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Influence of AC System Parameters on DC Current Distribution

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Abstract. The ground current of HVDC transmission will cause DC bias of transformer in AC system. In order to master the influence of typical AC grid parameters on DC current distribution, a direct field-circuit coupling model of AC and DC power grid is established, and the evaluation parameters of DC current distribution are proposed. The influence of various factors such as the grid density, transformer and transmission line branch resistance, tower-ground wire system on DC current distribution in AC grid are quantitatively analyzed by grid examples. The results show that the denser the grid of a certain voltage level, and the smaller the circuit resistance of transformer and transmission line branch of a voltage level, the larger the DC current of the voltage level and the total DC current of the AC grid. When considering the tower-ground wire system, the DC current entering the AC power grid increases, and the smaller the wire DC resistance and the tower grounding resistance, the more DC current increases. In a line, the tower with the largest grounding current generally appears in the tower 1-4# near the substation with the larger current amplitude. In the calculation process of DC current distribution in large AC grid, ignoring the mutual resistance effect between substations will make the DC current of the AC grid larger, so it is not advisable to neglect the mutual resistance between substations in calculation.

1. Introduction

The grounding current of DC grounding electrode will produce ground potential rise, which not only causes step voltage around the grounding electrode, but also produces potential difference between tens or even hundreds of kilometres near the grounding electrode. If the transformer neutrals of two substations are grounded, DC current will flow into the AC grid system from one transformer neutral point of one substation to another. DC current flowing through transformer windings may cause transformer core half-circle magnetic saturation and a series of electromagnetic effects, such as harmonic amplification and noise increase, some components overheating, and even cause transformer damage [1-4].

With the continuous development of China's power grid, the AC power grid is becoming more and more dense, making the location of DC grounding electrode project increasingly difficult. The influence of the DC grounding electrode on the DC bias of transformers has attracted more and more attention, and has even become a key factor in the feasibility of the grounding electrode site scheme for the UHV/EHV DC transmission project.



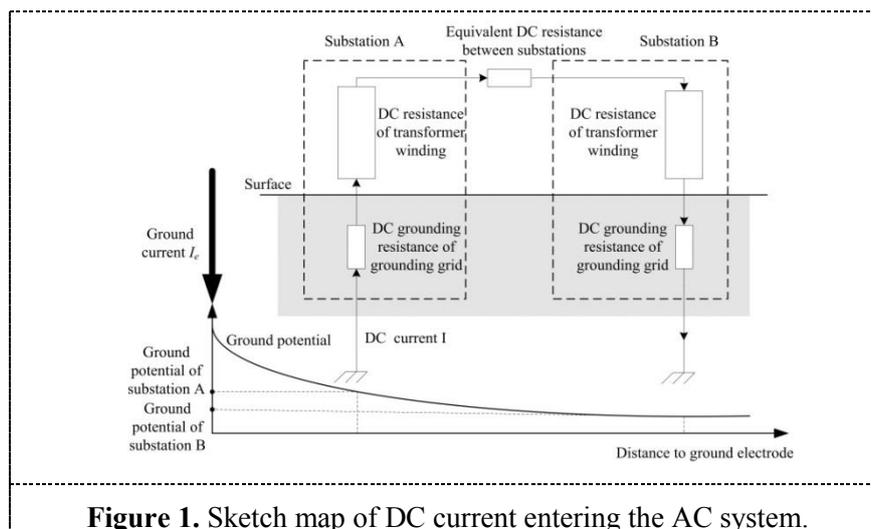
There are many researches on DC bias of transformer caused by HVDC transmission in China, but it is usually calculated for a certain project to obtain the DC bias distribution of the substations around it [5-9], or for the characteristics and influencing factors of DC bias of a single site [10-11]. The research on the influencing factors and variation characteristics of the DC content of the entire AC grid is lacking. In the calculation method, the calculation of DC magnetic bias is usually based on the complex image method, finite element method, boundary element method, moment method and other methods to solve the ground constant flow field generated by DC grounding current, to obtain the ground potential distribution caused by the grounding current. Then according to the length of the AC line, the line direction, the substation grounding resistance, the DC resistance of the transformer winding and other parameters, the DC current in the neutral point of the transformer is calculated by the circuit theory. In the second step, the simple method is to ignore the influence of the overhead line current between substations on the substation potential, and directly take the ground potential of the first step as the input parameter, which is called the indirect field-circuit coupling model algorithm. The other is the direct field-circuit coupling model algorithm, which considers the influence of substation and transmission line current on the surface potential. The accuracy of the direct field-circuit coupling model algorithm is significantly higher than that of the indirect field-circuit coupling model algorithm [12].

