Electrical Power and Energy Systems 94 (2018) 15–26

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A novel Single-phase-to-ground fault identification and isolation strategy in wind farm collector line

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ARTICLE INFO

Article history:
Received 20 March 2017
Received in revised form 13 June 2017
Accepted 23 June 2017
Available online 29 June 2017

Keywords:
Single-phase-to-ground fault
Wind farm collector system
D-S evidence theory
Overvoltage
Fault isolation

ABSTRACT

The collector system of wind farm is a non-effectively grounding (small current grounding) system, where the single-phase-to-ground fault can easily develop into a three-phase fault, and without timely identification and isolation, it may cause incalculable hazard to wind farms. In fact, the present fault identification methods based on single fault characteristic quantity or majority voting rule all have certain limitations when dealing with some certain faults theoretically. Furthermore, the wind turbine could be possibly exposed to overvoltage several times of the rated voltage after the fault isolation by direct switching off the grid-side breaker in collector line. To solve these problems, this paper first analyzes the mechanism of overvoltage by constructing the resonance model of wind farm with distributed parameter. A novel single-phase-to-ground fault identification method based on D-S evidence theory is proposed. Then two flexible fault isolation methods are further proposed. Simulation results verify the validity and superiority of the proposed strategy.

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1. Introduction

All wind farm step-up substation transformers are delta connected at the collector line side, which means that the collector system is a non-effectively grounding (small current grounding) system [1]. In the case of a wind farm single-phase-to ground fault, the fault is generally permanent since the collector lines are mostly cables, and the capacitive current is much larger than that of conventional overhead lines, so that the single-phase-to-ground fault can easily develop into a three-phase fault. If the fault is not timely detected and isolated, it may inflict incalculable harm upon the wind farm [2].

By analyzing the isolation time sequence of collector line single-phase-to-ground fault, it is found that if the breaker of the collector line at the grid side is switched off directly, the wind turbine group will be disconnected and consequently become an island at the downstream of the collector lines. The later section of the paper reveals that under certain fault condition and wind turbine operation mode, the wind turbine terminal will possibly be exposed to an overvoltage several times of the rated voltage in a short time after the fault collector line is switched off, the mechanism of which has not been researched before. Indeed, the overvoltage could cause various damages and contribute to failures in wind farm [3,4]. In general, the wind turbine will be tripped off by overvoltage protection once the voltage exceed the threshold. But the setting time of overvoltage protection is usually about 100 ms so as to avoid system disturbances and coordinate with other protections. During the wait time, the overvoltage will possibly reach a very high value before the overvoltage protection action. In severe cases, wind turbine may be burned down. At present, the wind turbine is usually equipped with its own voltage-regulating system. For example, [5–7] proposed to use the FACTS devices such as STATCOM and SVC under fault and stable conditions for voltage regulation. However, the terminal overvoltage of wind turbine is such a high and transient value that it will not always be automatically regulated to zero rapidly by this voltage-regulating system. Furthermore, when switching off the grid-side breaker directly, all the wind turbines connected to the fault collector line will be tripped off. Therefore there will be a large amount of instantaneous power shortage, which could lead to instability to the whole system [8].

To prevent this kind of situation, reliable identification method for single-phase-to-ground fault should be deeply studied in the first place. Wind farm is essentially an active distribution system [9]. In the zero-sequence network, all the wind turbines are isolated. Due to the serial connection mode of the

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http://dx.doi.org/10.1016/j.ijepes.2017.06.031
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single-phase-to-ground fault sequence network, the single-phase short circuit fault at the collector line will not be perceived by the wind turbines [10]. As a power supply, the influence of wind turbine on fault analysis merely reflects in the fault point voltage establishment before the fault occurs. Theoretically, fault line selection methods applied in traditional power distribution system can be transplanted accessibly to fault line selection in wind farm, and most of them have been put into field application. Aiming at fault line selection in the conventional distribution network, scholars have proposed a variety of fault line selection algorithms and strategies. According to the different fault information adopted in the fault identification, these fault line selection methods can be classified into three representative types:

(1) The steady-state power frequency fault component method, for example, [11] proposed the zero-sequence admittance compensation method, [12] proposed the negative-sequence current method, [13] proposed the group amplitude comparison method;
(2) The higher-order harmonic method, for example, [14] proposed the 5th harmonic method;
(3) The transient characteristic quantity method, for example, [15,16] proposed the first half-wave method, [17] proposed the zero-sequence transient current method, [18] proposed the Prony algorithm.

However, due to the variety of wind farm structures, operation modes and fault types, all the previous fault line selection methods based on single fault characteristics are not capable of covering all the scenarios [11]. But the integration of them is an effective solution. In general, majority voting is a simple method that does not require any parameters to be trained or any additional information for later results [19]. Fault identification method based on majority voting rule could consider the results of multiple fault information comprehensively [20–22], improving the accuracy of fault line identification to some extent. Nevertheless, this majority voting rule makes the judgement without any prior knowledge, and the fault characteristic information under specific operation condition is not considered. Therefore, it is possible that the major fault criteria have relatively low accuracy when the majority voting is applied to a specific system. Therefore, there still exists some improvement rooms. In this case, as a reasonable decision making method, D-S evidence theory is proposed to solve this problem [23,24]. By using this theory, it is possible to make a reasonable decision based on historical evidence after accumulating enough evidence.

