Double-K Differential Protection Principle of Regional Power Grid Based on Voltage Vector Compensation

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Abstract. In the regional active distribution network where the Distributed Generation (DG) penetration rate is getting higher and higher. When a high-resistance ground fault occurs in a heavy-load line, the traditional current differential protection has very low sensitivity, the protection may refuse to act. And the power differential protection has the voltage dead zone. In addition, the T-type branch will further reduce the sensitivity of the traditional differential protection. In order to solve the problems, this paper proposes a new principle of double-K differential protection with voltage vector compensation. The principle can flexibly adjust the braking zone range by setting two parameters, and then introduce the voltage vector to compensate the operating point, which effectively improves the protection sensitivity in the case of high-resistance ground fault occurs in a heavy-load line, and there is no voltage dead zone. Simulation shows that the principle can greatly improve the reliability of protection.

1. Introduction
The current differential protection is not affected by the direction of the current, with simple principle and fast action, which can better adapt to the requirements of current power system operation and protection [1]. However, when a high-resistance ground fault occurs on the line with heavy load, there is a large through current, and the protection sensitivity is not high. Many literatures have been improved on the basis of traditional current differential protection to improve the sensitivity of protection [2-7]. Literature [8] proposed a calculation power differential protection based on a two-port network, but there is a voltage dead zone problem. Literature [9] proposed a virtual active power differential protection principle based on the fault component. Literature [10] proposed a three-stage active differential threshold protection principle based on the split-phase active power. Literature [11-13] proposed a new line protection principle suitable for new energy access by calculating the integrated impedance of the line. However, most of the above principles did not consider the T-type branch, and this situation needs to be considered in the context of an increasing proportion of new energy sources and flexible access to controllable sources.

According to the above analysis, this paper proposes a new principle of double-K differential protection with voltage compensation. The main work of this paper are: 1) Considering the T-type branch, a new principle of differential protection with dual setting values is proposed, which can flexibly adjust the range of the braking zone; 2) The voltage compensation value of the current differential protection is calculated by using the voltage signal and the line parameters, which effectively increases the protection sensitivity, The compensated action equation has the nature of
power differential protection, and the protection criterion does not have the voltage dead zone; 3) A dual-terminal power supply circuit was built on the MATLAB/simulink, and the line fault simulation was performed to verify the validity of the new principle.

2. Traditional Split-phase Current Differential Protection Principle

The operating conditions of the traditional current longitudinal differential protection is:

\[
\begin{align*}
|I_m + I_n| & \geq I_{sc} \\
|I_m - I_n| & \leq K|I_m - I_n|
\end{align*}
\]

In the equation, the braking coefficient \( K \) is a positive number not greater than 1. Call \( \rho = \frac{I_m}{I_n} = x + jy \) as the operating point, \( I_m \) is the measured current with a larger current amplitude, and \( I_n \) is the smaller one. \( \rho \) is located inside a unit circle. The scope of the braking zone is:

\[
|I_m + I_n| \leq K|I_m - I_n|
\]

Divide both sides of the equation by \( I_m \), substitute it into \( \rho = x + jy \), and get simplified:

\[
(x + \frac{1+K^2}{1-K^2})^2 + y^2 \leq \left( \frac{1+K^2}{1-K^2} \right)^2 - 1
\]

The braking zone is a circular area with a center \((-\frac{1+K^2}{1-K^2},0)\) and a radius \((\frac{1+K^2}{1-K^2})^2 - 1)^{1/2}\). Increasing \( K \) will increase the range of the braking zone, and the protection will not be easy to misoperation, but the sensitivity will decrease. Usually \( K \) is between 0.3 and 0.9 [14]. Under normal circumstances, the protection principle has very high reliability, but the protection sensitivity is low when the heavy load is grounded with high resistance. In particular, the Distributed Generation (DG) connected to the distribution network through T-type branch have a greater impact on traditional differential protection [15]. The differential current during normal operation or a fault outside the protection zone will increase; and will decrease during a fault within the protection zone. And the degree of effect will increase with the increase of T-type branch capacity, which seriously affects the reliability of protection.

3. Principle of Double-\( K \) Differential Protection with Voltage Vector Compensation

3.1. Double-\( K \) Differential Protection Principle

In order to ensure the optimal protection reliability and sensitivity, it is necessary to introduce a parameter to change the traditional current differential protection into a double \( K \) value current differential protection. The operating conditions of the protection are:

\[
|K_1 I_m + I_n| \geq K_2 |I_m|
\]

In the equation, \( K_1 \) and \( K_2 \) are two new braking coefficients.