Based on the direct field-circuit coupling model algorithm, the calculation model of DC ground current distribution in AC power grid is established, and the evaluation parameters of DC current distribution is proposed. Then the influence of grid density, transformer and transmission line branch resistance, tower-ground wire system and mutual resistance between substations on DC current distribution in AC power grid are quantitatively analyzed by virtual grid examples.

2. Establishment of Power Grid Model

2.1. The basic principle of DC current distribution calculation

The path of the DC current into the AC transmission system can be illustrated in Figure 1. The grounding current generates potential distribution in the earth, and the DC current flows into the transformer and transmission line low resistance branch through the grounding neutral point of the nearby substation to the distant substation.



2.2. Line model

Low resistance line is an important factor affecting DC current distribution, and its key parameters are DC resistance and connection mode. In the calculation of DC current distribution, only lines of the 110kV and above voltage level directly grounded by neutral points can be considered.

2.3. Substation model

The substation model is complex, which can be divided into above-ground parts and underground parts. The equivalent DC model of the substation shown in Fig. 2(a) is shown in Figure 2(b).

The above-ground part of the substation is a pure circuit problem. The model mainly includes the transformer model and the neutral point series equipment model. The transformer model includes transformer winding type, winding DC resistance, and transformer bus. The equivalent resistance branch of the neutral point series device is connected to the transformer neutral point and the substation node. If the neutral point series device is a capacitor, disconnect the neutral point from the substation node.

The underground part model of the substation is a field problem, and the model is equivalent according to the Thevenin's principle. In the case of all neutral points being disconnected, the grounding resistance is the equivalent resistance between the substation node and the zero potential point, and the induced potential is the entrance potential between the substation node and the zero potential point. The substation grounding resistance is only related to the soil near the station site, which is in conflict with the global soil parameters when calculating the DC current distribution. The corresponding treatment method is to approximately take the measured value of the power frequency grounding resistance of the substation instead of the DC resistance. The substation induced potential is excited by the ground current of the grounding electrode and other substations.

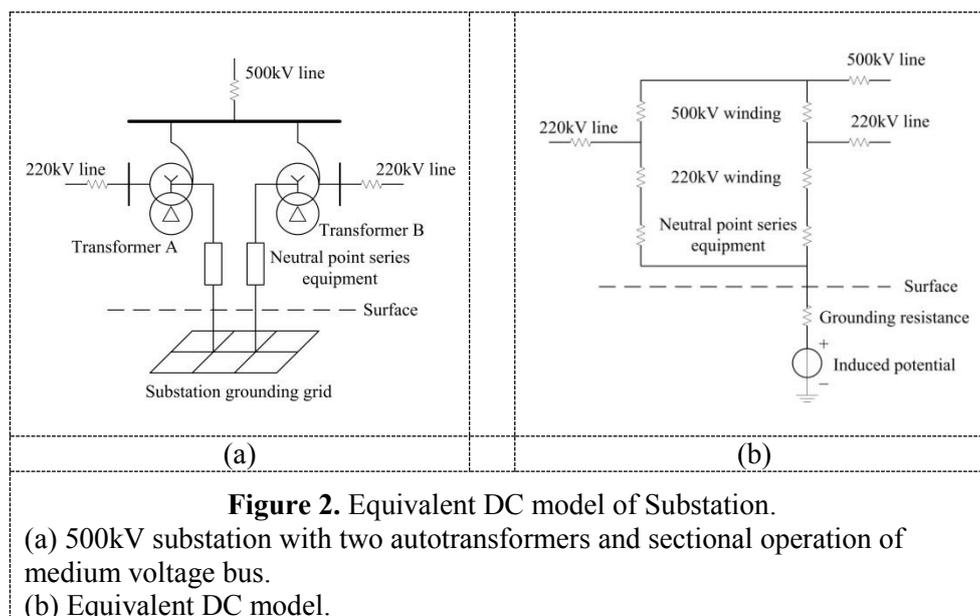


Figure 2. Equivalent DC model of Substation.

(a) 500kV substation with two autotransformers and sectional operation of medium voltage bus.

