Fault characteristics and protection scheme of islanded microgrid

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Abstract. Fault characteristics of islanded microgrid are different from that of grid-connected microgrid due to the system structure and control strategy of microsource, which is important to adaptability issues of traditional protections in islanded microgrid. Considering effects of load impedance and microsource models during the fault, this paper analyzed current characteristics of different branches during an asymmetrical fault in the line, presented phase characteristics of line currents on both sides of the line and the operating performance of current differential protection. A protection scheme based on real-time phase comparison of fault component of negative sequence current is proposed to identify the fault line and cut it reliably. Finally, a simulation model of islanded microgrid is built with PSCAD/EMTDC, the characteristics analysis and proposed protection scheme are verified by simulation results.

1. Introduction

Microgrid is an emerging technology which is defined as a low/medium-voltage distribution system containing distributed sources such as diesel generators, photovoltaic (PV) sources, energy storage sources, loads, and protection devices. A microgrid can work at islanded mode which is applicable for remote mountainous areas and islands far away from the public grid [1]. When diesel generators with large fault current in this microgrid quit running, low-level fault current of distributed source converters and bidirectional flow make the characteristics of line current different from that in grid-connected system. This brings the applicability problem of traditional protection principles in islanded microgrids.

Fault characteristics of islanded microgrid is the basis of protection scheme. In [2], the output current of source converter is analyzed considering the limit of inner current loop, which is much less than that of traditional sources. In [3], the source with fault-ride-through (FRT) ability is equivalent to a current source model controlled by its power reference. In [4], the distributed source is equivalent to a voltage-controlled current source model. In combination with topology of microgrid, the change of microsource sequence impedance and its influence on fault component protection are analyzed in [5], but the conclusions are mainly summarized by simulation results instead of sufficient theoretical analysis.

A inverse-time protection scheme for microgrid based on load impedance is proposed in [6], which is improved through low-voltage acceleration and coordinative acceleration. And a protection based on change of measured bus admittance is proposed in [7] to implement the detection and location of the fault. Only electrical data of local measurement is used to construct these protection schemes, but the transition resistance has a great impact on the reliability and operation time of protections. In [8], a fault
detection method which starts by voltage dip and scans the largest positive sequence fault component is explored, and it needs to work with differential protection to guarantee the rapidity of operation.

In this paper, the typical topology of islanded microgrid and equivalent models of sources considering their control strategies are analyzed firstly. And the fault current characteristics of islanded microgrid are analyzed based on current phasors of load branch and PV source branch considering the load power factor and transition resistance at the fault point. The phase-angle difference between two sides of the fault line is discussed based on the current relationship of different branches, and then the operating performance of current differential protection in isolated microgrid is analyzed. Furthermore, a protection scheme based on real-time phase comparison of fault component of negative sequence current is proposed to cut off the fault line reliably.

2. Islanded microgrid and equivalent model of sources

A typical system of islanded microgrid is shown in figure 1. The islanded microgrid runs with the master-slave control, and the voltage level is 400V. In this microgrid, an energy-storage source of voltage frequency (VF) control is connected to the main bus P and it is able to maintain the voltage and frequency of islanded microgrid when diesel generators quit running in normal working conditions. PV sources of constant power (PQ) control can be connected to different buses and provide power to the loads.

![Figure 1. Topology of islanded microgrid.](image)

During microgrid fault, the frequency of voltage is given by the energy-storage source of VF control directly and is consistent with that in normal working conditions[9]. The output current of the VF source increases controlled by voltage loop of the converter, aiming to maintain the positive sequence voltage of the microgrid. However, the amplitude of positive sequence voltage can not maintain normal value in the islanded microgrid when output fault current of the VF source reaches the upper limit. The unsymmetric current flowing through the impedance of line and source filter brings about the negative sequence voltage at access point of the VF source. Therefore, the positive sequence voltage \( \hat{U}_{s(1)} \) and negative sequence voltage \( \hat{U}_{s(2)} \) at access point of the VF source during the fault are given as

\[
\begin{align*}
\hat{U}_{s(1)} &= \hat{i}_{s,\text{max}} Z_{\text{eq(1)}} \\
\hat{U}_{s(2)} &= \frac{Z_{L(2)}}{Z_{L(2)} + Z_{\text{int(2)}}} \hat{U}_{L(2)}
\end{align*}
\]