The braking range can be obtained from the protection operating conditions. Both sides of the equation are divided by \( I_m \) and substituted into \( \rho = x + jy \). After simplification, we get:

\[
(K_1 + x)^2 + (y)^2 \leq K_2^2
\]

The center of the braking zone of the new differential protection criterion is \((-K_1,0)\) and the radius is \( K_2 \). The range of the braking zone can be flexibly adjusted by changing the values of \( K_1 \) and \( K_2 \).

3.2. The Principle Advantage of Double-\( K \) Differential Protection and the Selection of \( K \)

Take \( I_m \) as the horizontal axis unit vector of the plane coordinate system to make the action characteristics of the current differential protection, as shown in figure 1.
Define the length of the line segments AB and CD in figure 1 as the horizontal and vertical ranges of the braking zone, respectively. Operating point $\rho$ is within the unit circle. Generally, the differential current when the line fails is relatively large, and $\rho$ falls in the right semicircular area, and the protection operates reliably. However, when a high-resistance ground fault occurs in a heavy-load line, $\rho$ will move to the left, approaching the braking zone, and the protection sensitivity is low.

For the active distribution network connected by DG through T-type branch, when the protection zone is normal, the differential current of the line is mainly reflected in the amplitude. This is because the line power factor is close to 1, and the inverter of DG usually sets the reactive current to 0. It can be considered that the proportion of T-type branch current is the same as that of T-type capacity. Different from the traditional differential protection with a single $K$, the double-$K$ differential protection principle can realize the separate control of the horizontal and vertical ranges of the braking zone by changing the values of $K_1$ and $K_2$. It can increase the horizontal range of the braking zone without changing the vertical range to improve the reliability of protection.

The selection of double-$K$ needs to meet the requirements of protection reliability and sensitivity. In order to simplify the calculation, refer to the traditional current differential protection, here is a rough value method for $K_1$ and $K_2$: 1) For lines without T-type branch, since the normal operating point is always near (-1,0), this point is set as the center of the braking zone, that is, $K_1$ takes 1. The selection of the radius of the braking zone needs to be determined according to the line operating conditions and the measurement error of the device. Generally, the reasonable value of $K_2$ is between 0.4 and 0.9; 2) For lines with T-type branch, assuming that the proportion of T-type branch capacity is $\lambda$ ($0 \leq \lambda \leq 1$), it can be considered that the operating point of DG is near ($-(1-\lambda), 0$) at the rated output. Because of the uncertainty of new energy output, the actual operating point will fluctuate between ($-(1-\lambda), 0$) and (-1,0). Therefore, the center of the braking zone is set as the midpoint of the two points, that is, $K_1$ takes $\frac{2-\lambda}{2}$, and the value of $K_2$ is adjusted to be between $\frac{2-\lambda}{2} - 0.6$ and $\frac{2-\lambda}{2} - 0.1$ accordingly.

3.3. Voltage Vector Compensation
In order to solve the problem of low protection sensitivity when the heavy-load line is grounded with high resistance, this paper introduces the split-phase bus voltage signal at the protection installation to compensate the operating point $\rho$ and improve the protection sensitivity. This compensation is suitable for the protection of regional power grids with potential transformers at both ends.

3.3.1. DG is Connected to the Grid Through the Bus of the Public Grid Substation. When there is no fault in the line in the protection zone, as shown in figure 2. In the figure, $Z_f$ is the impedance of the line, and $Y$ is the earth capacity of the line; $U_m$ and $U_n$ are the voltage vectors at both ends of the line; $I_m$ and $I_n$ are the measured values of the current at both ends of the line; $I_{mc}$ and $I_{nc}$ are the earth capacity current; $I'_m$ and $I'_n$ are the line current after subtracting the earth capacity current.
In the medium and low-voltage distribution network, the line-to-ground capacitance current is very small and can be ignored. The voltage and current relationship is as follow:

\[ U_m - U_n = I_m Z_l \]
\[ U_n - U_m = I_n Z_l \]  \hspace{1cm} (6)

When a short-circuit fault occurs in the area, as shown in figure 3. In the figure, \( D \) is the line fault point, \( \alpha \) is a constant between 0 and 1, which represents the position of the fault point \( D \) in the line; \( I_p \) is the short-circuit point that flows out of the line current.