(b) Equivalent DC model.

2.4. Other parts of the model

Although the main distribution paths of the DC current in the AC grid are the neutral point grounding transformers and transmission line low resistance branches, there are many other DC current paths in AC power grid, such as shunt reactors and towers-grounding wire system.

Shunt reactors are usually installed on the outgoing lines of 330kV and above substations in China. The connection mode is direct grounding, which is equivalent to parallel connection with substation transformers. The DC resistance of shunt reactor winding is much larger than that of transformer winding [13-14], which can reach more than 30 times of transformer winding resistance. Therefore, the resistance of shunt reactor can be neglected in establishing substation equivalent model, thus simplifying the calculation model.

The overhead ground line is connected to grounding grids of the two substations, and part of the DC current flows through the overhead ground wire, which will change the potential difference between the substations, thus affecting the DC current flowing through the transformer windings. The

model of the tower-grounding wire system is consistent with the previous model. The grounding wire model is similar to the transmission line model, and it connects the substation grounding grid and the tower. The tower model is similar to the substation model, and the tower body resistance (the above-ground part of the tower) connects the grounding wire and the tower grounding body, and the underground part of the tower also needs to be equivalent according to the Thevenin principle.

If the proportion of grounding wire current is very small, the influence of grounding wire can be neglected in the calculation of DC current distribution, thus simplifying the calculation.

3. Influence of AC power grid parameters on DC current distribution

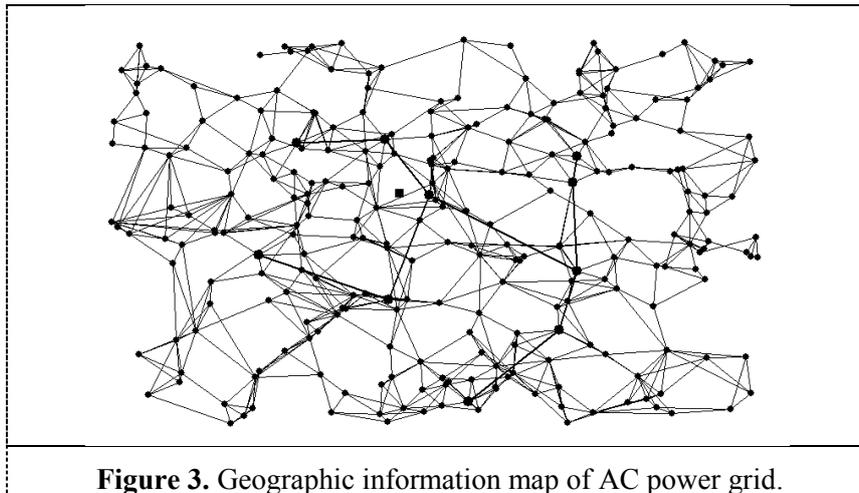
3.1. Evaluation parameters of DC current distribution

At present, the neutral point DC current of the transformer is usually regarded as the only evaluation standard for the DC current distribution, which is not comprehensive. On the one hand, the neutral point DC current of the transformer is the superposition of the grounding currents of multiple transformers, and the current flowing into and out of the earth may be offset. On the other hand, the neutral point DC current cannot reflect the DC current flowing through the series winding of the autotransformer. Therefore, this paper comprehensively uses the DC current in the transformer windings of different voltage levels to evaluate the DC current distribution.

The DC current of transformer windings is marked by "*I*" or "*J*" + "winding type initials" + "voltage level" + "current direction symbol", where "+" indicates the direction of current flowing into the earth and "-" indicates the direction of current flowing out of the earth. Then the total DC current flowing into the earth direction and flowing out of the earth direction of 500kV common windings is marked as I_{C500+} and I_{C500-} respectively, and that of series windings is marked as I_{S500+} and I_{S500-} . Similarly, in the 220kV substation, the 220kV winding current is marked as I_{N220+} and I_{N220-} , and 110kV winding current is marked as J_{N110+} and J_{N110-} ; respectively. And the total DC currents flowing into earth and following out of earth of 220kV substations is marked as I_{220+} and I_{220-} . In the 110kV substation, the current of 110kV winding current is marked as I_{N110+} , I_{N110-} . As the AC power grid is a DC passive network, the total DC current flowing into the earth should be equal to that of flowing out of the earth, and either of them can be used as the total DC current of the grid neutral point I_Z .

