Hazard evaluation of ground potential difference within grounding grid on personal safety under impulse current

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Abstract
Due to the impedance characteristic of conductor, the ground potential rise is different within grounding grid when impulse current is injected. When staff touches objects with different GPR at the same time, the GPD will be applied to human body, leading to potential personal safety problem. The impact of GPD on human body needs to be evaluated. The method of moment was used to calculate the ground potential rise of grounding grid under impulse current. By regarding the human body as a resistance, the current flowing through it because of ground potential difference was obtained. Methods based on current amplitude and electrical charge was used to evaluate personal safety. The effects of injecting current waveform, injecting position, soil resistivity, grounding conductor and grounding grid structure on ground potential difference and safe current threshold were studied. Results show the ground potential difference near injecting point may pose a threat to personal safety. The evaluation method based on electrical charge was recommended. In field test, the injecting point of grounding grid should be far away from corners, and staff should be kept away from the injecting point, so as to mitigate the risk of ground potential difference on personal safety.

1 INTRODUCTION

Grounding device is a very important part to ensure the safety of operators and equipment in substation. When a lightning strike or a ground short-circuit fault occurs in substation, grounding grid plays the role of draining current into ground and balancing ground potential. Under the effect of grounding current, grounding grid has a potential rise relative to the distant ground which is called ground potential rise (GPR). Due to the impedance characteristics of conductor, current flowing through will produce a voltage drop on it. The GPR within grounding grid is not equal, leading to ground potential difference (GPD). When grounding experiments with high current are carried out in substation [1–3], if staff touches objects with different grounding points at the same time, the GPD will be applied to human body.

Current research on GPD mainly focuses on the case of power frequency short circuit, and the calculation method and influencing factors of the GPD within the grounding grid were studied [4–6]. Since GPD will be coupled to secondary equipment through shielded layer of cable, the GPD should be limited to a safe value. Li analysed a breaker mis-operation accident during a 500 kV current transformer grounding fault, and suggested GPD should be limited to 1000 V [7]. The voltage response characteristics of grounding grids under impulse current are quite different from those of power frequency [8, 9]. A lot of experiments and numerical calculations on the impulse characteristics of grounding grid have been done [10–15]. Although calculation results show that there are obvious differences in GPR within grounding grid under impulse current [16, 17], the influence of GPD is not deeply considered. Grcev calculated the GPR of a 60 m × 60 m grounding grid when current with waveform 1/20 µs 1 kA was injected into centre of grounding grid [18]. Soil resistivity is 100 Ω·m in the calculation. The amplitude difference of GPR within grounding grid reached 3 kV, and the GPD will be larger and may cause safety problem when the soil resistivity is higher or grounding grid size is larger. In recent years, the problem of GPD under impulse current has begun to attract attention. Cable voltage coupled by GPD under impulse current was measured [19]. If grounding down leads of lightning rods, arresters and door structures are simply one-point connected to grounding grid,
great GPD may appear when substation suffers from lightning [20]. Although the GPD waveform is obtained in the above study, its influence on personal safety is not considered. In terms of grounding design, only the contact voltage and step voltage under power frequency short circuit current are specified as evaluation criterion of personal safety [21–23], and the case of impulse current is not considered.

Duration of impulse current is short, but it may still cause cardiopulmonary arrest [24]. Although there have been a lot of studies on impact of current on human body, the current waveforms concerned are quite different from the lightning current waveform or impulse current waveform that commonly used in test [25]. IEC/TR 60479-4 discusses the impact of lightning strikes on human beings and livestock, but it focuses on the difference between electric shock generated by lightning strikes and power systems [26], and the safe current threshold is not involved. IEC 60479-2 provides the safe current threshold for current duration from 0.1 to 10 ms [27]. Kopsidas refers this result to evaluate personal safety caused by pipeline induced voltage when lightning strikes the transmission line [28]. Safe current amplitude of 8 A and body resistance of 500 Ω were used in the study, which shows that the impulse voltage will pose a threat to personal safety when exceeding 4 kV. Panescu proposed a ventricular fibrillation threshold (VFT) model based on the amount of electrical charge was proposed in 2015 [29], which can be applied to currents with duration of 1 µs to 300 s. IEC 60479-2 mentions that ventricular fibrillation depends on the amount of electrical charge \( I \times t \) when current duration is less than 10 ms, and cites the work by Panescu, but the personal safety evaluation based on electrical charge in lightning domain was not reported so far as author knows. As there is no recognized method for personal safety evaluation under impulse current, methods based on current amplitude and electrical charge were both used and compared in this paper.

