Protection Strategy of Islanded Micro-Grid Based on Short-Time Energy Segment

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Keywords: Islanded micro-grid; Inverter-based generator; Fault detection; Micro-grid protection

Abstract. Islanded micro-grid’s fault status and normal state are difficult to be distinguished, because of the small inertia of the micro-grid system and the impact of the inverter-based generators. In the viewpoint of energy, this paper presents a feature that can reflect the energy magnitude of the feeder, called short-time energy segment (SES). Hence, a new adaptive protection strategy for the islanded micro-grid is proposed based on analysis of the fault current and SES; and the fault location is obtained by the information of the fault current. Finally, the islanded micro-grid protection strategy is achieved combining the method of fault detection and fault location. An islanded micro-grid model is simulated in the DIgSILENT software, and simulated data is calculated in MATLAB software. Theory and simulation results demonstrate that the proposed method of fault detection and fault location can correctly detect the islanded micro-grid’s fault state and fault feeder, and effectively enhance the security and stability of the islanded micro-grid.

Introduction

Micro-grid is a mini-system of generating and distributing electricity to integrate distributed generations (DGs), loads and energy storage devices through power electronic converters, which can sufficiently use DG power production ability and have a broad application prospects [1-3]. But the fault currents are significantly low because of the current limiting of the inverter in the islanded micro-grid. The operating conditions and network topology of the islanded micro-grid change flexible. Furthermore, there is bidirectional power flow due to the presence of DGs in the islanded micro-grid [4-6]. Thus, the conventional overcurrent relays with fixed setting, normally employed for islanded micro-grid protection, does not distinguish the fault state and normal state, which cannot satisfy the demand of the islanded micro-grid [7]. A new protection method should be studied to protect the islanded micro-grid safe and stable operation.

Several micro-grid protection techniques have been proposed previously. In [8], an adaptive relaying strategy for micro-grid protection is proposed, but it does not consider islanded mode of operation. The author in [9] proposed an approach based on symmetrical current components. Zero-sequence current and negative-sequence current were measured to distinguish single line-to-earth and line-to-line faults, respectively. But the protection fails when a three-phase symmetrical fault occurs. In [10], the authors presented a data-mining-based intelligent differential protection scheme for the micro-grid, which processes the current and voltage differential features at both ends of the respective feeder using discrete Fourier transform to build the decision tree-based data-mining model. However, this differential features processed using Fourier transform are not accurate because the frequency will fluctuate seriously when the islanded micro grid is disturbed [11]. Han and Mu, in [12], established a graph model describing the overall structure of a micro-grid. By using the graph model and monitoring state variables in the micro-grid, a protection algorithm for fault detection is proposed. In [13], an adaptive protection scheme based on identifying the direction of fault current was proposed. It adaptively set the operation values and time limits using the node tree searching process and node path identification algorithm. When the islanded micro-grid have more dynamic load or is interfered seriously by external circumstances, These methods mentioned above
cannot accurately distinguish the islanded micro-grid’s fault state and normal state and the protection devices may be caused malfunction.

In the viewpoint of energy, this paper presents a feature that can reflect the energy magnitude of the feeder, called SES. A new adaptive protection strategy for the islanded micro-grid is proposed based on the feature of fault current and SES; finally, theory and simulation results illustrate the reliability and effectiveness of the proposed method.

**The Definition of the Short-Time Energy Segment**

The traditional protection features cannot validly distinguish the islanded micro-grid’s fault state and normal state due to the system capacity and fault current is small. From the viewpoint of energy, this paper found that the energy of the lines is quite different in the islanded micro-grid between the normal state and the fault state. Thus, this paper presents a feature that can reflect the energy magnitude of the feeder, called short-time energy segment (SES). It indicates the energy magnitude of the feeder within the power cycles. SES is defined as follows:

\[
SES(t) = \int_{t-a}^{t} \left[ u_i(t) \cdot i_u(t) + u_u(t) \cdot i_u(t) + u_i(t) \cdot i_u(t) \right] dt
\]

Where \( u(t) \) and \( i(t) \) is the line voltage and current at time \( t \). SES(\( t \)) is the line short-time energy segment at time \( t \). As shown in equation (1), SES is the integral of the product of voltage and current on the time of the power cycles. It will not be influenced by the transient disturbance and the distortion of the voltage and current, and can reflect the energy magnitude of the feeder at any time. SES has important application value in the microgrid fault detection.