Define the maximum line calculated voltage drop as \( \Delta U_{\text{max}} = I_m Z_l \), and the minimum line calculated voltage drop as \( \Delta U_{\text{min}} = I_n Z_l \). When there is no fault in the protection zone, the actual voltage drop of the line \( \Delta U = \Delta U_{\text{max}} - \Delta U_{\text{min}} \) \; ; when there is a fault in the zone, \( \Delta U = [\alpha I_m - (1-\alpha)I_n] Z_l = \Delta I \cdot Z_l \).

Thus, the \( M \)-side compensation is defined as:

\[ \delta_m = \frac{\Delta U}{\Delta U_{\text{max}}} \]  \hspace{1cm} (7)

The corrected operating point is \( \rho_m = \delta_m \cdot \rho \). Draw a vector diagram in the coordinate system of figure 1. In the figure, \( I_n \) is the same as \( \rho \), and \( \Delta I \) is the same as \( \delta_m \), as shown in figure 4.

In the figure, \( \overline{OM}, \overline{ON}, \overline{OP}, \overline{OQ} \) represents \( I_m, I_n, \Delta I, \rho_m \) respectively, \( \theta_l \) is the compensation angle provided by \( \delta_m \), and \( \Delta OMP \) is similar to \( \Delta ONQ \).

In most cases, \( \delta_m \) has a good compensation effect. But when \( \alpha \) is close to 1, point P is very close to point M, and there is almost no compensation effect, as shown in figure 5(a). And when the differential current at the time of failure is large and \( \alpha \) is close to 0, the compensation angle \( \theta_l \) is large, it will shift \( \rho \) to the braking zone instead, which has the opposite effect, as shown in figure 5(b).
Figure 5. When the compensation effect of M-side compensation amount is not well.

Therefore, it is necessary to introduce another compensation amount for the above two cases, and define the N-side compensation amount as:

\[ \delta_n = \frac{\Delta U_{nm}}{-\Delta U} \]  

(8)

The corrected operating point is \( \rho_n = \delta_n \cdot \rho \). Similarly, draw a vector diagram in the coordinate system of figure 1, and draw \( \rho_n \) for the above two cases, as shown in figure 6.

Figure 6. Operating point after adding N-side compensation.

In the figure, \( OG \), \( OH \) represents \( -\Delta I \), \( \rho_n \) respectively, and \( \theta_2 \) is the compensation angle provided by \( \delta_n \). It is easy to prove that \( ONG \) is similar to \( OHN \). It can be seen that \( \delta_n \) can provide a better compensation effect when the compensation effect of \( \delta_m \) is not good.

3.3.2. DG is connected to the grid through T-type branch. The line model is shown in figure 7.

Figure 7. The line model of T-type branch DG.

In the figure, \( U_{DG} \) is the voltage of T-type branch point, \( I_{DG} \) is the current provided by the DG, the T-type branch point divides the line into two parts, the line resistance are \( Z_1 \) and \( Z_2 \) respectively. The compensation also needs to be divided into two parts.

- When the fault occurs between the M terminal and the T-type branch, need to replace \( U_n \) with \( U_{DG} \), replace \( I_n \) with \( I_n + I_{DG} \), and replace the line resistance with \( Z_1 \).
When the fault occurs between the N terminal and the T-type branch, need to replace $U_m$ with $U_{DG}$, replace $I_m$ with $I_m + I_{DG}$, and replace the line resistance with $Z_2$.

The calculation method of the compensation amount in the two cases is the same as previous section.

4. Simulation

Build a 35kV system model in MATLAB/simulink, the system wiring diagram is shown in figure 8.

![Figure 8. Topology diagram of simple active network with DG.](image)

Figure 8(a) shows the photovoltaic connection line through the bus; Figure 8(b) shows the photovoltaic connection line through the T-type branch. In the figure, the sizes of Load1 and Load2 are 30MW and 20MW, respectively. D1, D2, and D3 are three short-circuit points set. To verify that the new principle does not have voltage dead zone, points D2 and D3 are taken in the vicinity of bus B.

4.1. Simulation Results

Generally, the farther the operating point is from the braking zone in the event of a fault, the higher the sensitivity of the protection. Therefore, the distance from the fault operating point to the braking zone can be used to intuitively reflect the protection sensitivity.

By simulating the fault waveforms when different DG capacity proportion $\lambda$ is connected, the sensitivity comparison between different criteria is calculated and drawn.