In order to study the impact of GPD within grounding grid on personal safety under impulse current. The mechanism of the impact of GPD on human body was analysed first, then the personal safety evaluation methods were introduced. The influence of GPD on personal safety was analysed through specific example. Safe current threshold obtained by different evaluation methods were compared, and the influencing factors on GPD and safe current threshold were studied. Finally, suggestions for grounding experiments with high current in substation were put forward.

2 MECHANISM OF THE IMPACT OF GPD ON PERSONAL SAFETY

2.1 Hazardous conditions analysis

When staff touches objects with different GPR at the same time, the GPD will be applied to human body. Figure 1 shows two cases in which GPD affects personal safety. In case A, staff touches the test lead, the GPD between test lead and ground under feet is applied to human body. In case B, staff touches the test lead with one hand and the nearby grounding conductor with the other hand, the GPD between test lead and grounding conductor is applied to human body. In case A, in addition to human body impedance, the grounding resistance of foot also needs to be considered. The bottom of shoe is generally insulated, which can limit the influence of GPD. Therefore, the impact of GPD on personal safety mainly focuses on case B.

2.2 Evaluation method of impulse current on personal safety

2.2.1 Evaluation method A based on current amplitude

IEC TS 60479-2 2019 provides safe current threshold that causes ventricular fibrillation at different durations when current flows from left hand to left foot. Using the heart-current factor \( F \) in IEC TS 60479-1 2018, the safe current threshold \( I_h \) when current flows through human body by different paths can be obtained by Equation (1).

\[
I_h = \frac{I_{ref}}{F}
\]  

(1)

Where, \( I_{ref} \) is safe current threshold when current flows from left hand to left foot. Since this study mainly focuses on the current flowing through both hands, the value of \( F \) is set to 0.4. Duration of GPD under impulse current is about 100 µs, and...
2.2.2 Evaluation method B based on electrical charge

Panescu summarized the relationship between the amount of electrical charge $Q$ flowing through chest and ventricular fibrillation, proposing the VFT model with the $Q$ as evaluation criterion, the $Q$ can be calculated by Equation (2).

$$Q = \int I_{body}(t) dt$$  \hspace{1cm} (2)

When current duration is less than 100 $\mu$s, the electrical charge threshold of ventricular fibrillation can be taken as 1 mC.

2.3 Calculation and evaluation of the impact of GPD on personal safety

The GPR of grounding grid was calculated by method of moment [30], and the GPD waveforms between different positions within grounding grid can be obtained based on GPR waveforms. The human body resistance is set as 1000 $\Omega$ referring to IEEE Std 80–2013. Current waveform flowing through human body can be obtained based on GPD waveform and body resistance. The safety evaluation methods mentioned above are used to calculate safe current threshold.

A 240 m $\times$ 240 m grounding grid model with mesh size of 15 m $\times$ 15 m was established as Figure 2. The grounding steel conductor is with the depth of 0.8 m, radius of 0.01 m, relative resistivity of 10 and relative permeability of 636. Soil resistivity is 500 $\Omega\cdot$m, and current with waveform of 8/20 $\mu$s 1 A is injected at point A.

GPR waveforms at different positions are shown in Figure 3. Injecting current waveform is positive while part of GPR waveform is negative. This is because the length of ground conductor is too long, so that catadioptric effect of current in grounding conductor is obvious. And negative current mainly appears near the injecting point. The point further away from injecting point has less negative current. GPR decreases with distance increasing from injecting point, and the decreasing rate also decreases. GPR at point A is the largest, while GPR at point H is the smallest. When it is far enough from injecting point, GPR no longer has obvious changes, such as point G and H.

Consider the most extreme case of GPD, namely the GPD between point A and H, current waveform flowing through human body is shown in Figure 4. The calculation results of GPD are linear without considering the soil ionization. When the magnitude of injecting current reaches 3.5 kA, the current amplitude applied by GPD on human body will reach 20 A. Since part of current waveform is negative, the absolute value of current is used in integration to obtain the value $Q$. When the magnitude of injecting current reaches 9.3 kA, the electrical charge $Q$ flowing through human body reaches 1 mC. Safe
TABLE 1  Safe current thresholds when touching different positions

| Safe current thresholds [kA] | A–F | A–E | A–D | A–C | A–B |
|-----------------------------|-----|-----|-----|-----|-----|
| Method A                    | 3.5 | 3.7 | 4.2 | 5.0 | 7.2 |
| Method B                    | 9.9 | 11.0| 13.3| 16.1| 24.2|
| B–F                        | 6.2 | 7.1 | 9.8 | 15.6| 34.2|
| Method A                    | 15.9| 19.5| 28.8| 47.4| 78.6|
| Method B                    | 23.0| 32.5| 72.3|

current thresholds when touching different positions are shown in Table 1.