where \( \hat{i}_{s,\text{max}} \) is the maximum value of output current allowed by the VF source, \( Z_{\text{eq(1)}} \) is the external equivalent impedance for the source, \( Z_{L(2)} \) is the negative sequence impedance between fault point and access point of the source, \( Z_{\text{int(2)}} \) is negative sequence impedance of the source filter, and \( \hat{U}_{L(2)} \) is the additive negative sequence potential at the fault point.
The distributed PV sources usually operate at unity factor to make full use of renewable energy. During the fault, converters of PV source adopt a control strategy based on positive sequence component to improve the output characteristics, and only positive sequence current is outputted during different kinds of faults. The current references under this control can be calculated as[3]

\[
\begin{bmatrix}
    i_{PV(1)d}^* \\
    i_{PV(1)q}^*
\end{bmatrix} = \begin{bmatrix}
    u_{PV(1)d} / M & u_{PV(1)q} / M \\
    u_{PV(1)q} / M & -u_{PV(1)d} / M
\end{bmatrix} \begin{bmatrix}
    P^* \\
    Q^*
\end{bmatrix}
\]

(2)

where subscript (1) represents the positive parameter, subscript d and q represent the d and q-axis components in synchronous reference frame, \(u\) is the voltage at the access point of PV source, \(i\) is the current reference, \(P^*\) and \(Q^*\) are the active and reactive power reference, \(M=(u_{PV(1)d})^2+(u_{PV(1)q})^2\).

3. Fault characteristics analysis and protection scheme

3.1. Fault current characteristics analysis

Considering the high similarity of PV sources belonging to different zones, a fault that happens in the line between bus P and Q is taken to analyze characteristics of fault current in the microgrid. The equivalent circuit of this system is shown in figure 2. Bus P is connected with the equivalent system containing a energy-storage source, a certain number of PV sources and load lines which have been shown in figure 1. Bus Q is connected with a load branch and a PV source that is able to provide power to the load in this specific zone.

As analyzed in section 2, the frequency of voltage in the islanded microgrid is given by the energy-storage source of VF control and it is consistent with that in normal working conditions. Due to the limited current of its source converter, a drop of voltage amplitude happens in the microgrid, and positive sequence voltage of bus Q can be expressed as

\[
U_{Q(1)}=U_{Q(1)}e^{j\phi_{Q(1)}}
\]

(3)

where \(U_{Q(1)}\) is the positive sequence voltage amplitude of bus Q, \(\phi_{Q(1)}\) is the positive sequence voltage phase-angle of bus Q, and the positive sequence voltage phase-angle of phase A \(\phi_{A(1)}\) is set as 0°.

The PV source doesn’t make a dynamic reactive power compensation in the control strategy because resistive component takes up a majority in the impedance of low-voltage lines, especially for the cable lines. Therefore it can be expressed as \(Q^*=0\) in equation (2). The output current of converter increases aiming to maintain the active power reference \(P^*\) until it reaches the upper limit(\(I_{PV,max}\)). Furthermore, q-axis voltage components at the access point of PV source is 0 considering the method of voltage oriented control. Positive sequence current of the PV source connected to bus Q can be calculated as

\[
I_{PV(1)}=I_{PV(1)}e^{j(\phi_{PV(1)}+180^\circ)}
\]

(4)

where \(I_{PV(1)}=\min\{P^*/U_{Q(1)}, I_{PV,max}\}\), is the positive sequence current amplitude of the PV source, and the positive direction of current is shown in figure 2.

The phase-angle difference between positive sequence current and voltage of the load branch connected to bus Q depends on power factor of the equivalent load. The positive sequence current of this load branch can be expressed as

\[
I_{L(1)}=I_{L(1)}e^{j(\phi_{L(1)}-\phi_{L})}
\]

(5)

where \(I_{L(1)}\) is the positive sequence current amplitude of the load line, and \(\phi_{L}\) is the power factor angle of the equivalent load.
Since transition resistance often exists in fault point of the line, current at the fault point can be expressed as

\[ \dot{I}_{f(1)} = I_{f(1)} e^{j(\Delta \theta_{(1)} + 180^\circ)} \] (6)

where \( I_{f(1)} \) is the positive sequence current amplitude at the fault point, and \( \Delta \theta_{(1)} \) is the phase-angle difference of positive sequence voltage between fault point and bus Q. \( \Delta \theta_{(1)} \) is nearly \( 0^\circ \) because the microgrid lines are very short and resistive component takes up a majority in the impedance.

Based on Kirchhoff’s current law, positive sequence currents on both sides of the fault line can be calculated as

\[
\begin{align*}
\dot{I}_{Q(1)} &= -\dot{I}_{PV(1)} - \dot{I}_{L(1)} \\
\dot{I}_{P(1)} &= -\dot{I}_{Q(1)} - \dot{I}_{f(1)}
\end{align*}
\] (7)

Combined with previous equations and typical load power factor 0.9, positive sequence current phasors of different branches are shown in figure 3.