3.2. Analysis object

Establish an AC power grid covering an area of 450km × 350km. The total number of 500 kV substations (all auto-transformers) in the grid is N_{500} , and the total number of 220kV and 110kV substations (all three-winding transformers) is N_{220} and N_{110} . All substations are distributed randomly in the grid coverage area. The neutral points of all transformers are directly grounded. Take $N_{500}=10$, $N_{220}=150$, $N_{110}=100$, the geographic information diagram of the AC grid is shown in Figure 3. In the figure, dots indicate substations, straight lines indicate transmission lines, and the small square indicates DC grounding electrode. The DC ground current is 3000A, and the line length is 1.4 times the distance between substations.



The typical parameters are selected as follows: 1) the resistance of common winding and series winding of 500kV autotransformer is 0.05Ω , and normal winding of 220kV and 110kV transformer is 0.1Ω . 2) The grounding resistance of 500kV, 220kV and 110kV substation is 0.378Ω , 0.522Ω and 0.723Ω respectively. 3) The equivalent soil model of the AC grid coverage area is selected according to Table 1.

Table 1. Soil model.

Number of layers	First floor	Second floor	Third floor	Fourth floor
Soil resistivity ($\Omega \cdot m$)	100	400	14000	10
Thickness (m)	50	1000	50000	∞

3.3. Influence of mutual resistance between substations on DC current distribution

In the example of figure 3, $I_Z=1691.3A$ when the mutual resistance between substations is not considered, and $I_Z=1263.9A$ when considering the mutual resistance, and detailed calculation results are shown in Table 2. Since the mutual resistance between substations changes the induced potential of substations, the mutual resistance between substations has a great influence on the distribution of DC current in large-scale power grid. It plays a role in suppressing the DC current distribution of the AC grid to a certain extent and should not be ignored.

Table 2. Calculation results of DC current distribution (A).

DC current (A)	I_Z	I_{S500+}	I_{C500+}	I_{C500-}	I_{N220+}	I_{N220-}	J_{N110+}	J_{N110-}	I_{220+}	I_{220-}	I_{N110+}	I_{N110-}
Considering mutual resistance	1263.9	249.3	187.9	82.7	535.8	641.0	353.5	281.8	537.8	571.3	186.6	258.3
No consideration of mutual resistance	1691.3	344.7	225.8	116.5	736.9	846.2	476.9	371.2	776.0	779.5	251.7	357.4

3.4. Influence of power grid density

In the network shown in Figure 3, when the number of substations of each voltage levels is changed, the calculation results of DC current distribution are shown in Table 3. It can be seen that the denser the grid of a certain voltage level, the larger the DC current of the voltage level and the total DC

current of the AC grid. However, the mutual resistance effect between substations makes the DC current distribution saturated. No matter how densely distributed the substations are, the total DC current in the AC grid is necessarily less than the ground current of the DC transmission.

Table 3. Calculation results of DC current distribution (A) under different grid density.

Changed parameter	I_z	I_{S500+}	I_{C500+}	I_{C500-}	I_{N220+}	I_{N220-}	J_{N110+}	J_{N110-}	I_{220+}	I_{220-}	I_{N110+}	I_{N110-}
No change	1263.9	249.3	187.9	82.7	535.8	641.0	353.5	281.8	537.8	571.3	186.6	258.3
$N_{500}=5$	1237.4	170.1	177.6	41.2	511.7	648.1	366.2	288.2	515.2	573.7	181.9	259.9
$N_{220}=75$	759.9	257.6	223.4	105.8	193.4	311.1	200.2	155.1	200.1	272.7	142.6	187.7
$N_{110}=50$	1057.4	269.1	196.9	84.5	526.7	639.1	309.3	181.9	567.1	552.2	24.6	151.9

3.5. Influence of transformer and transmission line circuit resistance

In the network of Figure 3, changing the transformer winding resistance R_T and the line DC resistance R_L , which are the main paths of the DC current, the change of DC current distribution in AC grid are shown in Table 4. It can be seen that the transformer winding resistance and line DC resistance have a great influence on the DC current distribution. The larger the circuit resistance of a voltage level is, the smaller the DC current of the voltage level grid and the total DC current of the AC grid are. The neutral series small reactance with grounding is beneficial to suppress the DC current distribution, and the parallel grounding operation of multiple transformers will increase the DC current distribution in the AC grid.