After the correct identification of fault collector lines, a corresponding single-phase-to-ground fault isolation strategy should be seriously taken into considerations to avoid the wind turbine terminal overvoltage. In this paper, a novel single-phase-to-ground fault identification and isolation strategy in wind farm collector line is proposed. First, the mechanism of wind turbine terminal overvoltage caused by improper fault isolation is revealed in detail. Then the D-S evidence theory is introduced into fault line selection from the collector line system in order to realize accurate fault identification. Subsequently, two kinds of fault isolation strategies based on gradual tripping of wind turbines and installation of wind-turbine-side breaker are proposed to avoid the overvoltage. Simulation results indicate that the fault line selection method based on D-S evidence theory can achieve better selection accuracy and applicability than single fault characteristics based method or majority voting rule, furthermore the two proposed fault isolation strategies could realize the isolation of single-phase-to-ground fault without causing wind turbine terminal overvoltage.

2. Mechanism analysis of wind turbine terminal overvoltage caused by improper single-phase-to-ground fault isolation in wind farm

A typical wind farm model is built to analyze the mechanism of overvoltage, as shown in Fig. 1 [25,26].

The wind farm has 5 collector lines, each collector bus is connected with several wind turbines. When a single-phase-to-ground fault occurs at point F_1 of collector line 2, the system to which the bus-bar at step-up transformer low voltage side is connected and the wind turbine group to which each collector line is connected can be equivalent to an infinite power source with an internal impedance. Wind turbine group at the downstream of collector line 2 can be equivalent to one wind turbine. Accordingly, a two-unit-single-line model is formed as shown in Fig. 2.

After the grid-side breaker of the collector line is switched off and the system is separated off, the zero sequence network is established as shown in Fig. 3 [27]. Elements of wind turbine will not be included in zero sequence network because Yn/Δ connection mode is adopted by wind turbine box-type transformer.

In Fig. 3, X_{LC0} is the zero sequence capacitive reactance of the line; X_{L0} is the zero sequence inductive reactance of the line; $\dot{U}_{G(0)}$ is the high-voltage-side zero sequence voltage of the box-type transformer; $\dot{U}_{a(0)}$ is the zero sequence voltage at the fault point. Because $X_{LC} \gg X_L$, it can be considered that

$$\dot{U}_{a(0)} = \dot{U}_{G(0)} \tag{1}$$

Namely, the amplitude of the zero sequence voltage at the fault point is similar in value to the high-voltage-side zero sequence voltage of the wind turbine box-type transformer.

The corresponding positive sequence fault component network and negative sequence network is shown in Fig. 4 and Fig. 5 respectively.

In Fig. 4, X_{LC1} is the positive sequence capacitive reactance of the line; X_{L1} is the positive sequence inductive reactance of the line; X_{GC1} is the equivalent positive sequence capacitive reactance of the wind turbine terminal capacitors; assuming $X_{C1} = X_{LC1} + X_{GC1}$. X_{G1} is the equivalent positive sequence inductive reactance of the wind turbine; $\Delta\dot{U}_{G(1)}$ is the fault component of the positive sequence wind turbine terminal voltage; $\Delta\dot{U}_{a(1)}$ is the fault component of the positive sequence voltage at the fault point. In Fig. 5, X_{LC2} is the negative sequence capacitive reactance of the line; X_{L2} is the negative sequence inductive reactance of the line; X_{GC2} is the equivalent negative sequence capacitive reactance of the wind turbine terminal capacitors. Assuming $X_{C2} = X_{LC2} + X_{GC2}$. X_{G2} is the equivalent negative sequence inductive reactance of the wind turbine; $\dot{U}_{G(2)}$ is the negative sequence wind turbine terminal voltage after a fault occurs; $\dot{U}_{a(2)}$ is the negative sequence voltage at the fault point.

The following derivation process is based on the premise that the parameters of positive sequence impedance and negative sequence impedance are consistent. Firstly, negative sequence scene is analyzed. The negative sequence current at the fault point $\dot{I}_{a(2)}$ is:

$$\dot{I}_{a(2)} = \frac{\dot{U}_{a(2)}}{jX_{L2} + (-jX_{C2})//jX_{G2}} \tag{2}$$

Moreover, negative sequence wind turbine terminal voltage $\dot{U}_{G(2)}$ can be derived:

$$\begin{aligned}\dot{U}_{G(2)} &= \dot{I}_{a(2)} \cdot (-jX_{C2}//jX_{G2}) \\ &= \frac{X_{C2} \cdot X_{G2}}{X_{C2} \cdot (X_{L2} + X_{G2}) - X_{L2} \cdot X_{G2}} \cdot \dot{U}_{a(2)}\end{aligned} \tag{3}$$

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