Study on sensitivity and selectivity of three-stage current protection in distribution network with distributed generation

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Abstract. The connection of DG (Distributed Generation) changes the topology of distribution network, which will lead to the change of current detected by relay protection, and the sensitivity and scope of protection will be affected. On the basis of introducing the setting calculation principle of three-stage current protection in distribution network, taking a 10kV distribution network with DG as a model, the influence of DG capacity change on the selectivity and sensitivity of three-stage current protection is discussed in detail when short circuit occurs in different locations such as downstream, adjacent and upstream lines. The corresponding restrictive factors are analyzed and the influence degree of DG access on the original protection is given after comprehensive comparison. It is concluded that comparing different short circuit locations, DG has the most serious impact on the stage-I selectivity of downstream protection when the short circuit occurs at DG downstream line. The conclusions in this paper are of great value to ensure the reliability of power supply of distribution network when a large number of DGs are connected to the grid.

1. Introduction

When DG is connected to distribution network, the system will become a multi-power interconnection structure and DG will cause a series of changes in the magnitude and direction of short-circuit current [1]-[3]. For this reason, the std. IEEE 1547 clearly stipulates that DG should be isolated first when fault occurs in distribution network with current protection as the main protection [4]. Therefore, various adaptive protection schemes based on digital microprocessor protection are proposed in many literatures [5], [6]. However, an in-depth analysis of the impact of DG access on protection is an important prerequisite. At present, distribution networks in China are mostly the radial grid structure with one-side power supply, which are equipped with traditional three-stage current protection. In recent years, the capacity of DG access has become larger and larger, so it is particularly important to analyse the impact of DG access [7], [8]. The operating characteristics of inverse-time overcurrent protection with the changing of fault location with and without DG connection were revealed in literature [9]. The scheme of improving protection sensitivity in distribution network with DG was analysed in references [10], [11], but the short-circuit point was only located on DG downstream line, and the short-circuit locations of upstream or adjacent lines were not considered. The over-current protection system proposed in reference [12] can reduce mis-operation and many fault locations were set, but there was no comparison between them to analyze the impact degree. The location of short-circuit will directly affect the performance of the original protection. The principle of three-stage over-
current protection is introduced, and then a typical 10kV distribution network model with DG is established in this paper. For different short-circuit locations, the influence of DG on the selectivity and sensitivity of three-stage current protection is studied and compared.

2. Principles of three-stage current protection in distribution network

Classical three-stage current protection is widely used in distribution networks in China, i.e., current fast-break protection (I), time-limited current fast-break protection (II) and time-fixed over-current protection (III)[13].

1) Current fast-break protection (I)

Stage I is set according to the condition of avoiding the short circuit at the outlet of the next line, and the action current value is:

$$I_{1\text{set}(l)} = k_{rel}^{I}I_{k1,\text{max}}^{(3)}$$

(1)

The subscript "1" in equation (1) indicates line 1. Reliability coefficient of stage I is $k_{rel}^{I} = 1.2\sim1.3$. $I_{k1,\text{max}}^{(3)}$ is the three-phase short-circuit current value at the end of line 1 under the maximum operating mode. Generally, the two-phase short circuit is checked under the minimum operating mode, requiring the protection range to be greater than 15%~20% of the total length of the protected line. The operation time of fast-break protection depends on the inherent operation time of the relay itself, which is generally less than 10 ms.

2) Time-limited current fast-break protection (II)

Stage II is required that the full length of line 1 can be protected under all circumstances. It must have sufficient sensitivity and the action current value is:

$$I_{1\text{set}(ll)} = k_{rel}^{II}I_{2\text{set}(l)} = k_{rel}^{II}k_{rel}^{I}I_{k2,\text{max}}^{(3)}$$

(2)

Subscript "2" in equation (2) indicates the next line adjacent to line 1. Reliability coefficient of stage II is $k_{rel}^{II} = 1.1\sim1.2$. $I_{2\text{set}(l)}$ is the setting value of stage I of line 2 and $k_{rel}^{I}$ is reliability coefficient of stage I. $I_{k2,\text{max}}^{(3)}$ is the three-phase short-circuit current value at the end of line 2 under the maximum operating mode. The sensitivity should be satisfied,

$$K_{sen}^{II} = \frac{i_{k2,\text{min}}^{(2)}}{I_{1\text{set}(ll)}} \geq 1.3\sim1.5$$

(3)

$K_{sen}^{II}$ in formula (3) is the sensitivity coefficient of stage II. $i_{k2,\text{min}}^{(2)}$ is two-phase short-circuit current value at the end of line 2 under the minimum operating mode. The operation time $t_{1}^{II}$ of stage II should be a time step $\Delta t$ higher than $t_{2}^{I}$ of fast-break protection of the next line adjacent to line 1, i.e., $t_{1}^{II} = t_{2}^{I} + \Delta t$. The value of $\Delta t$ is usually 0.5s.

