lines, the DC power provides power for DC loads through the MN areas. Virtual balancing machine is located between Q and R, voltage of the spot is controlled as a constant value with certain controlling methods. The spot offers reference voltage to the DC network, also, balance of DC power is realized at the spot of O, then the rest DC power is transmitted with inverters from R to PQ, which belongs to another voltage level or the same voltage level separated from...
DC network. In addition, it connects external AC network. Virtual balancing machine is the same as transferring the balanced spot of DC network to AC network whose capacity is bigger. When calculating the power flow of DC and AC network, the spot is treated as balanced spot for DC network, as for AC network, after calculation of DC network, the power changed between DC network and AC network is calculated, then power flow calculation of AC network is carried out together with initialization of all spots. At last, calculation of complex voltage will be carried out which is also effective value of phase voltage compared to the ground, after calculation of DC voltage and AC voltage on all spots.

Concerning the method of AC and DC transmitting simultaneously along the same feeder line in distribution network, the relationship between DC network and AC network on the location of DC loads and virtual balancing machine is a simple algebraic relation taking no account of controlling characteristics. However, feeder network of distributed DC power supply is independent of AC network. At the spot of virtual balancing machine, exchange of power between DC network and AC network with controlling methods is to get constant DC voltage. When calculating the power flow, DC network power flow should be calculated firstly through calculating DC network, after coupling cancelled between DC current and AC current, the actual power or current at AC spots can be reached. Then AC power flow calculation will be carried out according to conventional algorithm of AC network, at last, calculation of integrated performance index can be carried out. Comparing to HVDC systems, the method of AC and DC power flow calculation has faster calculation speed with no need for alternately solving and simultaneously solving.

The same result with single-line analysis with calculation of example.

4 POWER FLOW ANALYSIS OF AC AND DC TRANSMITTING SIMULTANEOUSLY ALONG THE SAME FEEDER LINE

There are many ways of DC current generated by distributed generation flowing into the network, according to different controlling methods, they can be divided into constant voltage, constant current and constant power. Power flows to the network from constant voltage source and constant current source are unknown, which includes the network loss, so as to get balanced power in DC network. There should be a device to balance power in DC network, which can be replaced with constant voltage source and constant current source. There can be several DC power supplies in DC network, then the DC network will have many devices to balance power, and the active unbalance will be undertaken by the balancing devices to reach active balance in DC network.

Actually, at the starting stage, the capacity of distributed generation is usually small, which can’t be used as balancing device. After getting legal permission of full generation, distributed generation will operate fully to get more benefits. By the way, all distributed generation will operate with constant power. So, in this paper, virtual balancing machine was raised to get the balance of active power in DC network.

Power flow calculation will be discussed as below with AC and DC transmitting simultaneously along the same feeder line in distribution network.

1) Solution of DC network
Assume that node number of DC network is N with AC and DC transmitting simultaneously along the same feeder line, all the distributed generation are controlled by constant power or constant current. The balancing device is virtual balancing machine, and voltage of the spot is given as V. The iterative equation of DC network to be solved is as below:

\[ I^{(i)} = G I^{(i-1)} \]

(1)

G is nodal-admittance matrix of DC network, the order is N-1, \( V(k) \) is the voltage vector of the k-th time, \( I^{(k)} \) is the current vector of the k-th time, also,

\[ I^{(i)}(j) = \frac{P_{dc}(i)}{I^{(i-1)}(j)} + I_{dc}(i) \]

(2)

\( P_{dc}(i) \) is the DC constant power of the k-th time.

2) Treatment of AC-DC coupling
DC load related to DC network in primary AC network is supplied by DC source in DC network, the deficiency and the rest are coupled with AC network by virtual balancing machine. So, there are two situations of AC-DC coupling to be handled when calculating the AC network.