**Analysis of the Inverter-Based Generation Fault Characteristics**

The islanded microgrid power are almost inverter interfaced generations based on PQ and V/f control strategy. It limit the fault currents to 1-2 pu by the means of combination of hardware and software to avoid the damage of the power electronic devices[14][15]. Thus, it should consider the effect of the control strategy to fault state when we analyze the islanded microgrid characteristics.

**Three-Phase Short Circuit Fault**

![Figure 1. Equivalent circuit of the inverter-based generators fault analysis.](image)

For simplification of analysis, we simplify the equivalent circuit of the inverter-based generators fault analysis to the circuit expressed as figure 1[16]. Where \( \dot{U} \) and \( \dot{i} \) are the output voltage and current of the inverter, \( Z_{\text{Line}} \) and \( Z_{\text{Load}} \) is the equivalent impedance of the output lines and loads.

Under the condition of normal operation, according to the theory of circuit, it can be concluded as follows:

\[
\dot{U} = \dot{i}(Z_{\text{Line}} + Z_{\text{Load}})
\]

When the three-phase short-circuit at the end of the lines:
\[ U_f = \dot{i}_f (Z_{line} + R_f / Z_{load}) \]  

(3)

When occurred three phase metallic short circuit faults, because the fault resistance is little, the equation (3) can be simplified as the follows:

\[ U_f = \dot{i}_f Z_{line} \]  

(4)

When the power supply is PQ inverter power supply, the inverter power supply in order to maintain a constant output power, the output current is increased to meet the following formula:

\[ S_{ref} = 3i_f Z_{line} \]  

(5)

According to the Formula (5), the fault current \( I_f \) is:

\[ I_f = \frac{S_{ref}}{3Z_{line}} \]  

(6)

The line impedance is far less than the load impedance due to the line of the islanded microgrid is short in the practical engineering. Meanwhile the fault current is limited to 1.5-2 pu in the islanded microgrid. So the output current reach the limit value \( I_{max} \) under the three-phase short circuit fault. Taking the limit value \( I_{max} = 2I_e \), it can derived the Formula (7):

\[ \dot{U}_f = 2I_e Z_{line} \]  

(7)

It can deduce that \( |U_f| \cdot \dot{i}_f \ll |\dot{U}_f| \cdot \dot{i}_f \) and \( SES_i \ll SES_z \) from the analysis of the above, where \( SES_z \) is the short-time energy segment of the grid Normal operation. The SES of the three-phase short circuit fault is far less than the normal operation. The output current of the inverter-based generation increase but not more than 2 times rated current. The fault current and fault SES meet the following equation:

\[ \begin{cases} \text{SES}_i \ll \text{SES}_z \\ I_f > I \end{cases} \]  

(8)

When the power is the V/f inverter-based generators, the inverter should increase the output current to keep the output voltage \( U_f \) in the rated value \( U \). Because the maximum fault current is \( 2I_e \) due to the current limiting of the inverter, the fault voltage can’t maintain the rated value and fell instantly as the formula (7). In conclusion, the fault voltage and current satisfy the formula (8).

**Two-Phase Short Circuit Fault**

The sequence network equivalent circuit of the figure 1 system expressed as the figure 2.
In the figure 2, $\dot{U}$ is the output voltage of the inverter; $\dot{i}_1$ and $\dot{i}_2$ is the positive and negative sequence fault current of the inverter-based generation. $\dot{u}_{k1}$, $\dot{u}_{k2}$ and $\dot{i}_{k1}$, $\dot{i}_{k2}$ is the positive and negative sequence voltage and current of the fault point respectively. $Z_{\text{Line}}$, $Z_{\text{Line}}$ and $Z_{\text{Load}}$, $Z_{\text{Load}}$ is the positive and negative sequence impedance of the line and the load respectively. The boundary condition of fault point is expressed by the fault component as the following formula.

$$\begin{cases}
\dot{i}_{k1} + \dot{i}_{k2} = 0 \\
\dot{u}_{k1} = \dot{u}_{k2}
\end{cases}$$

(9)

According to the equation (9), meet the boundary conditions of the complex sequence network of two-phase short circuit shown in Figure 3.