3) Time-fixed over-current protection (III)

Stage III is generally used as the far backup protection of next line and the near backup protection of this line. Its starting current is set to avoid the maximum load current, and the value is:

$$I_{1\text{set}(III)} = \frac{k_{rel}^{III}k_{ss}}{k_{re}}I_{\text{max}}$$

(4)

Reliability coefficient of stage III is $k_{rel}^{III} = 1.15\sim1.25$. $k_{ss}$ is a self-starting coefficient with the value greater than 1, which should be determined by the specific wiring and load characteristics of the network. Return coefficient of current relay is $k_{re} = 0.85\sim0.95$. $I_{\text{max}}$ is maximum load current in normal operation. When overcurrent protection is the main protection of this line, $K_{sen}^{III} \geq 1.3\sim1.5$ is required. When overcurrent protection is the backup protection for adjacent line, $K_{sen}^{III} \geq 1.2$ is required. The operation time of Stage III is determined according to the principle of reverse steps.
3. Analysis of the influence of DG on three-stage current protection at different short circuit locations

3.1. Typical 10 kV distribution network

As shown in Figure 1, the typical 10 kV distribution network is constructed. The lengths of AB, BC, CD and AE, EF are 5km and 4km, respectively. Line impedance parameters are $R = 0.013 \Omega/km$, $L = 0.9337 \times 10^{-3} H/km$, $C = 12.74 \times 10^{-9} F/km$ and load parameters are Load1=1MVA, Load2=1.5MVA. $Z_{DG}$ is the equivalent impedance of DG. Considering the slow attenuation of DG fault current, the sub-transient impedance $Z_{DG}^{st}$ will be used to analyze stage I protection and the transient impedance $Z_{DG}^{tr}$ will be used to analyze stage II, stage III protection.

![Figure 1. 10 kV distribution network.](image)

3.2. Short circuit occurs on DG downstream line

As shown in Figure 1, three-phase short circuit occurs at the end of line 2 when $t = 0.1s$.

1) Analysis of the influence on protection 2

When DG is not connected, the three-phase short-circuit current flowing through protection 2 is

$$I_{2_{before}} = \frac{E_S}{Z_S + Z_{L1} + Z_{L2}}$$

(5)

After DG is connected, the short circuit current detected by protection 2 is:

$$I_{2_{after}} = \frac{E_{S-G}}{(Z_S + Z_{L1})/Z_{DG} + Z_{L2}}$$

(6)

$E_{S-G}$ in equation 6 indicates that the system S and DG provide power together at this time. Obviously, equation 6 has more DG equivalent impedance in parallel than equation 5, so $I_{2_{after}} > I_{2_{before}}$ may lead to wrong operation of protection 2. In theory, stage II of protection 2 should operate to remove the fault when the short circuit occurs at the end of line 2, but with the increasing capacity of DG, the measured current $I_{2C}$ value flowing through protection 2 will be larger than the set value $I_{2set}$ (I) of stage I when DG=7.6 MVA in the experiment. The result is that the stage I of protection 2 mis-operates as shown in Figure 2, which will lead to wider blackouts when the short circuit occurs at the head of L3. Figure 3 shows the relationship between the A and C phase current amplitudes $I_{2A}$ and $I_{2C}$ flowing through protection 2 and the setting values $I_{2set}$ (I), $I_{2set}$ (II) and $I_{2set}$ (III) of protection 2.

![Figure 2. The relationship between $I_{2C}$, $I_{2set}$ (I) and DG capacity.](image)

![Figure 3. The relationship between $I_{2set}$ (I), $I_{2set}$ (II), $I_{2set}$ (III) and $I_{2A}$, $I_{2C}$.](image)
When downstream short circuit occurs, the selectivity of stage I of protection 2 is the key. When DG is not connected, the setting value of stage I of protection 2 is:

$$I_{set.2}^I = 1.2 \times \frac{E_s}{Z_{Smin} + Z_{L1} + Z_{L2}}$$  \hfill (7)

When three-phase short circuit occurs at L2 terminal under maximum operation mode with DG, the following formula should be satisfied according to protection selectivity if DG access does not lead to maloperation:

$$\frac{E_s}{(Z_{Smin} + Z_{L1})/Z_{DG} + Z_{L2}} < I_{set.2}^I$$  \hfill (8)