One of them is that DC load should be taken out when calculating AC network:

\[ P_L(j) = P_L(j) - P_{dc}(j) \]

\[ I_L(j) = I_L(j) - I_{dc}(j) \]

(3)

\( P_L(j) \) and \( I_L(j) \) are corresponding active power and active current at the j-th spot of primary AC network, \( P_{dc}(j) \) and \( I_{dc}(j) \) are actual value of DC load at the j-th spot, \( P_L(j) \) and \( I_L(j) \) are values of loads at the j-th spot when calculating in AC network.

At the location of virtual balancing machine, the active power transferred from AC network to DC network is \( P_{sw} \), then the AC injection of the spot should cut down \( P_{sw} \), in contrast, if the active power transferred from DC network to AC network is \( P_{sw} \), the spot should add this part of injection when calculating AC network:

\[ P(j) = P(j) - P_{sw} \]

(4)
P(j) is AC active power at the spot of the AC network, P'(j) is injection of active power at the j-th spot after treatment of AC-DC coupling. Psw should be distinguish between positive and negative, which means flow direction of active power between AC network and DC network, assume that the direction is positive when active power flows from AC network to DC network.

Process of power flow calculation with AC and DC transmitting simultaneously along the same feeder line is shown in Figure 3. It can be shown that there is no need for alternately solving and simultaneously solving by treatment of AC-DC coupling. The power flow calculation of DC network should be carried out before initial processing of AC part, and then power flow calculation with AC and DC transmitting simultaneously along the same feeder line can be carried out easily.

Process of power flow calculation with AC and DC transmitting simultaneously along the same feeder line is shown in Figure 3. It can be shown that there is no need for alternately solving and simultaneously solving by treatment of AC-DC coupling. The power flow calculation of DC network should be carried out before initial processing of AC part, and then power flow calculation with AC and DC transmitting simultaneously along the same feeder line can be carried out easily.

When the system adopts three-phase model, we can regard it as the situation that the DC current is just single-phase or double-phase.

5 EXAMPLE

In order to compare the results under the AC and DC operation method with results of traditional AC operation, assuming that the loads are the same and they remain unchanged. With the method of AC and DC transmitting simultaneously along the same feeder line, part of the active power is taken over by DC sources, and then loads are taken over by AC system decrease. While operated with traditional AC distribution network, DC loads or frequency doubling is gotten by rectifying or inversion.

On the basis of changed IEEE system, distribution system with AC and DC transmitting simultaneously along the same feeder line can be gotten by setting DC sources and DC loads. Single line figure of the system is shown in Figure 4.

Per unit value of the system can be seen in Table 1 and Table 2. Dates of branches are shown in Table 1, and all branches are ordinary; dates of loads are shown in Table 2. Balancing node of AC system is the fiftieth node, whose voltage is set as 1.0(p.u.) with the phase angle of zero.

Table 1. Branch data of test system.
| Branch(left and right) | Resistance/R | Reactance/X |
|-----------------------|--------------|-------------|
| 32 45                 | 0.000339765  | 0.001157993 |
| 33 32                 | 0.010184141  | 0.001213264 |
| 33 34                 | 0.011000001  | 0.020000002 |
| 45 46                 | 0.000203858  | 0.00694796  |
| 50 32                 | 0.001359065  | 0.004631968 |
| 52 84                 | 0.000543625  | 0.001852786 |
| 71 32                 | 0.001359065  | 0.004631968 |
| 71 84                 | 0.000203858  | 0.00694796  |
| 71 150                | 0.000679767  | 0.002315985 |
| 75 71                 | 0.000339768  | 0.001157996 |
| 84 911                | 0.000203855  | 0.00694791  |