When objects touched by both hands are far away from the injecting point, GPD has less impact on personal safety. The shape of current waveform cannot be considered in evaluation method A, and the safe current threshold obtained by method A is about 1/3 of that obtained by method B.

The evaluation criteria for method A is based on Figure 23 of IEC 60479-2, which gives the safe currents flowing through the human body at different current durations. The current flowing through the human body with smaller duration is allowed to have larger amplitude. But minimum duration of the current in Figure 23 is 100 $\mu s$. The safety current corresponding to 100 $\mu s$ is used to hazard evaluation while the duration of GPD waveform is less than 100 $\mu s$. Therefore, the evaluation criterion of method A is excessively strict. Considering the waveform characteristics of GPD, method B is recommended for evaluation. Evaluation method B is used in the following study.

3 | INFLUENCING FACTORS OF GPD

Based on the previous grounding grid model, the influencing factors of GPD were studied. For the convenience of comparison, the situation with maximum GPD is taken, that is, the waveform of GPD between points A and H.

3.1 | Current waveform

The impulse current waveform of 1.2/50 $\mu s$ and 8/20 $\mu s$ was considered respectively, and current amplitude was 1 A. Maximum GPD of grounding grid is shown in Figure 5. Part of GPD waveform under current of 8/20 $\mu s$ is negative, while GPD waveform under current of 1.2/50 $\mu s$ is always positive. The electrical charge value $Q$ flowing through human body under current with waveform of 8/20 $\mu s$ is 1.2 times of that under current with waveform of 1.2/50 $\mu s$. The 1.2/50 $\mu s$ current waveform reaches peak faster and lasts longer, but GPR waveform of ground grid is significantly different from injecting current waveform. GPR drops rapidly after reaching peak, leading to a smaller integrated area of absolute value.

3.2 | Injecting position

The current was injected into point A, B, C, D, E and F, respectively, and maximum GPD of grounding grid is shown in Figure 6. When current is injected at different positions,
TABLE 2  Safe current thresholds under different injecting points

| Injecting point | A    | B    | C    | D    | E    | F    |
|-----------------|------|------|------|------|------|------|
| Safe current    |      |      |      |      |      |      |
| threshold [kA]  | 9.3  | 13.2 | 16.6 | 19.5 | 23.0 | 26.3 |

FIGURE 7  Maximum GPD under different soil resistivity

the safe current thresholds are shown in Table 2. When current is injected at points D and F, the safe current thresholds are 2.1 and 2.8 times of that injected at point A, respectively. When injecting point is closer to the centre of grounding grid, maximum GPD is smaller. Current evenly distributes around when it was injected at the centre point. If the injecting point is deviated from centre point, current will be biased towards the direction with a smaller grounding impedance, resulting in larger potential difference on conductors towards that direction.

### 3.3 Soil resistivity

The soil resistivity is taken to be 500, 1000, 1500 and 2000 Ω·m, respectively. Maximum GPD of grounding grid is shown in Figure 7, the safe current thresholds are shown in Table 3. The GPD increases with soil resistivity. When soil resistivity increased from 500 to 1000 Ω·m, the GPD peak increased by 1.8 V and safe current threshold decreased by 22.6%, while when soil resistivity increased from 1500 to 2000 Ω·m, the GPD peak increased 0.9 V and the safe current threshold is reduced by 7.8%. Therefore, GPD is more sensitive to changes in soil resistivity when soil resistivity is small.

TABLE 3  Safe current thresholds under different soil resistivity

| Soil resistivity [Ω·m] | 500  | 1000 | 1500 | 2000  |
|------------------------|------|------|------|-------|
| Safe current threshold [kA] | 9.3  | 7.2  | 6.4  | 5.9   |

FIGURE 8  Maximum GPD under different grounding conductors

3.4 Grounding conductor

The radius of grounding conductor is 0.01 or 0.005 m, and materials are chosen to be steel or copper. Maximum GPD waveform of grounding grid is shown in Figure 8, and safe current thresholds are shown in Table 4. When radius is 0.01 m, the safe current threshold for copper conductor is 15.1% greater than that for steel conductor. When the radius increased from 0.005 to 0.01 m, the safe current threshold increased by 17.7% and 5.9%, respectively for steel conductor and copper conductor. Because the copper conductor is already well conductive, the further increase in radius has a poor improvement on reducing conductor resistance.