Table 4. Calculation results of DC current distribution (A) under different main circuit resistance.

Changed parameter	I_z	I_{S500+}	I_{C500+}	I_{C500-}	I_{N220+}	I_{N220-}	J_{N110+}	J_{N110-}	I_{220+}	I_{220-}	I_{N110+}	I_{N110-}
No change	1263.9	249.3	187.9	82.7	535.8	641.0	353.5	281.8	537.8	571.3	186.6	258.3
$2R_{T500}$	1253.2	226.8	177.8	76.7	533.7	634.9	354.7	283.7	537.0	567.1	186.9	257.9
$2R_{T220}$	1200.9	247.2	190.1	84.4	496.5	602.2	328.8	259.5	522.8	559.2	185.5	254.8
$2R_{T110}$	1257.9	249.1	188.3	83.0	534.3	639.7	355.2	283.6	540.9	574.7	180.1	251.6
$2R_T$	1185.1	224.7	180.4	78.4	492.9	594.9	332.4	263.8	525.1	558.5	179.4	248.0
$2R_{L500}$	1250.3	166.2	176.5	69.3	519.1	626.3	370.5	297.7	520.4	554.8	184.2	257.0
$2R_{L220}$	1123.7	253.3	183.7	97.3	413.3	499.7	352.4	293.2	474.2	501.4	174.2	233.5
$2R_{L110}$	1119.2	268.9	185.5	84.7	546.6	647.4	228.9	184.3	503.6	559.8	158.2	202.9
$2R_L$	942.0	192.3	163.8	78.4	406.6	492.1	227.6	193.2	400.8	452.0	144.0	178.3

3.6. Influence of tower-grounding wire system

There are a large number of towers and grounding wires in the power grid. In this section, a small power grid is selected as the analysis object, as shown in Figure 4. The typical parameters of the simulated grid are as follows: the grid coverage area is 100km×100km, and the number of 500kV and 220kV substations is 4 and 50 respectively. In the figure 4, H1~H4 are 500kV substations, and the rest are 220kV substations. The tower spacing of 500kV and 220kV lines is 500m and 250m respectively, and the tower position is assumed to be on a straight line connecting the starting substation and terminating substation. The soil model is selected according to Table 1.

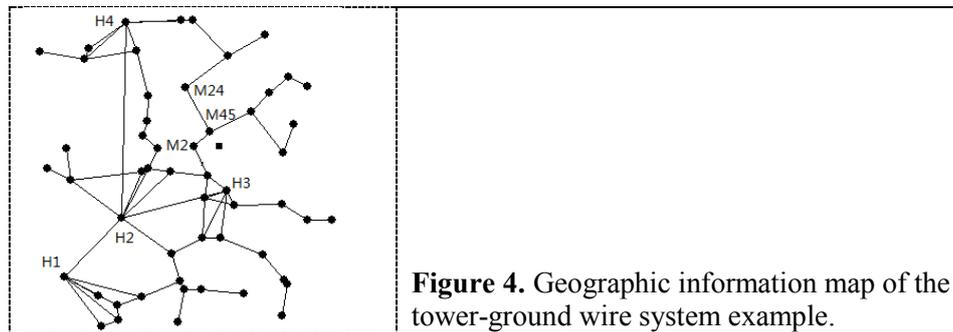


Figure 4. Geographic information map of the tower-ground wire system example.

The DC resistance of the ground wire is $0.588\Omega/\text{km}$. The calculation results of DC current under different tower grounding resistance R_t are shown in Table 5. It can be seen that the tower-ground wire system will increase the DC current distribution in the AC grid, and the smaller the tower grounding resistance, the more the DC current increases.

Table 5. Calculation results under different tower grounding resistance.

DC (A)	I_Z	I_t	I_{S500+}	I_{C500+}	I_{C500-}	I_{N220+}	I_{N220-}
No tower	908.5	0	330.1	142.7	125.0	765.8	783.4
$R_t=3\Omega$	1047.2	1005.4	359.4	171.8	137.3	875.4	909.9
$R_t=5\Omega$	1034.8	897.3	357.4	170.4	136.3	864.4	898.6
$R_t=10\Omega$	1015.6	744.7	354.0	168.0	134.6	847.6	881.0
$R_t=20\Omega$	993.8	590.1	349.9	164.8	132.5	829.0	861.3
$R_t=30\Omega$	980.4	500.7	347.3	162.6	131.2	817.8	849.2

Optical fiber composite ground wire (OPGW) is often used for overhead ground wire in reality. The OPGW has a very small DC resistance, so the current flowing through the ground line may be larger. Changing the DC resistance of ground wire R_w , the calculation results are shown in Table 6. It can be seen that the smaller the ground wire resistance, the more the DC current increases.

