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# An Adaptive Protection Scheme for Power Systems Considering the Effects of HVDC Interfaced Distributed Generations

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**ABSTRACT** Distributed Generations are usually connected to the ac grid through HVDC transmission systems. However, due to the current injected by the grid-side voltage source converter (GVSC), the voltage drop after a short-circuit fault will be partly compensated. For this reason, the viewed impedance of distance relays will be affected, which is a challenge for the distance protection scheme. For this issue, this paper proposed an adaptive distance protection scheme for the system containing distributed generations. Firstly, the proposed scheme controls the current of the GSVC to be proportional to the current of the AC transmission line. Secondly, an adaptive distance protection criterion is proposed, which can obtain the impedance from the relay to the fault-point accurately. The effectiveness of the proposed approach was validated through simulation using MATLAB/Simulink.

**INDEX TERMS** Protection delay, distance protection, high-voltage direct current, distributed generations.

## I. INTRODUCTION

The distance protection of high voltage transmission systems is an essential safety measure and plays a vital role to ensure the stability and security of power systems [1]–[5]. In the transmission system of a large-scale power system, the high-voltage long-distance transmission lines are irreplaceable. As the increase of the distance, the probability of short-circuit failure is also increasing. Once a short-circuit fault occurs, it will cause great safety hazards and economic losses. Therefore, distance relay is important to protect the high-voltage transmission system [6]–[10].

### A. DRAWBACKS OF THE TRADITIONAL DISTANCE PROTECTION ALGORITHM

When a short-circuit fault occurs in the high-voltage transmissions, the line impedance will be greatly reduced compared to normal operation. Then, the distance relay will act if the viewed impedance is less than the set value ($Z_{set}$), which is the main principle of distance protection [2]. Moreover, the impedance is proportional to the distance from the fault to the relay, which can help to locate the fault point [2]. Therefore, impedance measurement is important for the distance protection. Traditional distance protection algorithm was proposed at the basis of the short-circuit model, where the impedance to the fault was calculated by the local voltage and current [9], i.e., $|U/I|$. The traditional algorithm was easy to implement, but it mainly had two drawbacks. Firstly, the fault transition impedance was assumed to be zero. In fact, the fault transition impedance of ground fault was able to be regarded as a resistance [2], which introduced an error in impedance measurement. Secondly, the effect of the distributed generation was not considered. Many distributed generations were connected to the high voltage transmission system through the HVDC transmission systems. When a short-circuit fault happened, the current injected by the distributed generation improved the voltage of the fault point, which produced an non-ignorable error in impedance measurement. These errors reduced the reliability of the distance relay [3]–[8].

### B. IMPEDANCE MEASUREMENT METHODS CONSIDERING THE FAULT TRANSITION RESISTANCE

To overcome the errors introduced by the fault transition impedance, several improved impedance measurement

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methods were proposed [1]–[3], [11], [12]. In [1], a protection scheme based on improved virtual measured voltage was proposed. The main idea of this method was to feedback the voltage of the fault-point, and the virtual measured voltage was proposed by combining the voltage of the fault-point, local current and the threshold of impedance ($Z_{set}$). Then, the distance relay needed to act if the amplitude of the measured local voltage was less than the virtual measured voltage. In [2], the fault resistance calculation method based on monitoring the active power of the fault-point was proposed. Since the impedance from the fault-point to the ground was almost pure resistive, then its value was solved according to the power balance equation. Then, by subtracting the fault resistance in the original measured impedance, a more accurate impedance was obtained. In [3], the distance protection strategy based on voltage deviation was proposed. Firstly, the voltage droop equation was proposed according to the V-I characteristics of the transmission lines. Given that the fault transition resistance can not affect the voltage droop equation, the errors introduced by the fault transition resistance will be eliminated. Compared with [2], the method in [1] and [3] needed to feedback the information of the voltage at fault-point.

Moreover, to improve the performance of the distance relay in long-distance cables, a protection scheme based on distributed parameter model was developed in [11]. A method based on the current increments at the fault-point was presented in [12], which can also overcome the error brought by the fault transition resistance. The above proposed methods were proposed based on the system with single source and lines, a protection scheme for long-distance parallel cables was proposed in [13].

On the other hand, several fault distance methods based on traveling-waves were developed [14], [15]. The basic principle of these methods was measuring the distance according to the time interval of traveling-waves [15]. Hence, how to recognize the wavefront returning from the fault-point is a key problem. For this issue, the algorithm based on principal component analysis was proposed for quickly data processing, which helps identify internal faults and external faults [15].

### C. IMPROVED DISTANCE PROTECTION ALGORITHM CONSIDERING THE EFFECT OF THE DISTRIBUTED GENERATIONS

However, the above mentioned works do not consider the influence of the distributed generation. Distributed generation based on renewable energy is usually connected to the AC transmission grid through high-voltage direct current (HVDC) transmission systems. Compared with the AC transmission systems, DC transmission systems provide high transmission efficiency, high reliability, controllability and flexibility [16]–[20]. Although the HVDC transmission system has these advantages, it will bring challenges to the protection relay of the AC transmission system. When a short-circuit fault occurs, the voltage of the fault-point and PCC point will drop rapidly. Then, the grid-side voltage source (GVSC), which is a typical flexible ac transmission system (FACTS) device, will inject reactive power to the PCC point to compensate the voltage quickly. Then, it will bring a notable error for impedance measurement.

