Electric Power Systems Research 131 (2016) 41–48

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Single-phasing detection and classification in distribution systems with a high penetration of distributed generation

M.S. ElNozahy [a,b,*], R.A. EL-Shatshat [a], M.M.A. Salama [a]

[a] Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1
[b] Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt

ARTICLE INFO

Article history:
Received 16 June 2015
Received in revised form 22 August 2015
Accepted 5 October 2015

Keywords:
Artificial neural network
Characteristic signature
Discrete wavelet transform
Single-phasing

ABSTRACT

This paper presents a robust wavelet-ANN based algorithm for single-phasing detection and single-phasing classification in distribution systems with a high penetration of distributed generation (DG). In traditional vertically integrated distribution systems, single-phasing events are detected easily, as the current of one of the phases is lost completely, resulting in a significant current unbalance ratio. However, this is not the case for distribution systems with a high penetration level of DG units, as the backfeed current from the DG units will support the current in the lost phase, hence masking the single-phasing operation. In the proposed algorithm, the transient current signals generated at the onset of the single-phasing condition are combined into a modal signal. This signal is analyzed using discrete wavelet transform (DWT) to extract the feature vector denoting the distinctive features for each frequency band. Finally, artificial neural networks (ANNs) are used to detect single-phasing conditions and to classify the lost phase. Simulation results have confirmed the dependability and security of the proposed algorithm.

1. Introduction

Single-phasing is a special type of open circuit fault in which only one phase of a three-phase system is disconnected, causing the remaining two phases to form a single-phase system [1]. Single-phasing may happen for a variety of reasons. For example, a tree branch falling on a transmission line may cut only one of the conductors, leaving the other two intact. It can also occur in switchgears' terminal connections if one of the connections is loose and eventually lost. Likewise, single-phasing may happen due to equipment malfunction. A very common example occurs in circuit breakers [2]: while energizing a circuit, only two poles of the breaker are closed and the third pole is stuck and remains open. The utilization of single-phase protective devices is another common cause for single-phasing: most electrical utilities use single-phase fuses to protect three-phase distribution networks. During a single line-to-ground fault, only one phase is interrupted and single-phasing is developed in the remaining two phases [3].

Since power system equipment is designed to operate under balanced (or near-balanced) conditions, any unbalanced operating conditions (such as single-phasing) lead to equipment malfunction. Single-phasing operation results in the formation of significant negative sequence currents in the system, causing overheating in electrical equipment, which may lead to equipment failure [4]. Moreover, the voltage unbalance accompanying the single-phasing operation will cause three-phase power electronic loads, such as adjustable-speed drives (ASDs), to draw unequal current in each phase. These unequal currents result in excessive direct current (DC) bus voltage ripple, which in turn leads to premature aging of the DC link capacitor [5]. Ferroresonance is a special form of resonance that occurs in distribution systems between the magnetizing reactance of a distribution transformer and the system's stray capacitance. In Ref. [6], it was shown that ferroresonance occurs more frequently during single-phasing conditions, resulting in the development of high voltages (up to 500% of the rated voltage) across distribution transformer terminals [7,8]. Such overvoltages may lead to insulation failure [2].

The previous discussion makes it clear that single-phasing conditions should be detected and eliminated in a timely manner. In traditional vertically integrated distribution systems, this is an easy task as the current of the open phase is lost completely, while the currents in the other two phases remain the same, resulting in a significant current-unbalance ratio, which will trigger

* Corresponding author at: University of Waterloo, Department of Electrical and Computer Engineering, Waterloo, ON, Canada N2L 3G1. Tel.: +1 519 888 4567x33372; fax: +1 519 746 3077.
E-mail address: mnozahy@uwaterloo.ca (M.S. ElNozahy).