Assuming that the positive and negative sequence impedance of the line and the load are equal, the fault positive current is shown as the follows according to the complex sequence network.

$$\dot{i} = \frac{\dot{U}}{Z_{\text{Line}} + \frac{Z_{\text{Load}} \cdot Z_{\text{Line}}}{2Z_{\text{Line}} + Z_{\text{Load}}}}$$

(10)

The fault negative current is:

$$\dot{i}_2 = \frac{Z_{\text{Load}}}{2Z_{\text{Line}} + Z_{\text{Load}}} \cdot \dot{i}_1$$

(11)
Due to the line impedance is far less than the load impedance, so $\hat{I}_2$ is approximately equal to $-\hat{I}_1$. The fault phase current is the following formula binding (10) and (11).

$$\hat{I}_{\Phi} = (a^2 - a) \frac{\hat{U}_1}{Z_{\text{line}} + Z_{\text{load}} + Z_{\text{line}}}$$ \hspace{1cm} (12)

$$\hat{I}_{\varphi} = (a - a^2) \frac{\hat{U}_1}{Z_{\text{line}} + Z_{\text{load}} + Z_{\text{line}}}$$ \hspace{1cm} (13)

Where $a = \angle 1 \leq 20$. Because line impedance of the islanded microgrid is small, the formula (12) and (13) can be simplified as follows.

$$\hat{I}_{\Phi} = (a^2 - a) \frac{\hat{U}_1}{2Z_{\text{line}}}$$ \hspace{1cm} (14)

$$\hat{I}_{\varphi} = (a - a^2) \frac{\hat{U}_1}{2Z_{\text{line}}}$$ \hspace{1cm} (15)

According to the formula (14) and (15), when the two-phase short circuit fault occurs in the island microgrid, the fault phase current is very large. But the fault current will be limited at the 1.5-2 pu due to the current limiting of the power electronic device. Therefore, the fault phase voltage and SES will be lowered severely, and the fault current and SES satisfy the formula (8).

In conclusion, when two phase and three phase short circuit happens, the output current of the inverter-based generators is increased but not exceeding 2 times rated current, and the SES of the inverter-based generators is decreased seriously. So SES can signify the running state of the islanded microgrid.

**Protection Strategy of Islanded Microgrid Based on SES**

**Fault Detection**

The islanded microgrid inertia small, topology variable, and is influenced significantly by external disturbance. The output current of the islanded microgrid may increase more than the protection set value and leading to protection malfunction because the external disturbances and load mutation\(^{17,18}\). However, under normal operation of the islanded microgrid, the output current is increased due to the effect of the exterior interference and load mutation, the SES will be also increased; the output current is decreased due to the effect of the exterior interference and load mutation, the SES well be also decreased. This characteristic is opposed to the fault characteristics that the output current is increased and the SES decreased seriously when a fault occurs in the islanded microgrid. Therefore, using the characteristics of current increasing and SES decreasing as the fault detection criterion, which can judge the operational status of the islanded microgrid accurately.

Because the islanded microgrid topology is flexible and variable, the current RMS and SES of the fault previous cycle is used as the basis for the setting value of the fault criterions. Thus, the setting method of the islanded microgrid fault detection is shown as (16).
\[
\begin{cases} 
I_{t+T} \geq K_p I_t \\
\text{SES}_{t+T} \leq K_q \text{SES}
\end{cases}
\] (16)

According to the equation (16), when the current effective value at time \( t+T \) is equal to or greater than the \( K_p \) times of the current RMS at time \( t \) in any line of the Islanded micro-grid, and the SES at \( t+T \) is less than or equal to \( K_q \) times of SES at time \( t \), it indicate that there is a malfunction in the micro-grid. Where \( K_p \) and \( K_q \) are the reliable coefficients of the fault initiation criterion. According to the islanded micro-grid fault current is limited to 1.5-2 times the rated current, taking \( K_p=1.5 \). Combining with short-term energy segment definition, take \( K_q=0.25 \).