To overcome this problem, several works were proposed [21]–[23]. Most of them focuses on the effect of two typical FACTS devices static var compensators and static synchronos compensators on distance relay. In these researches, the FACTS device was equivalent to the constant impedance, then the apparent error was analyzed [22], [23]. The grid-converter of the distributed generation was also a typical FACTS device, which was usually under advanced control methods. So, it can not be equivalent to a constant impedance. To consider the effect of the distributed generation, a robust distance protection scheme based on $\mu$ synthesis analysis technique was proposed [10]. This method controlled the current to keep the defined current ratio $\alpha$ constant. Then, the real impedance can be obtained. However, this work did not consider the effect of the fault resistance.

### D. MOTIVATIONS AND CONTRIBUTIONS

In summary, the fault transition resistance and distributed generation introduced non-ignorable errors in impedance measurement. However, most of the existing methods only overcome the error caused by one of them. This paper studies the protection scheme for the AC transmission system considering the effect of the distributed generation and fault transition resistance simultaneously. Main contributions are as follows.

1. An adaptive protection scheme immune to the fault transition resistance and the distributed generation is proposed. Firstly, the current from the distributed generation is controlled to keep a fixed proportion to the current of the AC transmission line. Secondly, the new adaptive distance protection criterion is proposed to judge whether the fault is in-zone and out-of-zone.

2. The proposed distance protection scheme only need the local current, voltage and the impedance between the relay to the PCC point (where the distributed generation is connected). Compared with [1] and [2], the proposed method does not need to feedback the information (i.e., voltage and active power) of the fault-point.

The remainder of this paper is organized as follows: Section II introduces some related works and problem formulations. Section III describes the proposed adaptive distance protection scheme. Case studies are presented in Section IV. Section V concludes the paper.

## II. RELATED WORKS AND PROBLEM FORMULATIONS

The conventional short-circuit model is presented in Fig. 1. M is the power transmitting terminal, and F is the point where the short-circuit fault occurs. MP is the designed protection zone, i.e., if there is a fault occurs in the interval between M and P, the distance relay will operate. Assume the setting value is $Z_{set}$, then the distance relay will operate if the viewed impedance is less than $|Z_{set}|$. Let $\dot{U}_M$ and $\dot{U}_F$ denote the voltage of the M and F.

In the traditional protection scheme, the voltage of the fault-point is assumed as zero, i.e., the fault transition resistance is zero. Then, the impedance from the relay to the fault-point ($Z$) is obtained as

$$Z = \frac{\dot{U}_M}{\dot{I}_M} \tag{1}$$

where $\dot{I}_M$ is the measured current at M. However, the fault transition resistance is not zero, i.e., $\dot{U}_F \neq 0$. Then, the viewed impedance ($\dot{U}_M/\dot{U}_F$) satisfies

$$\frac{\dot{U}_M}{\dot{I}_M} = \frac{\dot{I}_M Z + \dot{U}_F}{\dot{I}_M} = \frac{\dot{I}_M Z + R_F \dot{I}_M}{\dot{I}_M} = Z + R_F \tag{2}$$

The result in (2) shows that the viewed impedance is not be equal to the impedance from the relay to the fault-point. Moreover, if the distance of MF is long, the fault transition resistance $R_F$ is large, resulting in a great error.

### A. THE EXISTING IMPROVED DISTANCE PROTECTION ALGORITHM IN [3]

To overcome the error brought by the fault transition resistance, an improved distance protection algorithm is proposed in [3]. The short-circuit model considering the fault transition resistance is presented in Fig. 2. There is a transition resistance in F. In this circuit, $\dot{U}_M$, $\dot{U}_F$, $Z$, $R_F$ and $\dot{I}_M$ satisfies

$$\begin{cases} \dot{U}_M = \dot{I}_M Z + \dot{U}_F \\ \dot{U}_F = \dot{I}_M R_F \end{cases} \tag{3}$$

To obtain the accurate value of $Z$, the key is whether $Z$ is derived from equation (3). In (3), $\dot{U}_M$ and $\dot{I}_M$ are known complex numbers, $R_F$ is an unknown real number, $\dot{U}_F$ and $Z$ are unknown complex numbers. Without loss of generality, assume $\dot{I}_M = |\dot{I}_M|\angle 0°$. Then, $\dot{U}_F$ is also a real number as well as $\dot{I}_M$. Thus, equation (3) is equivalent to

$$\begin{cases} Real(\dot{U}_M) = |\dot{I}_M| Real(Z) + |\dot{U}_F| \\ Imag(\dot{U}_M) = |\dot{I}_M| Imag(Z) \\ \dot{U}_F = |\dot{I}_M| R_F \end{cases} \tag{4}$$

Then, it is obtained $Imag(Z) = Imag(\dot{U}_M)/|\dot{I}_M|$. If the $R/X$ of the lines is known, the impedance $Z$ is obtained.

Under the assumption that $R/X$ is known, a geometric method is provided to solve $Z$ in [3], however, the process is complex. Next, this paper provides a more concise and simple method to solve $Z$ based on the Law of Sines.