2) Analysis of the influence on protection 1

After DG is connected, the current flowing through protection 1 is:

$$I_{laffer} = \frac{E_s}{(Z_s + Z_{L1})/Z_{DG} + Z_{L2}} \times \frac{Z_{DG}}{Z_s + Z_{L1} + Z_{DG}} = \frac{1}{Z_s + Z_{L1} + Z_{DG} (1 + \frac{Z_{setL2}}{Z_{DG}})}$$  \hfill (9)

Clearly, DG capacity ↑⇒ $I_{laffer} \downarrow$⇒ Sensitivity ↓⇒ Protection 1 refuse action. When the short circuit occurs at the end of line 2, the stage III of protection 1 should act as the far backup protection. But when DG=59.2MVA in the experiment, the current value measured by protection 1 is less than the stage III setting value. Consequently, the stage III of protection 1 refuses to operate and the far backup fails, as shown in Figures 4 and 5. Although the measured current value of protection 1 will decrease, the downstream short circuit itself does not belong to the protection scope of stage I, II of protection 1, so it has no effect on the stage I,II of protection 1 at this time. Compared with protection 2, the stage III of protection 1 may refuse to operate when large capacity DG is connected, so the impact of DG on upstream protection 1 is far less than that on downstream protection 2.

When DG downstream short circuit occurs, only stage III of protection 1 is used as a far backup. If DG access does not cause refusal action of protection, the corresponding sensitivity should be satisfied:

$$\frac{\sqrt{3}}{2} \times \frac{E_s}{(Z_{Smax} + Z_{L1})/Z_{DG} + Z_{L2}} > 1.2 I_{set.1}^{III}$$  \hfill (10)

Conclusion:(a) The downstream current increases with DG, which may cause protection mal-operation;(b) The upstream current reduces with DG, which may cause protection rejection;(c) The influence of DG on downstream protection is far greater than that on upstream protection.

3.3. Short circuit occurs in adjacent E bus

1) Analysis of the influence on protection 4

Because of the augmentation effect of DG, the current measured by protection 4 will increase, which is helpful to improve the sensitivity of protection 4[14], but at the same time it will extend the range of stage I of protection 4. When the permeability reaches a certain value, the stage I of protection 4 will mis-operate. The stage I setting value of protection 4 is:

$$I_{set.A}^I = 1.2 \times \frac{E_s}{Z_{Smin} + Z_{L4}}$$  \hfill (11)
The two-phase short-circuit current flowing through protection 4 is:

\[ I^{(2)} = \frac{\sqrt{3}}{2} I^{(3)} = \frac{\sqrt{3}}{2} \times \frac{E_S}{Z_{\text{Smax}}/(Z_{DG}+Z_{L4})+aZ_{L4}} \] (12)

In the equation (11) and (12), \( Z_{\text{Smax}} \) and \( Z_{\text{Smin}} \) represent the system impedances under the minimum and maximum operating modes respectively. The sensitivity check requires that the protection range of stage I is larger than 15% of the total length of the protected line, so \( \alpha \geq 15\% \). Sensitivity check requirements for stage I of protection 4 is \( I^{(2)} > I_{\text{set.1}}^{(2)} \), i.e.,

\[ \frac{\sqrt{3}}{2} \times \frac{1}{Z_{\text{Smax}}/(Z_{DG}+Z_{L4})+0.15Z_{L4}} > \frac{1.2}{Z_{\text{Smin}}+Z_{L4}} \] (13)

Considering the selectivity of stage I of protection 4, the three-phase short-circuit current at line 4 terminal bus E should be less than the stage I setting value under the maximum operation mode, that is to say, the following requirement should be met.

\[ \frac{1}{\sqrt{3}} \times \frac{1}{Z_{\text{Smax}}/(Z_{DG}+Z_{L4})} < \frac{1.2}{Z_{\text{Smin}}+Z_{L4}} \] (14)

To meet the sensitivity of stage II of protection 4, the following requirement should be met.

\[ \frac{\sqrt{3}}{2} \times \frac{1}{Z_{\text{Smax}}/(Z_{DG}+Z_{L4})+Z_{L4}} > 1.3 \times 1.1 \times \frac{1}{Z_{\text{Smin}}+Z_{L4}+Z_{L5}} \] (15)

The stage II of L4 can protect the whole length of L4. After DG is connected, the protection range of stage II of L4 is extended to the next feeder L5. However, the selectivity of stage II of L4 is guaranteed by the time limit \( \Delta t \), so the increase of current caused by DG access will not affect the selectivity of stage II of L4. Similar analysis shows that the sensitivity of stage III of protection 4 is improved and its selectivity is guaranteed by \( \Delta t \).