### 3.5 Mesh size

Different mesh size such as 15 m × 15 m, 24 m × 24 m and 30 m × 30 m are considered. Maximum and minimum GPR of grounding grid are shown in Figure 9, and maximum GPD of grounding grid is shown in Figure 10. As the mesh size increases, maximum GPR decreases, while minimum GPR shows no significantly change. To sum up, the GPD decreases as mesh size increases. Table 5 shows the safe current thresholds with different mesh sizes. When mesh size is 15 m × 15 m,

TABLE 4  Safe current thresholds under different grounding conductors

| Material       | Copper | Copper | Steel | Steel |
|----------------|--------|--------|-------|-------|
| Radius [m]     | 0.005  | 0.01   | 0.005 | 0.01  |
| Safe current   | 10.1   | 10.7   | 7.9   | 9.3   |

TABLE 5  Safe current thresholds under different mesh sizes

| Mesh size [m] | 15 × 15  | 24 × 24  | 30 × 30  |
|---------------|----------|----------|----------|
| Safe current  | 9.3      | 8.1      | 7.6      |
| threshold [kA]|          |          |          |
the safe current threshold increased by 22.4% compared with the mesh size of 30 m × 30 m.

3.6 Grounding grid size

Grounding grid models of 240 m × 240 m, 180 m × 180 m and 105 m × 105 m are established respectively. Maximum and minimum GPR of grounding grid are shown in Figure 11, and the maximum GPD of grounding grid is shown in Figure 12. As grounding grid size increases, minimum GPR increases, while maximum GPR shows no significant change. Therefore, the GPD increases as grounding grid size increases. However, due to the inductance effect of ground conductor, GPD tends to saturate after grounding grid increasing to a certain extent. Table 6 shows the safe current thresholds with different grounding grid size. When grounding grid size increases from 180 m × 180 m to 240 m × 240 m, safe current threshold increases by 2%. Generally, the area of substation is large, so grounding grid size has less influence on maximum GPD.

3.7 Summary and recommendation

Since the area of substation grounding grid is generally large, the problem of GPD within grounding grid is common. In the case of higher soil resistivity and larger mesh size of grounding grid, GPD caused by impulse current is more likely to pose a threat to personal safety. Due to the inductance effect of grounding conductor, the size of substation grounding grid has less effect on the maximum GPD. The influence of GPD can be reduced by improving conductivity of ground conductor or reducing mesh size, but improvement is poor as the safe current thresholds are below 11 kA under different mesh sizes and grounding conductors, while material cost will be greatly increased. The influence of GPD can be reduced better by selecting injecting point reasonably. When injecting point is 64 m from corner, the safe current threshold increases to 19.5 kA.

| Mesh size [m]  | 240 × 240 | 180 × 180 | 105 × 105 |
|----------------|-----------|-----------|-----------|
| Safe current threshold [kA] | 9.3       | 8.1       | 7.6       |
4 CONCLUSIONS

GPD may pose a danger to personal safety when impulse current is injected into grounding grid. The method of moment was used to calculate the GPD within grounding grid. Body resistance of 1000 Ω was used to obtain the current flowing through human body by GPD. The evaluation method based on electrical charge is recommended for personal safety evaluation.

Influencing factors of GPD and safe current threshold were analysed. When injecting point is near the centre of grounding grid, the maximum GPD will decrease significantly. The safe current thresholds when current is injected at the centre are 2.8 times of that injected at the corner. The increase in soil resistivity from 500 to 1000 Ω·m resulted in a 22% decrease in safe current threshold. The size of substation grounding grid has less influence on the maximum GPD. When grounding grid size increases from 180 m × 180 m to 240 m × 240 m, safe current threshold increases by 2%. The improvement is poor by reducing the mesh size of grounding grid or improving the conductivity of grounding conductor, as the safe current thresholds are increased less than 20% under different mesh sizes and grounding conductors, while material cost will be greatly increased.

It is suggested to select the current injecting point away from corners to reduce the influence of GPD. And staff in substation should ensure the insulation of shoes, wear insulating gloves and avoid touching objects with different grounding points during experiment.

ACKNOWLEDGEMENT

This research was supported by State Grid Corporation of China (No. 52170219001D).

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How to cite this article: Li C, Wen X, Guo L, Chen J, Chen J, Lu H. Hazard evaluation of ground potential difference within grounding grid on personal safety under impulse current. IET Sci. Meas. Technol. 2021;15:544–550. https://doi.org/10.1049/smt2.12055