The vector graphics of $\dot{U}_M$, $\dot{U}_F$ and $\dot{I}_M$ is shown in Fig. 3, where $\varphi_{line}$ is the angle of the transmission line, $\varphi_{ui}$ is the angle difference between $\dot{U}_M$ and $\dot{I}_M$. It is noted that $\varphi_{line}$ is known since $R/X$ of the transmission line is known. Then, in Fig.2, $\angle\varphi_{line}$, $\angle\varphi_{ui}$ and $|OM|$ are known. By invoking the Law of Sines to $\triangle OFM$, (5) is obtained

$$\frac{|OM|}{sin(\pi - \angle\varphi_{line})} = \frac{|MF|}{sin\angle\varphi_{ui}} \tag{5}$$

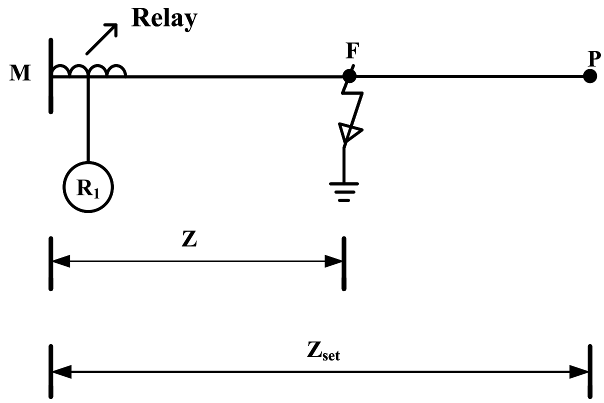


**FIGURE 1.** The short-circuit model of the transmission line without fault transition resistances.

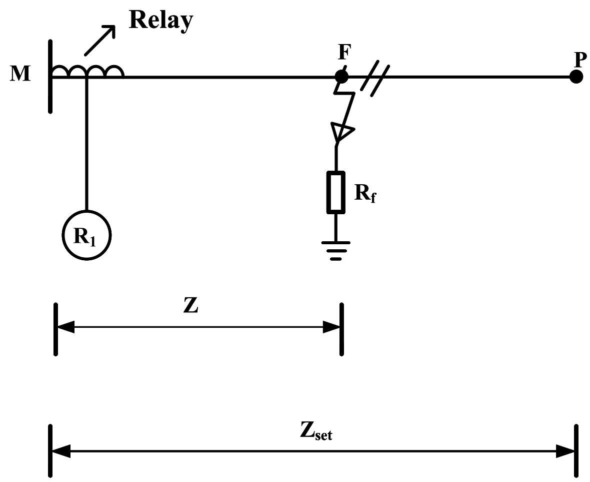


**FIGURE 2.** The short-circuit model of the transmission line with a fault transition resistance.

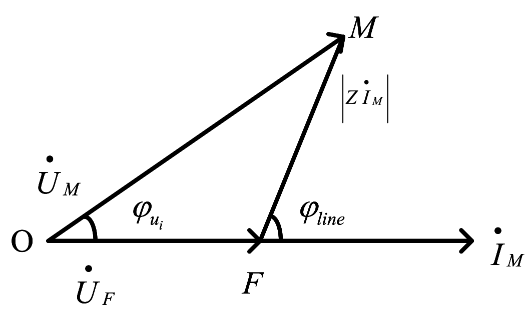


**FIGURE 3.** The vector graphics of $\dot{U}_M$, $\dot{U}_F$ and $\dot{I}_M$.

Considering

$$|OM| = |\dot{U}_M|, |MF| = |Z\dot{I}_M| \tag{6}$$

Combining (5) and (6), $|Z|$ is obtained as

$$|Z| = \frac{|\dot{U}_M|}{|\dot{I}_M|} \frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} \tag{7}$$

Then,

$$Z = \frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}}(cos\angle\varphi_{line} + jsin\angle\varphi_{line}).$$

*Remark 1:* In fact, the ratio of $R/X$ is usually a constant, i.e., it does not change with the length of the transmission line. Then, it is not difficult to obtain. Hence, the method in [3] is able to measure the accurate impedance with only local information for the model in Fig. 2.

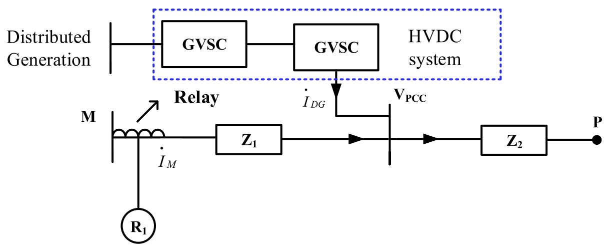


**FIGURE 4. The high-voltage AC transmission system containing distributed generation.**

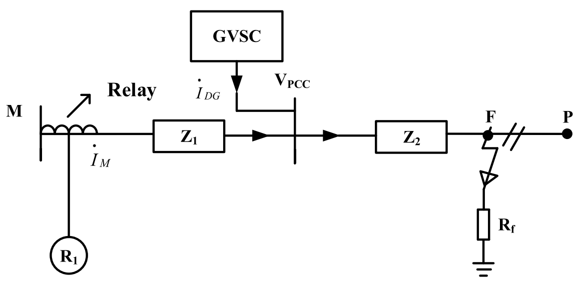


**FIGURE 5. The short-circuit model of the high-voltage AC transmission system containing distributed generation.**

### *B. PROBLEM FORMULATIONS CONSIDERING THE EFFECT OF DISTRIBUTED GENERATIONS*

With the development of the renewable energy, a large number of distributed generations is put into use. There are two main ways to absorb distributed generations. The first is to form a microgrid to supply power to local loads [24], [25], and the second is to connect to the AC transmission grid through HVDC. A high-voltage AC transmission system containing distributed generation is presented in Fig. 4. Let $\dot{I}_{DG}$ denote the current of the GVSC, which is a problem that can not be ignored in measuring impedance after short-circuit fault. A short-circuit model of the high-voltage AC transmission system containing distributed generation is shown in Fig. 5. The impedance from the relay to the fault-point is given by