2) Analysis of the influence on protection 1

When short circuit occurs at E-bus without DG, the load current of line 1 detected by protection 1 is very small. When short circuit occurs at the adjacent E-bus with DG, the reverse boost current provided by DG will be detected by protection 1, whose value is:

\[ I_1 = I_4 \times \frac{Z_S}{Z_{L1}+Z_{DG}+Z_S} = \frac{E_S}{Z_{L1}+Z_{DG}+Z_S} \times \frac{Z_S}{Z_{L1}+Z_{DG}+Z_S} = \frac{E_S}{Z_{L1}+Z_{DG}+Z_S} \] (16)

Clearly, DG capacity \( \uparrow \Rightarrow I_1 \uparrow \Rightarrow I_4 \uparrow \Rightarrow \) current flowing through protection 1 \( \uparrow \). This will probably cause the measured current value to exceed the stage II setting value of protection 1, which will lead to the mis-operation of stage II to remove the whole non-fault line 1, resulting in widening the blackout scope and seriously affecting the reliability of power supply. It can be seen from the above equation that when short circuit occurs at the adjacent line, \( I_1 \ll I_4 \), the probability of mis-operation of protection 1 is far less than that of protection 4, and DG has greater influence on protection 4.

After DG is connected, the situation of short circuit occurring at the head of L4 is analyzed. In the case of this most serious short circuit, the following formula should be satisfied in order to meet the selectivity of protection 1.

\[ \frac{E_S}{Z_{\text{Smin}}/(Z_{DG}+Z_{L1})} < I_{\text{set.1}}^{(2)} = 1.2 \times \frac{E_S}{Z_{\text{Smin}}+Z_{L1}} \] (17)

This formula is easy to satisfy, which shows that compared with mis-operation of stage I of protection 2 under DG action in downstream short circuit, the probability of mis-operation of stage I of protection 1 in short circuit of adjacent lines is much lower.

3.4. Short circuit occurs on DG upstream line

When a short circuit occurs at a point F of L1 line upstream of DG, the total current of the fault point F will be provided by both the system S and DG. The current detected by protection 1 is not affected by DG, but because protection 1 can only detect the short-circuit current supplied by the system power supply S, its detection value will be less than the actual short circuit current value. The problem is that the short-circuit current is very large, but it can not be detected by the original protection, resulting in protection 1 refusal action, unable to remove the fault. At the same time, because there is no protective device between f-point and DG access point, it is impossible to remove the short-circuit current
supplied by DG to the short-circuit point. To solve this problem, a set of directional protection device is added at the end of L1. Limited to space, this issue will be further discussed in another article.

3.5. Analysis of the influence factors of DG access on the original protection

Based on the above analysis, the summary is shown in Table 1 and Table 2.

**Table 1.** Short circuit at different locations, sensitivity and selectivity analysis of each protection.

| Short circuit position | selectivity and sensitivity analysis of each protection |
|------------------------|------------------------------------------------------|
| Short circuit on DG downstream line | |
| Protection 1 | Stage-I Sen. Sel. | Stage-I F10 Δt |
| Protection 2 | Stage-I Δt F8 |
| Stage-I | |
| Conclusion: DG access makes the current of protection 1 decrease slightly, and the possibility of protection 1 rejection caused by DG access is very small. |

| Table 2. The degree of impact by DG access on each protection. |
|---------------------------------------------------------------|
| Short circuit location | protection 1 | protection 2 | protection 4 |
|------------------------|--------------|--------------|--------------|
| DG downstream line     | / RCR※       | ICM※※※       | / / / / / /  |
| DG adjacent line       | ICM※ ICM※   | / / / / ICM※※ | / / / / / /  |
| DG upstream line       | PR PR        | / / / / / / / | / / / / / /  |
| Notes: "※" means the degree of impact by DG access. "ICM※" = "Increase Causes Maloperation." "RCR※" = "Reduction Causes Rejection." "PR" = "Possible Rejection." |

Based on the previous analysis and comprehensive comparison, it can be concluded that the most significant impact of DG access on the original protection is the influence of DG on the stage I selectivity of downstream protection 2 when downstream short circuit occurs. At the same time, directional protection should be added at the end of DG upstream line to remove the reverse short circuit current provided by DG.
4. Conclusions
DG access changes the distribution of short-circuit current in the original network. The influence of DG on the sensitivity and selectivity of the original three-stage current protection is studied when short-circuit occurs in different locations. The conclusions are as follows: (1) When short-circuit location is on DG downstream line, DG's contribution to downstream protection is far greater than its reduction to upstream protection. (2) When short-circuit location is on DG adjacent line, compared with upstream protection, DG is more likely to cause adjacent protection malfunction. (3) When short-circuit location is on DG upstream line, DG causes the upstream protection detection current value to be less than the actual current value, and thus refuses to operate. (4) Comparing all short-circuit locations, the greatest influence by DG access is on the stage I selectivity of downstream protection when DG downstream line is short-circuited.

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