![Figure 3. Positive sequence current phasors of different branches.](image)

It can be concluded that when active current component of the load branch is more than that of PV source connected to the same bus during the fault, i.e. \( I_{L(1)} \cos \phi_L > I_{PV(1)} \), phase-angle of positive current components between PV source and Q side of the fault line is less than \( 90^\circ \), and phase-angle of that between two sides of the fault line is more than \( 90^\circ \) consequently, as shown in figure 3(a).

On the contrary, phase-angle of positive current components between PV source and Q side of the fault line is more than \( 90^\circ \) when \( I_{L(1)} \cos \phi_L < I_{PV(1)} \). But phase-angle of that between two sides of the fault line increases and still may be more than \( 90^\circ \) as positive sequence current at the fault point decreases, as shown in figure 3(b).

Furthermore, the boundary condition of phase voltages and currents at the fault point is shown in equation (8) when a fault of phase B to C occurs, which is taken as an example.

\[
\begin{align*}
\dot{U}_{m} &= \dot{U}_{ic} \\
\dot{I}_{m} &= -\dot{I}_{ic}
\end{align*}
\] (8)

And it can be converted into boundary condition of sequence components by using symmetric component algorithms, which is shown in equation (9).

\[
\begin{align*}
\dot{U}_{(1)} &= \dot{U}_{(2)} \\
\dot{I}_{(1)} &= -\dot{I}_{(2)}
\end{align*}
\] (9)

As analyzed in section 2, only positive sequence current is outputted by PV sources during different kinds of faults. Negative sequence current of the PV source connected to bus Q can be expressed as

\[ \dot{I}_{PV(2)} = 0 \] (10)

Similar to the analysis of positive sequence phasors above, negative sequence current phasors of different branches are expressed in figure 4.

![Figure 4. Negative sequence current phasors of different branches.](image)

According to the control strategies and equivalent models of sources analyzed above, additive negative sequence potential at the fault point is the only negative sequence source in the islanded microgrid. As a result, equivalent negative sequence impedance of the system on P side is smaller than
that of the system on Q side on account that branches on P side of the fault line is more than that on Q side. Therefore, the amplitude ratio of negative sequence current at the fault point to that on the Q side of the fault line is greater than 2.

Current differential protection utilizes phase current phasors measured on both sides of lines to distinguish the fault area. Therefore not only amplitude but also phase-angle of current is needed to identify the fault phase. The operating criteria of phase-splitting current differential protection is shown as

\[
\left[ \begin{array}{c}
|\hat{I}_p + \hat{I}_q| > I_{p,o} \\
|\hat{I}_p + \hat{I}_q| > K|\hat{I}_p - \hat{I}_q| \\
\end{array} \right] \\
\text{(11)}
\]

where \( \hat{I}_p \) and \( \hat{I}_q \) are currents of the same phase measured on two sides of a specific line respectively, \( |\hat{I}_p + \hat{I}_q| \) and \( |\hat{I}_p - \hat{I}_q| \) are differential current and restraint current respectively, \( I_{p,o} \) is the start value of protection, \( K \) is the restraint coefficient and its value is from 0.25 to 0.8 in practical application[10].

When a fault happens inside the specific line, as analyzed above, phase-angle difference of positive current components between two sides of the fault line is very likely to be more than 90°. Consequently, this may cause current phase-angle difference of fault phases between two sides of the fault line to be more than 90°, such as current of phase C shown in figure 5 through phasor synthesis of positive and negative sequence current on two sides of the fault line.

As a result, value of differential current is smaller than that of restraint current for the fault phase. This is harmful to the sensitivity of differential protection and may cause the miss operation of protection. When zero sequence current component of asymmetrical ground faults is taken in consideration, the conclusion is the same as above. Due to limited space, it's not described in this article.

### 3.2. Microgrid protection scheme based on negative sequence network

As has been analyzed above, current angle difference of fault phase between two sides of the fault line could be more than 90° and the reliability of differential protection is affected on account of nonlinear output characteristic of sources and impact of load impedance during the fault.

When a fault happens inside the line, phase-angle difference of negative sequence current on two sides of the line can be derived by the use of figure 4 and cosine theorem, which is shown as

\[
\arg(I_{n2}, I_{q2}) = 180° - \arccos \frac{1 - k \cos \phi_L}{\sqrt{1 + k^2 - 2k \cos \phi_L}} \\
\text{(12)}
\]

where \( k=I_{n2}/I_{q2} \), is the amplitude ratio of negative sequence current at the fault point to negative sequence current on Q side of the fault line, which has been discussed above. Characteristic of this phase-angle difference in 3D form is shown in figure 6 when the value of \( k \) and \( \phi_L \) are in possible range.