$$Z = Z_1 + Z_2 \tag{8}$$

where $Z_1$ is the impedance from the relay to the PCC point, and $Z_2$ is the impedance from the relay to the fault-point. According to the traditional protection algorithm, the measured impedance is

$$\begin{aligned}\frac{\dot{U}_M}{\dot{I}_M} &= \frac{(R_F + Z_2)(\dot{I}_M + \dot{I}_{DG}) + Z_1\dot{I}_M}{\dot{I}_M}\\ &= Z + R_F + (R_F + Z_2)\frac{(\dot{I}_{DG})}{\dot{I}_M}\end{aligned} \tag{9}$$

Equation (9) indicates that the impedance error of the traditional method is $R_F + (R_F + Z_2)\frac{\dot{I}_{DG}}{\dot{I}_M}$, which is notable. Moreover, the methods in [1]-[3] [11]-[13] do not consider the effect of $\dot{I}_{DG}$. Let $\dot{U}_{PCC}$ denote the voltage of the PCC point. The relation among $\dot{U}_M$, $\dot{U}_F$, $\dot{U}_{PCC}$ is given by

$$\begin{cases}\dot{U}_M = \dot{I}_M Z_1 + \dot{U}_{PCC}\\ \dot{U}_{PCC} = (\dot{I}_{DG} + \dot{I}_M)Z_2 + U_F\\ \dot{U}_F = (\dot{I}_{DG} + \dot{I}_M)R_F\end{cases} \tag{10}$$

The vector graph of $\dot{U}_M$, $\dot{U}_F$ and $\dot{U}_{PCC}$ is given in Fig. 6. Clearly, the relation among the voltage vectors are more complex than Fig.3. Due to the presence of $\dot{I}_{DG}$, $Z_1$, $Z_2$ and $R_F$ can not be obtained from the local measured current $\dot{I}_M$ and voltage $\dot{U}_M$.

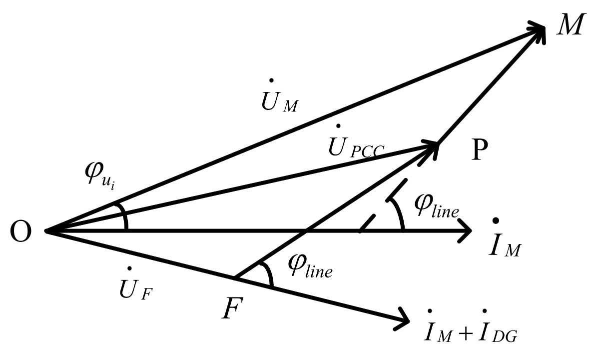


**FIGURE 6. The vector graph of $\dot{U}_M$, $\dot{U}_F$ and $\dot{U}_{PCC}$. $\vec{OF}$, $\vec{OP}$ and $\vec{OM}$ are $\dot{U}_F$, $\dot{U}_{PCC}$ and $\dot{U}_M$, respectively. $\varphi_{line}$ is the angle of $Z_1$ and $Z_2$.**

To the best knowledge of ours, how to design an adaptive distance protection algorithm for the system in Fig. 5 has not been addressed. For the distance relay, the main task is how to obtain the impedance from the relay to the fault-point only through the local measurement. Next, we will focus on the following two objectives.

Q1. Design a control scheme for GVSC to help the distance relay.

Q2. Design an adaptive distance protection algorithm to identify whether the fault is in-zone or out-of-zone by using the local information.

## III. THE PROPOSED ADAPTIVE DISTANCE PROTECTION SCHEME

This section proposes an adaptive distance protection scheme for the system considering distributed generations. It contains two part as follows:

- The proposed control strategy of GVSC;
- The proposed distance protection criterion.

### A. THE PROPOSED CONTROL STRATEGY OF GVSC

The main purpose of the GVSC is transforming the DC voltage to three-phase AC voltage. The average state-space model under d-q frame is given by

$$\dot{x} = Ax + Bu \tag{11}$$

where $x = \left[i_{Ld}\ i_{Lq}\ u_{Cd}\ u_{Cq}\right]^T$, $u = \left[u_d\ u_q\right]^T$, $A$ and $B$ are as follows.

$$A = \begin{bmatrix} 0 & \omega & -\frac{1}{L} & 0 \\ -\omega & 0 & 0 & -\frac{1}{L} \\ \frac{1}{C} & 0 & \frac{1}{CR_{eq}} & \omega \\ 0 & \frac{1}{C} & -\omega & \frac{1}{CR_{eq}} \end{bmatrix}, \quad B = \frac{U_{dc}}{L}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{12}$$

To make it easier to detect impedance from the relay to the fault-point, control $\dot{I}_D G$ as $\dot{I}_D G = \alpha \dot{I}_M$, where $\alpha$ is a constant. To achieve $\dot{I}_D G$ as $\dot{I}_D G = \alpha \dot{I}_M$ quickly, the control law of the input of GVSC is designed as

$$u = k_p\begin{bmatrix} I_{Md} - I_{DGd} \\ I_{Md} - I_{DGd} \end{bmatrix} + k_i\int\begin{bmatrix} I_{Md} - I_{DGq} \\ I_{Md} - I_{DGq} \end{bmatrix}dt \tag{13}$$

where $I_{Md}$, $I_{Mq}$, $I_{DGd}$ and $I_{DGq}$ are components of $\dot{I}_M$ and $\dot{I}_{DG}$ under d-q frame, respectively.