4.1.1. Photovoltaic is Connected to the Grid Through the Bus. The braking coefficient $K$ of the traditional differential protection is 0.45. The two parameters of the double-$K$ differential protection are $K_1=1$, $K_2=0.6$ respectively. The sensitivity comparison is shown in figure 9.

![Figure 8](image)
In this case, when the line is in normal operation and a phase-to-phase fault occurs at point D3, the measured operating points are shown in table 1.

| Operating status                      | DG capacity proportion $\lambda$ | $\rho$          | $\rho_m$         | $\rho_e$          |
|---------------------------------------|----------------------------------|-----------------|------------------|------------------|
| normal operation                      | 0.05                             | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ |
|                                       | 0.1                              | $1\angle 180^\circ$   | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ |
|                                       | 0.2                              | $1\angle 180^\circ$   | $1\angle 179.9^\circ$ | $1\angle 180^\circ$  |
|                                       | 0.3                              | $1\angle 180^\circ$   | $1\angle 180^\circ$   | $1\angle 180^\circ$  |
| D3 two-phase grounding short circuit   | 0.05                             | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ |
|                                       | 0.1                              | $1\angle 180^\circ$   | $1\angle 180^\circ$   | $1\angle 180^\circ$  |
|                                       | 0.2                              | $1\angle 180^\circ$   | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ |
|                                       | 0.3                              | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ | $1\angle 179.9^\circ$ |

4.1.2. Photovoltaic is Connected to the Grid Through T-type Branch. According to the different proportion of DG capacity, when $\lambda=0.05$ and 0.1, set the $K$ of the traditional differential protection to 0.45, and the two parameters of the double-$K$ differential are simply set to $K_1=0.95$, $K_2=0.6$. when $\lambda=0.2$ and 0.3, set the $K$ of the traditional differential protection to 0.5, and the two parameters of the double-$K$ differential are set to $K_1=0.9$, $K_2=0.6$. The sensitivity comparison is shown in figure 10.
Figure 10. Sensitivity comparison for line faults with T-type branch.

In this case, when the line is in normal operation and a phase-to-phase fault occurs at point D3, the measured operating points are shown in Table 2.

Table 2. Normal operation in the protected area.

| Operating status          | DG capacity proportion $\lambda$ | $\rho$       | $\rho_m$       | $\rho_n$       |
|---------------------------|----------------------------------|--------------|----------------|----------------|
| normal operation          | 0.05                             | $0.94 \angle 180^\circ$ | $0.94 \angle 179.9^\circ$ | $0.94 \angle 180^\circ$ |
|                           | 0.1                              | $0.88 \angle 180^\circ$ | $0.88 \angle 179.9^\circ$ | $0.88 \angle 179.9^\circ$ |
|                           | 0.2                              | $0.79 \angle 179.9^\circ$ | $0.79 \angle 179.8^\circ$ | $0.79 \angle 179.9^\circ$ |
|                           | 0.3                              | $0.72 \angle 179.6^\circ$ | $0.72 \angle 179.5^\circ$ | $0.72 \angle 179.6^\circ$ |
| D3 two-phase grounding short circuit | 0.05                             | $0.95 \angle 178.1^\circ$ | $0.95 \angle 178.1^\circ$ | $0.95 \angle 178.1^\circ$ |
|                           | 0.1                              | $0.94 \angle 177.4^\circ$ | $0.94 \angle 177.4^\circ$ | $0.94 \angle 177.4^\circ$ |
|                           | 0.2                              | $0.9 \angle 175.2^\circ$ | $0.9 \angle 175.2^\circ$ | $0.9 \angle 175.2^\circ$ |
|                           | 0.3                              | $0.88 \angle 173.5^\circ$ | $0.88 \angle 173.4^\circ$ | $0.88 \angle 173.4^\circ$ |
4.2. Result Analysis
From table 1: When DG is connected to the line through the bus, the operating point is close to (-1,0) under normal operation and outside the protected area. And the differential current is very small, and the protection generally does not misoperation.

From table 2: When DG is connected to the line through T-type branch, even no fault, there is still a large differential current, which is positively correlated with the DG capacity, and is mainly reflected in the current amplitude. This is consistent with the analysis in section 3.2. To prevent the protection from misoperation, the braking zone needs to be enlarged accordingly. For traditional differential protection, it can only be achieved by increasing the $K$. This will increase the horizontal and vertical range of the braking zone simultaneously, reducing the sensitivity of the protection. For double-$K$ differential protection, it can move the center of the braking zone to the right (reduce $K_1$), and the radius remains unchanged ($K_2$ is unchanged) to achieve the effect of only increasing the horizontal range of the braking zone. It is more in line with the change of the operating point in the case of T-type branch.