**Fault Location**

When a fault is detected by the fault detection method based on 3.1, the fault line should be located and removed to ensure the other lines operating normally and to avoid the expansion of the fault. Figure 4 shows a simplified structure diagram of the islanded microgrid.

![Simplified structure diagram of the islanded microgrid.](image)

According to the power flow direction, the islanded microgrid lines can be divided into unidirectional and bidirectional power flow lines. Line 1 and line 2 is the bidirectional power flow and line 3 is the unidirectional power flow in Figure 4. According to the analysis and results above, when line 1 or line 2 have fault, at least one intelligent electronic device (IED) can detect current increase. Positive direction of current is defined to flow from bus to lines. Then the directions of the fault currents from the two terminals both are positive. When line 3 has fault, the current detected by IED3.1 is increased, the current detected by IED3.2 is nearly zero.

According to the fault current characteristics, the method of faults location is gained:

a. When the current directions of the line two terminals is positive and at least one terminal current of the line meet \( I_{t+T} \geq K_p I_t \), it shows the line fault.

b. When only one terminal current of the line satisfy \( I_{t+T} \geq K_p I_t \) and the other terminal current is nearly zero, it shows the line fault.

Combining with the section 3.1 and 3.2, the real time information of the current and SES of all the lines is detected in the islanded micro-grid. If there is a line that its current and SES satisfy the fault detection criterion (16), it shows that the islanded micro-grid has a fault. At this time, fault alarm and fault location algorithm is activated. Compared the current value and direction at the terminals of line constantly, when the line current information satisfy the condition a or b, it shows the line fault.

**Simulation Verification**

The simulation model of the islanded microgrid as the Figure 5 was established in the DIgSILENT software and the SES was gained by programming in the MATLAB software to validate the accuracy of the islanded microgrid.
Fault Detection Methods Validation

Setting the point of the 50% line 1 has a three-phase short-circuit fault in 0.5 s. the fault current and SES waveform of the IED1.1 is shown in Figure 6.

As can be seen in Figure 6, when the line 1 has a three-phase short-circuit fault, the output current of the IED1.1 is increased but not more than 2 times rated current. The output SES of the IED1.1 was about 25MJ before the fault, but the SES instantly reduced to almost zero on the three-phase short-circuit fault. This simulation result is consistent with the theory analysis that the current increasing and the SES decreasing on a fault.

Setting the point of the 50% line 1 has a phase to phase short-circuit fault in 0.5 s. The fault current and SES waveform of the IED1.1 is shown in Figure 7.
As can be seen in Figure 7, when the line 1 has a phase to phase short-circuit fault, the output current of the IED1.1 is increased but not more than 2 times rated current. The output SES of the IED1.1 was about 25MJ before the fault, but the SES instantly reduced to about 2MJ on the phase-phase short-circuit fault. This simulation result is consistent with the theory analysis that the current increasing and the SES decreasing on a fault.

The simulation results shows that the new fault detection method is able to accurately distinguish the fault state and normal state, and it is not affected by the external interference, load mutation and the fault types.

**Conclusion**

Combining the physical concept of the SES and the characteristics of fault current, this paper presents a new adaptive protection strategy for the islanded microgrid. The core of the protection strategy is the fault detection method of the islanded microgrid, and the fault location algorithm is gained based on fault current information. Theory and simulation results demonstrate that the proposed method of fault detection and fault location can effectively enhance the security and stability of the islanded microgrid. And has the following advantages.

1) Based on the fault current and SES as the fault detection criterion, the protection devices of the islanded microgrid cannot occur mal-operation for the external disturbance or load mutation.

2) By comparing the two period current and SES to judge whether there is a fault in the islanded microgrid, which can adapt to the changes of topology and adaptively adjust the protection set value.

3) Based on the fault detection, using the fault current information can realize fault location to the unidirectional and bidirectional power flow lines of the islanded microgrid.

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