Then, if the system of GVSC is stable, $\dot{I}_{DG}$ is regarded as $\dot{I}_{DG} = \alpha \dot{I}_M$.

*Remark 2:* For distance protection, the key is to quickly measure the impedance between the relay and the fault point while using the local information as much as possible. If $\dot{I}_{DG} = \alpha \dot{I}_M$, the impedance can be obtained with only local information ($\dot{U}_M$, $\dot{I}_M$). So, the proposed method is not universal, but it is helpful for impedance measurement.

### B. THE PROPOSED DISTANCE PROTECTION CRITERION

To achieve measuring the impedance from the relay to the fault-point locally, the following assumptions are made.

- The impedance from the relay to the PCC point ($Z_1$) is known;
- The ratio $R/X$ of $Z_1$ is same with $Z_2$.
- There is no load connected to the PCC point, and loads are connected to the system at P.

In fact, the distance from the relay to the PCC point is fixed, so the impedance can be measured. Moreover, if the type of the cable is same, the ratio $R/X$ of $Z_1$ is same with $Z_2$. Hence, the above two assumptions are reasonable. Under these assumptions, the fault current is equal to $\dot{I}_M + \dot{I}_{DG}$.

Then, the relation among $\dot{U}_M$, $\dot{U}_F$, $\dot{U}_{PCC}$ is given by

$$\begin{cases} \dot{U}_M = \dot{I}_M Z_1 + \dot{U}_{PCC} \\ \dot{U}_{PCC} = (1+\alpha)\dot{I}_M Z_2 + U_F \\ \dot{U}_F = (1+\alpha)\dot{I}_M R_F \end{cases} \tag{14}$$

The vector graph of $\dot{U}_M$, $\dot{U}_F$ and $\dot{U}_{PCC}$ in (14) is given in Fig.7. Since $\dot{U}_M$, $\angle\varphi_{ui}$ and $\angle\varphi_{line}$ are known, by invoking the

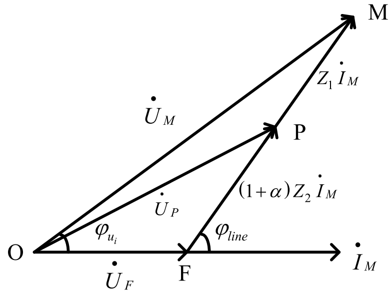


**FIGURE 7.** The vector graph of $\dot{U}_M$, $\dot{U}_F$ and $\dot{U}_{PCC}$ in equation (14). $\vec{OF}$, $\vec{OP}$ and $\vec{OM}$ are $\dot{U}_F$, $\dot{U}_{PCC}$ and $\dot{U}_M$, respectively. $\varphi_{line}$ is the angle of $Z_1$ and $Z_2$.

Law of Sines, (15) is obtained

$$\frac{|MF|}{sin\angle\varphi_{ui}} = \frac{|OM|}{sin\angle\varphi_{line}} \tag{15}$$

According to (15), $|MF|$ is obtained as

$$|MF| = |OM|\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} \tag{16}$$

On the other hand, $|FP|$ yields

$$|FP| = |FM| - |PM| \tag{17}$$

Combining (16) and (17), the following is obtained

$$|(1+\alpha)Z_2\dot{I}_M| = |OM|\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} - |Z_1\dot{I}_M| \tag{18}$$

From (18), $|Z_2|$ is obtained as

$$|Z_2| = \frac{1}{1+\alpha}\left(\frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} - |Z_1|\right) \tag{19}$$

Then, the impedance from the relay to the fault-point is obtained as

$$|Z| = |Z_1 + Z_2| = \frac{1}{1+\alpha}\frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} + \frac{\alpha}{1+\alpha}|Z_1| \tag{20}$$

If the fault occurs between M and PCC point, $Z$ is obtained in (7). If the fault occurs between PCC point and P, $Z$ is obtained in (20). Then, for the fault between M and P, $Z$ is obtained as follows

$$\begin{cases} |Z| = \frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} & if\ \frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} \leq |Z_1| \\ |Z| = \frac{1}{1+\alpha}\frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} + \frac{\alpha}{1+\alpha}|Z_1|, & otherwise \end{cases} \tag{21}$$

The quadrilateral characteristics of a wide application of distance relay in the power system is shown in Fig. 8, where $R_{set}$ and $X_{set}$ are the setting value of the resistance and reactance, respectively. When the measured impedance in (21) is in the protection zone in Fig. 8, the protection relay will act. Then, the proposed adaptive protection criterion is proposed as follows.