From figure 9 and figure 10 that due to the reasonable adjustment of the braking zone of the double-$K$ differential protection in the case of T-type branch, the sensitivity of the protection is improved compared to the traditional differential protection.

Combining table 1 and table 2, after adding the voltage compensation amount, when the line is operating normally or there is a failure at point D3, $\rho_\theta$, $\rho_\omega$, and $\rho$ are basically the same, which verifies that the voltage compensation will not increase the risk of protection misoperation. Combined with figure 9 and figure 10, when a fault occurs in the protection zone, the addition of voltage compensation can effectively improve the sensitivity of the protection, and can distinguish the faults at D2 and D3.

5. Conclusion
This paper considers the different access methods of DG. Aiming at the problem that the traditional differential protection may have too low sensitivity and cause the protection to refuse to operate, through the analysis of the relationship between the electrical quantities of the line. A new principle of double-$K$ differential protection with voltage vector compensation is proposed, and it is verified by simulation on the line with heavy load containing DG.

The simulation results show that the operating point $\rho$ is close to the braking zone when the protection zone fails, which causes the traditional differential protection sensitivity to be too low. The new principle can flexibly control the range of the braking zone by setting two parameters, reasonably reduce the braking zone, and increase the protection sensitivity when a fault occurs. Then the operating point is compensated by a voltage signal. This compensation will not interfere with the normal operation of the system, and can effectively improve the sensitivity of the protection. There is no voltage dead zone in the compensation amount, and it can effectively identify faults inside and outside the protection zone to meet the selectivity of protection.

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References
[1] Li Z, Liu C, Zhou Y, et al. 2019 Influence of user-side distributed generation on distribution network current protection Guangdong Electric Power 32(03): 81-87.
[2] Ma S, Wu Z G, Gao H L, et al. 2019 Amplitude comparison protection for distribution network with high permeability distributed generation Power System Protection and Control 47(04): 43-50.
[3] Gao Y, Li Y L, Chen X L, et al. 2021 Adaptive differential protection principle based on current amplitude ratio Proceedings of the CSU-EPSA 33(02): 1-7.
[4] Ma J, Pei X, Ma W, et al. 2014 Differential protection principle based on virtual impedance of fault component for power transmission line Electric Power Automation Equipment 34(12): 58-64+69.

[5] Li H X, Wang X G, Xie J, et al. 2018 A transmission line current differential protection based on virtual brake current Power System Protection and Control 46(09): 75-79.

[6] Zhang X S Ma X, Zhang L Q, et al. 2020 Novel current amplitude differential protection criterion for line with unmeasurable branch in active distribution network Electric Power Automation Equipment 40(02): 76-84.

[7] Deng X T, Yuan R X, Xiao Z F, et al. 2014 Split-phase differential current protection based on instantaneous power theory for power transmission line Electric Power Automation Equipment 34(11): 82-88+94.

[8] Wang L P, Wang X R 2013 Differential protection based on calculated power for uhv transmission lines Proceedings of the CSEE 33(19): 174-182+5.

[9] Huang J K, Gao H L, Peng F, et al. 2017 Virtual active power differential protection for transmission lines Automation of Electric Power System 41(14): 190-196.

[10] Li J, Miao S H, Liu P, et al. 2011 A protection criterion for high resistance grounding of transmission line based on phase-segregated active power differential principle Power System Technology 35(08): 197-201.

[11] Lei L, Tang C D, Qing Y C, et al. 2018 Pilot protection of positive sequence component integrated impedance for distribution network with inverter interfaced distributed generator Power System Protection and Control 46(18): 149-155.

[12] Suonan J L, Deng X Y, Li R S, et al. 2009 Principle of t-type transmission line pilot protection based on fault component comprehensive impedance Electric Power Automation Equipment 29(12): 4-9.

[13] Suonan J L, Liu K, Su X H, et al. 2008 Novel transmission line pilot protection based on integrated impedance Automation of Electric Power System (03): 36-41.

[14] Chen D S, Chen W, Yin X G, et al. 2002 The Phasor characteristic analysis of differential protection Relay (04): 1-3+7.

[15] Han B, Li H, Wang G, Zeng D, Liang Y 2018 A virtual multi-terminal current differential protection scheme for distribution networks with inverter-interfaced distributed generators IEEE Transactions on Smart Grid 9(5): 5418-5431.