Table 2. Load data of test system.
| Node of load | Active power/R | Reactive power/X | DC content |
|--------------|----------------|------------------|------------|
| 34           | 0.12786        | 0.0655           | 0.10       |
| 45           | 0.51157        | 0.37526          | 0.00       |
| 46           | 0.69065        | 0.39593          | 0.40       |
| 52           | 0.38373        | 0.25734          | 0.20       |
| 71           | 1.35096        | 0.77443          | 0.00       |
| 75           | 0.84417        | 0.46226          | 0.40       |
| 150          | 0.51156        | 0.45415          | 0.00       |
| 911          | 0.51157        | 0.24222          | 0.25       |

The results consist of AC voltage of all nodes, DC loss of different lines, AC loss of different lines, the whole loss of the system, minimum voltage of the system and the maximum voltage angle of the system. Results can be seen in Table 3 and Table 4, the first method is traditional operation of AC distribution network, and the second method is that with AC and DC transmitting simultaneously along the same feeder line.

It can be seen in Table 3 and Table 4 that the whole loss of system decreases with AC and DC transmitting simultaneously along the same feeder line, also, power electricity is saved, minimum voltage of the system increases, and balance of voltage in AC system is better. Meanwhile, minimum relative angle between nodes decreases, which improves overall performance of the power system, increase of single-phase voltage.
relative to the ground decreases, which meet the requirements of insulation totally.

Table 3. Voltages under two operation ways.

| Nodes | Voltage of method 1 | Voltage of method 2 |
|-------|--------------------|--------------------|
|       | Amplitude (p.u.)   | Phase(°)           | Amplitude of AC voltage (p.u.) | Effective value of single-phase voltage relative to ground (p.u.) |
| 32    | 0.9781             | 1.10               | 0.9793                          |
| 33    | 0.9778             | 1.10               | 0.9795                          |
| 34    | 0.9752             | 1.22               | 0.9778                          |
| 45    | 0.9767             | 1.16               | 0.9782                          |
| 46    | 0.9762             | 1.19               | 0.9781                          |
| 50    | 1.0000             | 0.00               | 1.0002                          |
| 52    | 0.9612             | 2.00               | 0.9645                          |
| 71    | 0.9623             | 1.92               | 0.9652                          |
| 75    | 0.9615             | 1.97               | 0.9643                          |
| 84    | 0.9618             | 1.95               | 0.9645                          |
| 150   | 0.9608             | 1.98               | 0.9634                          |
| 911   | 0.9615             | 1.97               | 0.9645                          |

Note: * Single voltage represents effective value of single-phase voltage relative to the ground.

Table 4. Indices of the general performance of the system.

| Index          | Method 1 | Method 2 |
|----------------|----------|----------|
| Active loss    | 0.0772   | 0.0512   |
| Reactive loss  | 0.2623   | 0.1746   |
| AC power       | 5.008+j3.283 | 4.187+j3.216 |
| DC power       | 0.0000   | 0.0800   |
| AC minimum voltage | 0.9608 | 0.9635   |
| Minimum phase angle | 2.00    | 1.53     |

It can be seen in Table 3 and Table 4 that the whole loss of system decreases with AC and DC transmitting simultaneously along the same feeder line, also, power electricity is saved, minimum voltage of the system increases, and balance of voltage in AC system is better. Meanwhile, minimum relative angle between nodes decreases, which improves overall performance of the power system, and increase of single-phase voltage related to the ground decreases, which meets the requirements of insulation totally.

6 CONCLUSION

(1) With the method of AC and DC transmitting simultaneously along the same feeder line, DC elements can flow in several distribution lines through certain isolation measures, also, exchange of power with AC network can be realized using inverter machine at the node of virtual balancing machine.

(2) Setting of virtual balancing machine adapts to the situation that capacity of distributed generation is small, which can’t be responsible for the balance of power.

(3) On the one hand, virtual balancing machine provides reference value of DC voltage for DC elements; on the other hand, it is convenient for AC-DC coupling, which is more efficient.

(4) With the method of AC and DC transmitting simultaneously along the same feeder line, balance of the system is better and there is less power loss in the system, requirements of insulation level can be reached with proper adding of DC voltage.

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