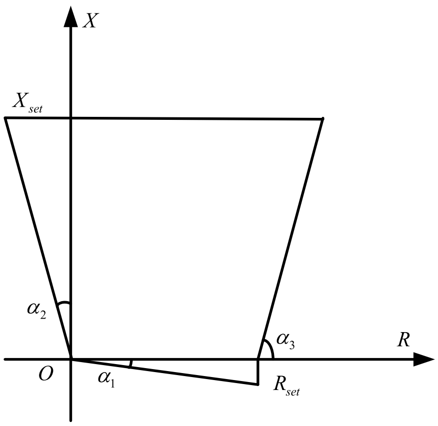


**FIGURE 8.** Distance relay with the quadrilateral characteristic.

In the quadrilateral characteristic, the operation equations of Quadrant I, II and IV are (22), (23) and (24), respectively.

$$\begin{cases} |Z|(cos\angle\varphi_{line} - sin\angle\varphi_{line}cot\angle\alpha_3) \le R_{set} \\ |Z|sin\angle\varphi_{line} \le X_{set} \end{cases} \tag{22}$$

$$\begin{cases} cos\angle\varphi_{line} \le sin\angle\varphi_{line}tan\angle\alpha_2 \\ |Z|sin\angle\varphi_{line} \le X_{set} \end{cases} \tag{23}$$

$$\begin{cases} |Z|cos\angle\varphi_{line} \le R_{set} \\ sin\angle\varphi_{line} \ge -cos\angle\varphi_{line}tan\angle\alpha_2 \end{cases} \tag{24}$$

### C. THE DISTANCE PROTECTION CRITERION OF THE SYSTEM WITH TWO DISTRIBUTED GENERATIONS

The short-circuit model of the system with two distributed generations is presented in Fig. 5 (b). Let $\dot{I}_{DG1}$ and $\dot{I}_{DG2}$ denote the current of the GVSC1 and GVSC2. Similarly, assume $\dot{I}_{DG1} = \alpha_1\dot{I}_M$, $\dot{I}_{DG2} = \alpha_2\dot{I}_M$, and

- $Z_1$ and $Z_2$ are known;
- $Z_1$, $Z_2$ and $Z_3$ has the same ratio $R/X$.
- There is no load connected to the $P_1$ and $P_2$.

Then, the relation among $\dot{U}_M$, $\dot{U}_F$, $\dot{U}_{P1}$ and $\dot{U}_{P2}$ is given by

$$\dot{U}_M = \dot{I}_M(Z_1 + (1+\alpha_1)Z_2 + (1+\alpha_1+\alpha_2)Z_3) + \dot{U}_F \tag{25}$$

Similarly, by invoking the Law of Sines, $|MF|$ is obtained as

$$|MF| = |OM|\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} \tag{26}$$

Then, the following is obtained

$$|(1+\alpha_1+\alpha_2)Z_3\dot{I}_M| = |OM|\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} - |Z_1\dot{I}_M| - |(1+\alpha_1)Z_2\dot{I}_M| \tag{27}$$

From (27), $|Z_3|$ is obtained as

$$|Z_3| = \frac{1}{1+\alpha_1+\alpha_2}(\frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} - |Z_1| - (1+\alpha_1)|Z_2|) \tag{28}$$

Then, the impedance from the relay to the fault-point is obtained as

$$|Z_3| = \frac{1}{1+\alpha_1+\alpha_2}(\frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}} + (\alpha_1+\alpha_2)|Z_1| + \alpha_2|Z_2|) \tag{29}$$

For the fault between M and P, $Z$ is obtained as follows

$$\begin{cases} |Z| = \bar{Z}, \quad if\,|\bar{Z}| \le |Z_1| \\ |Z| = \frac{1}{1+\alpha}\bar{Z} + \frac{\alpha}{1+\alpha}|Z_1|, if\ |Z_1| < |\bar{Z}| \le |Z_1| + |Z_2| \\ |Z_3| = \frac{1}{1+\alpha_1+\alpha_2}(|\bar{Z}| + (\alpha_1+\alpha_2)|Z_1| + \alpha_2|Z_2|), \\ if\,\bar{Z} > |Z_1| + |Z_2| \end{cases} \tag{30}$$

where $\bar{Z} = \frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}}$.

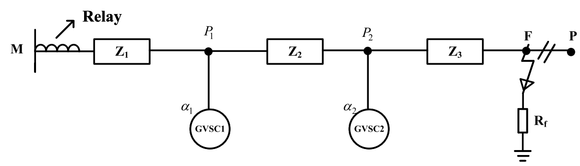


**FIGURE 9.** The short-circuit model of the high-voltage AC transmission system containing two distributed generations.

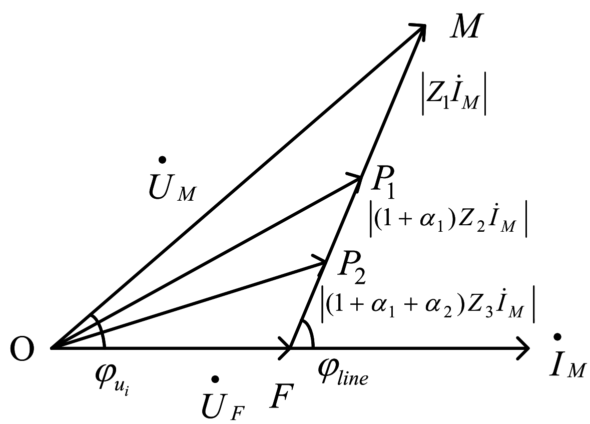


**FIGURE 10.** The vector graph of $\dot{U}_M$, $\dot{U}_F$, $\dot{U}_{P_1}$ and $\dot{U}_{P_2}$ in equation (25). $\vec{OF}$, $\vec{OP}$ and $\vec{OM}$ are $\dot{U}_F$, $\dot{U}_{P_1}$, $\dot{U}_{P_2}$ and $\dot{U}_M$, respectively. $\varphi_{line}$ is the angle of $Z_1$,$Z_2$ and $Z_3$.