Table 6. DC Current calculation results (A) under different DC resistances of ground lines (A).

R_t (Ω)	R_w (Ω/km)	I_Z	I_t	I_{S500+}	I_{C500+}	I_{C500-}	I_{N220+}	I_{N220-}
30	2	950.9	290.2	340.3	153.0	129.1	797.9	821.8
30	1	967.8	404.9	344.3	158.1	130.5	809.7	837.3
10	2	966.1	410.9	343.5	155.3	130.5	810.8	835.6
10	1	992.8	588.6	349.3	161.9	132.8	830.9	860.0
10	0.2	1052.9	1068.7	361.4	180.3	136.0	872.6	917.0
5	0.2	1084.6	1296.5	366.1	184.1	138.8	902.3	947.5

The DC current distribution in a single line is observed below, taking $R_w=1\Omega/\text{km}$ and $R_t=10\Omega$ as an example. The DC current distribution of the 500kV substation neutral point and the grounding wire is shown in Figure 5(a), and the DC current distribution in the two 220kV lines near the DC grounding electrode is shown in Figure 5(b).

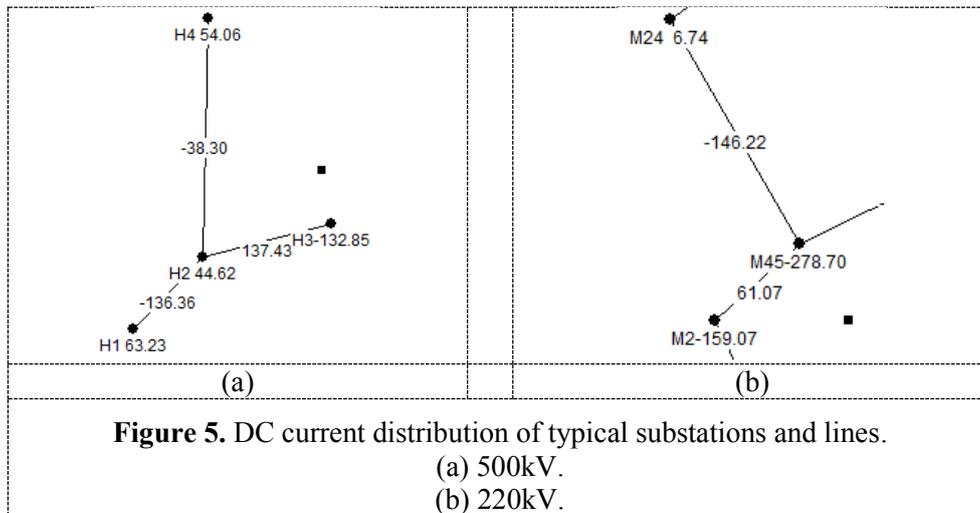


Figure 5. DC current distribution of typical substations and lines.
 (a) 500kV.
 (b) 220kV.

The current distribution of the towers along the lines H4 to H2, M24 to M45, and M45 to M2 are shown in Figure 6.