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**Figure 5. Current phasors of three phases on two sides of the fault line.**

As a result, value of differential current is smaller than that of restraint current for the fault phase. This is harmful to the sensitivity of differential protection and may cause the miss operation of protection. When zero sequence current component of asymmetrical ground faults is taken in consideration, the conclusion is the same as above. Due to limited space, it's not described in this article.
When a fault happens inside the protected line, phase-angle difference of negative sequence current on two sides of the fault line decreases with the increase of parameters $k$ and the decrease of $\phi_L$, and do not exceed 90° in the typical range of these parameters. While phase-angle difference of negative sequence current is almost 180° when an external asymmetrical fault happens because capacitive current of short lines in the low-voltage microgrid can be neglected for protection[1].

Therefore, the phase-angle difference of negative sequence current can be taken to identify the fault line. To avoid the influence of negative sequence current generated by unbalanced load, fault component of negative sequence current is calculated in real time through fast fourier transform(FFT) to identify the fault line. The protection criterion for all asymmetrical faults is set as

$$\delta_m = \text{arg}(\Delta I_{f(Q)}) - \text{arg}(\Delta I_{f(P)}) < \delta_{\text{set}}$$

(13)

On account that the phase-angle difference of fault component of negative sequence current $\delta_m$ between two sides of the fault line is less than 90° and the transmission error of CT is less than 15°, the threshold value $\delta_{\text{set}}$ is set as 105°. And circuit breakers of three phases are set to trip at the same time when the criterion is satisfied.

In addition, start criteria of protection should be set, because the variation of negative sequence current could be affected by the change of load power in normal working conditions. The logical criterion to reflect the sudden change of negative sequence current is shown as

$$\{ a = 1 | \Delta I_{f(C)} > \xi_I \}$$

(14)

where $a$ is the logical variable of the criterion, $\Delta I_{f(C)}$ is the sudden change of negative sequence current at each measuring point, $\xi_I$ is the threshold of mutation, which is set as 4% of the rated current of the line considering the limitation of unbalanced load in this system. When the measured value exceeds the threshold, the protection device is started and the phase-angle of fault component of negative sequence current is calculated to identify the fault line.

4. Simulation

To verify the analysis of fault characteristics and the proposed protection scheme, a simulation model of the 400V islanded microgrid in figure 1 was built in PSCAD/EMTDC. Rated capacity of energy-storage source of VF control is 200kVA and rated power of distributed PV source of PQ control is 160kW. The length of each line is 0.1km, positive and negative sequence impedance of the line is $0.336+j0.08\, \Omega/km$, and zero sequence impedance of the line is $3.36+j0.28\, \Omega/km$. Three-phase apparent power and power factor of load branch connected to bus Q are set as $120\, \text{kVA}/0.900$(phase A), $120\, \text{kVA}/0.900$(phase B), and $114\, \text{kVA}/0.888$(phase C) respectively.

A fault of phase B to C happens in the line between bus P and Q at 0.5 s, and transition resistance at the fault point is 0.1 $\Omega$. Voltage waveforms on bus P and Q are shown in figure 7(a) and (b) respectively. The voltage unbalance degree increases significantly after the fault happens. Negative sequence component of voltage increases and positive sequence component of voltage decreases, which is caused by the VF source in the islanded microgrid.
Figure 7. Voltage waveforms on bus P and Q of simulation results.

Phase-angles of current on both sides of the fault line are shown in figure 8. The operating characteristic of current differential protection for the fault line is shown in figure 9, and the value of restrain coefficient is set to 0.8\(10\). As shown in figure 8, the steady state phase-angle of current on two sides during the fault are 164.52° and -82.74°(the difference is 112.74°) for phase B. As a result, value of differential current is much smaller than that of restraint current for phase B, and current differential protection can’t operate correctly to cut off the fault line.

The results of proposed protection scheme that just uses phase-angles of fault component of negative sequence current calculated in real time are shown in figure 10 and figure 11. The steady-state angles of fault component of negative sequence current on two sides of the fault line are 121.73° and 105.05°, and the phase-angle difference \(\delta_m\) is 16.68°. As a result, the fault line can be identified and cut off correctly.
5. Conclusion
In this paper, the fault current characteristics and the operating performance of current differential protection are analyzed in a typical islanded microgrid. Control strategy of distributed sources during the fault and small load impedance cause the current angle difference between two sides of the fault line to be more than 90° and the differential protection could not operate reliably. Furthermore, the protection based on real-time phase comparison of fault component of negative sequence current is proposed to identify the fault line and cut it reliably. The analysis of the fault characteristics and the protection scheme are verified by simulation results.

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