## IV. SIMULATIONS

To verify the effectiveness of the proposed adaptive protection scheme, the simulation model of a 300kV AC transmission system containing distributed generation is established based on MATLAB. The system parameters are presented in Table 1. For convenience, the fault transition resistance is a constant. The expectation is that the distance relay operates correctly after a fault. To test the proposed adaptive protection scheme, the following two cases are designed.

**TABLE 1.** System Parameters.

| Parameters | Symbols | Values |
|---|---|---|
| The impedance from the relay to the PCC point | $Z_1$ | $2.2 + j20\Omega$ |
| The angle of the cable's impedance | $\angle\varphi_{line}$ | $6.28°$ |
| The fault transition resistance of the fault-point | $R_F$ | $100\Omega$ |
| The ratio between $I_{DG}$ and $I_M$ | $\alpha$ | 0.1 |
| / | $R_{set}$ | $5.5\Omega$ |
| / | $X_{set}$ | $50\Omega$ |
| / | $\alpha_1$ | $30°$ |
| / | $\alpha_2$ | $5°$ |
| / | $\alpha_3$ | $85°$ |

*Case 1:* The impedance from the fault-point to the PCC point is $1.76 + j16\Omega$, and $\alpha = 0.1$

*Case 2:* The impedance from the fault-point to the PCC point is $3.08 + j28\Omega$, and $\alpha = 0.4$.

## A. COMPARISONS WITH EXISTING DISTANCE PROTECTION ALGORITHMS

The conventional impedance algorithm is $Z = \dot{U}_M/\dot{I}_M$ and the improved impedance algorithm in [3] is $Z = \frac{|\dot{U}_M|}{|\dot{I}_M|}\frac{sin\angle\varphi_{ui}}{sin\angle\varphi_{line}}(cos\angle\varphi_{line} + jsin\angle\varphi_{line})$. The calculation results of the conventional algorithm, improved algorithm in [3] and the proposed algorithm are obtained in Table 2.

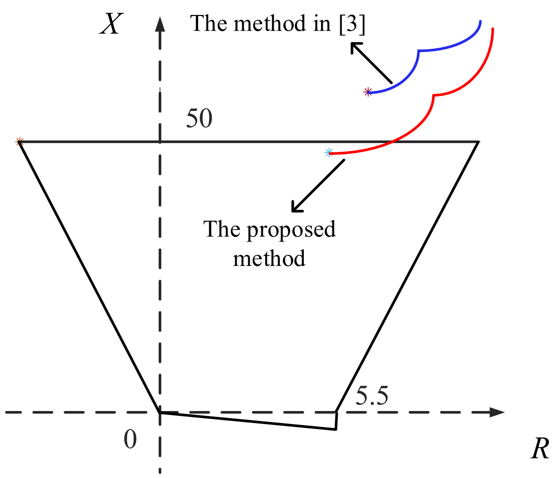


**FIGURE 11.** Simulation results of Case 2: the impedance trajectory of the system with the method in [3] and proposed adaptive protection scheme.

**TABLE 2.** Impedance measurement results of case 1 and 2.

| / | Case 1 | Case 2 |
|---|---|---|
| The actual impedance | $3.96 + j36\Omega$ | $5.28 + j48\Omega$ |
| The result obtained by the conventional algorithm | $114.14 + j37.6\Omega$ | $146.51 + j59.2\Omega$ |
| The result obtained by the method in [3] | $4.14 + j37.60\Omega$ | $6.51 + j59.20\Omega$ |
| The result obtained by the proposed method | $3.96 + j36\Omega$ | $5.28 + j48\Omega$ |

**TABLE 3.** Impedance measurement results of case 3 and 4.

| / | Case 3 | Case 4 |
|---|---|---|
| The actual impedance | $6.16 + j56\Omega$ | $7.216 + j65.6\Omega$ |
| The result obtained by the proposed method | $6.16 + j56\Omega$ | $7.216 + j65.6\Omega$ |

The results in Table 2 show that the result of the conventional algorithm has a large error comparing with the actual impedance. When $\alpha$ is small (i.e., $\alpha = 0.1$), the error between the result of the method in [3] and the actual impedance is not notable. When $\alpha = 0.4$, the error of the method in [3] is notable. However, the proposed method in this paper can obtain the impedance with no errors regardless of $\alpha$.

## B. DYNAMIC PERFORMANCES OF THE PROPOSED ADAPTIVE DISTANCE PROTECTION SCHEME

The impedance trajectory of Case 2 is shown in Fig. 11. As shown, the proposed adaptive distance protection scheme can calculate the impedance correctly, and the distance relay work effectively. Therefore, the effectiveness of the proposed method is verified.