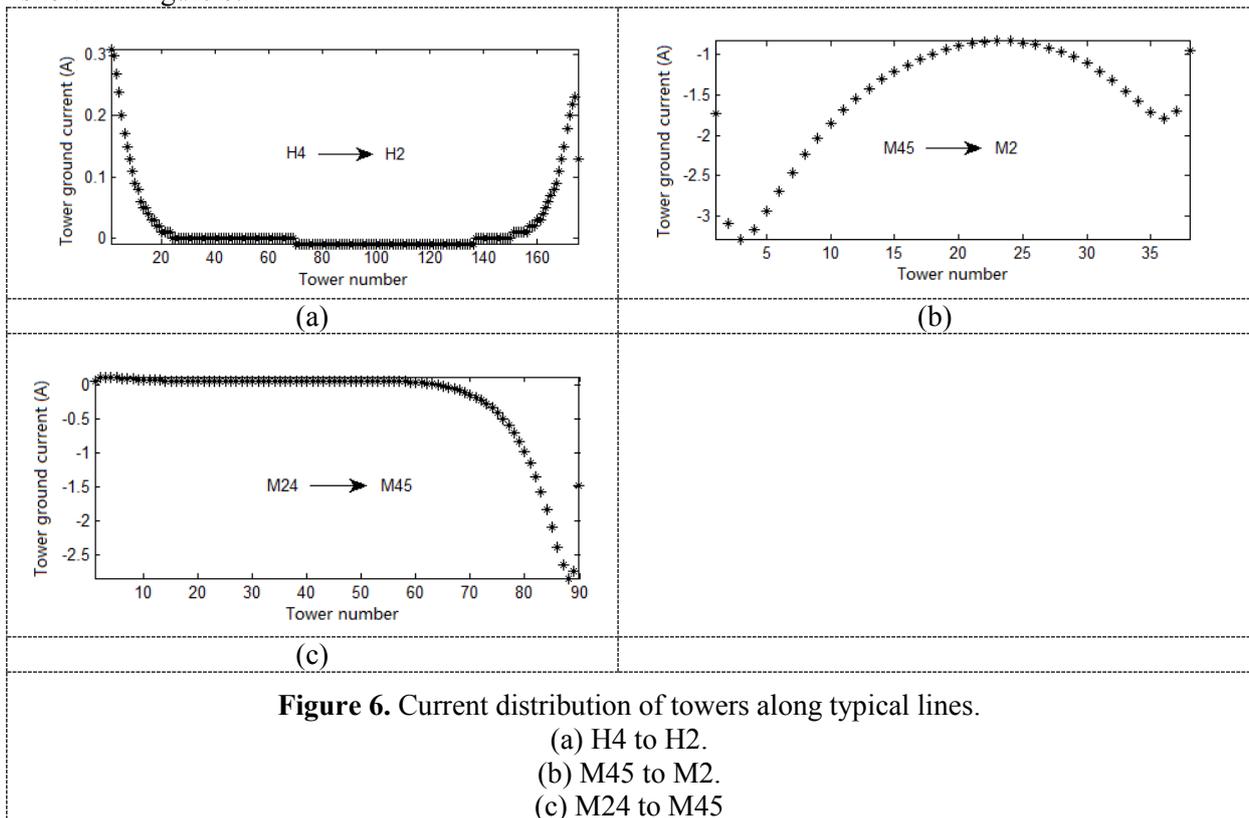


Figure 6. Current distribution of towers along typical lines.
 (a) H4 to H2.
 (b) M45 to M2.
 (c) M24 to M45

The results show that:

(1) Tower-ground wire system is also an important distribution path of DC current, which will increase the DC current distribution on transformer windings. This is because the grounding wire is connected to the substation grounding grid, and the current flowing into the towers is not equal to the current flowing out of the towers. The current flowing into the substation grounding grid from the ground wire changes the potential of the substation node, thus increasing the DC current distributed in the AC grid.

(2) The substation near DC grounding electrode is more affected by tower-ground wire system. In the above example, the DC current of some transformer windings near DC grounding electrode increases by more than 10% after considering tower-ground wire system.

(3) In a line, the grounding current of the tower is non-uniform, and the tower with the greatest current generally appears in the tower 1-4# near the substation with larger grounding current amplitude. Often the DC current of the tower closest to the substation is not the largest, which is due to the induced potential of the tower near the substation is distorted by grounding current of the substation.

4. Conclusion

(1) The simulation model of transmission line, substation, tower-ground wire system and mutual resistance between substations is established. The essence of the DC current distribution is that the AC grid provides a diffusing path for ground current in addition to the earth under the mutual resistance coupling of many buried grounding conductors.

(2) In the calculation of DC current distribution in large-scale AC power grid, neglecting the mutual resistance effect between substations will make the DC current distribution of AC power grid larger, so it is not appropriate to neglect the mutual resistance between substations in the calculation process.

(3) The denser the grid and the smaller the circuit resistance of transformer and transmission line branch of a certain voltage level, the larger the DC current of the voltage level grid and the total DC current of the AC grid, but there is a trend of saturation.

(4) The existence of tower-ground wire system increases the DC current distribution of AC power grid. The smaller the ground wire DC resistance and the tower grounding resistance, the more the DC current increases. In a line, the grounding current of the tower is non-uniform, and the tower with the greatest current generally appears in the towers 1-4# near the substation with larger grounding current amplitude.

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