## C. THE PROPOSED ADAPTIVE DISTANCE PROTECTION SCHEME OF THE CASE WITH TWO DISTRIBUTED GENERATIONS

The short-circuit model of the high-voltage AC transmission system containing two distributed generations is presented in Fig.9. The line parameters are $Z_1 = 2.2 + j20\Omega, Z_2 = 1.76 + j16\Omega, Z_3 = 3.96 + j36\Omega$. To test the performance of the proposed adaptive protection scheme in two distributed generations network, the following two cases are designed.

*Case 3:* The impedance from the fault-point to the PCC point is $5.28 + j48\Omega$ and $\alpha_1 = 0.1, \alpha_2 = 0.3$.

*Case 4:* The impedance from the fault-point to the PCC point is and $1.1 + j10\Omega$, and $\alpha_1 = 0.5, \alpha_2 = 0.7$.

The results in Table 3 show that the proposed method can accurately calculate the actual impedance of the system with two distributed generations.

**TABLE 4.** Impedance measurement results of case 5 and 6.

| / | Case 5 | Case 6 |
|---|---|---|
| The actual impedance | $5.28 + j48\Omega$ | $7.04 + j64\Omega$ |
| The result obtained by the proposed method | $5.28 + j48\Omega$ | $7.04 + j64\Omega$ |

## D. THE PROPOSED ADAPTIVE DISTANCE PROTECTION SCHEME IN RADIAL NETWORK

A radial high-voltage network with distance relay is presented in Fig.10. The line parameters are given in Fig. 12. The line between node 1 and node 2 is protected by Relay 1, and so on. To test the performance of the proposed adaptive protection scheme in high voltage radiation network, the following two cases are designed.

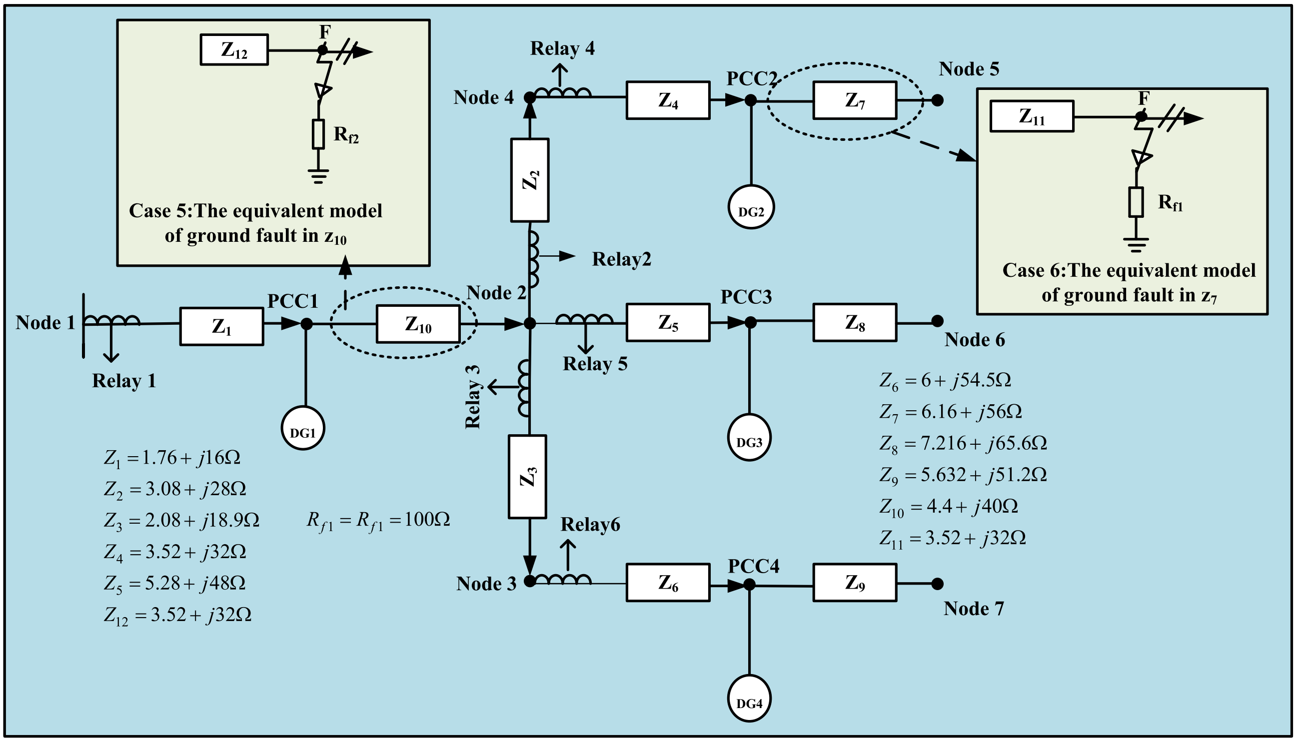


**FIGURE 12.** An radial High-voltage network with the proposed distance protection scheme.

*Case 5:* The impedance from the fault-point to the PCC point is $3.52 + j32\Omega$, and $\alpha = 0.2$.

*Case 6:* The impedance from the fault-point to the PCC point is $3.08 + j28\Omega$,and $\alpha = 0.6$.

The results in Table 4 show that the proposed method can accurately calculate the actual impedance between the relay and the fault point in the radial network.

## V. CONCLUSION

In this paper, an adaptive distance protection scheme is proposed, which considers the influence of fault transition resistance and distributed generation. The proposed method can accurately calculate the impedance only by using the local information. Simulation results verify the effectiveness of the proposed method.

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