http://dx.doi.org/10.1016/j.epsr.2015.10.008
0378-7796/

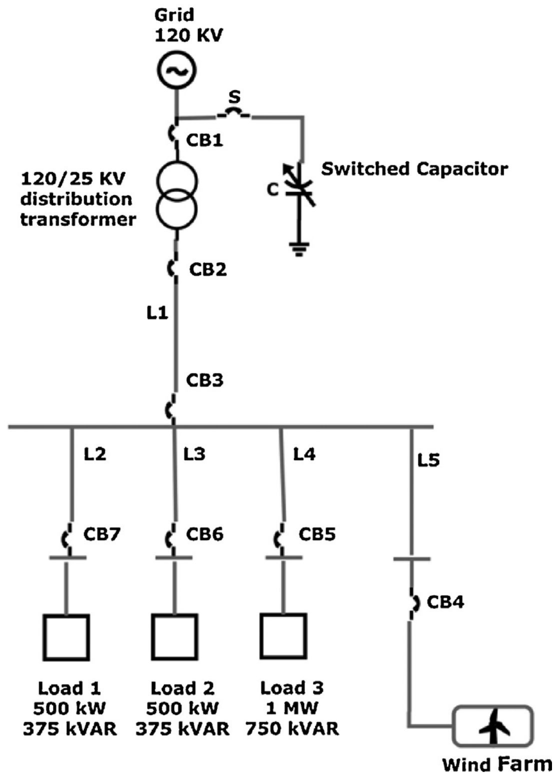

Fig. 1. Test system.

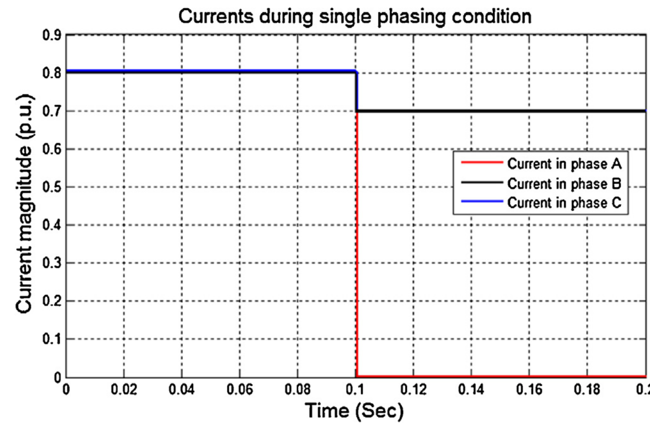

Fig. 2. RMS currents seen at load 3 terminals during single-phasing condition (no DG).

current-unbalance relays. However, this is not the case for distribution systems with a high penetration of DG, as the backfeed current from the DG units will support the current in the lost phase, thus masking the single-phasing operation. To the best of the authors' knowledge, this problem has not been tackled before. This point is explored in detail in the next section.

This paper proposes a novel algorithm for single-phasing detection and classification (i.e. identifying the lost phase) in distribution systems with a high penetration of DG units. The proposed algorithm utilizes the transient current signals to detect and classify the single-phasing condition in a timely and accurate manner. The remainder of the paper is organized as follows: Section 2 details the problem description, Section 3 presents the proposed single-phasing detection and classification algorithm, Section 4 includes the tests and results. Finally, Section 5 concludes the paper.

2. Problem description

This section studies the effect of the presence of DG units on the detection of single-phasing conditions.

2.1. Description of the test system

The single line diagram of the test system used to analyze the single-phasing phenomenon is depicted in Fig. 1. The selected test system represents a typical radial distribution system feeding several load centers. However, for this research, in order to keep the simulation burden at a manageable level, only three load centers are considered in the analysis. As explained, sensitive loads (i.e. large ASDs) should be protected against single-phasing condition. For this research, it is assumed that load 3 is the sensitive load to be protected, and so only current signals seen at the terminals of the circuit breaker (CB5) should be analyzed. The test system is modeled using SIMULINK. The test system has the following data:

- The grid is represented by a 120 kV source at a 500 MVA short circuit level
- Load 1 & load 2: 500 kW, 375 kVAR loads
- Load 3 (sensitive load to be protected): 1 MW, 750 kVAR load
- L1 & L5: 12.5 km distribution lines represented by their π models
- L2, L3, L4: 6 km distribution lines represented by their π models
- CB1: circuit breaker at the substation transformer high voltage (HV) side
- CB2, CB3: circuit breakers at the medium voltage (MV) side
- B4: circuit breaker at the terminals of the DG unit.
- CB5, CB6, CB7: circuit breakers protecting the loads
- C: 8.5 MVAR capacitor providing reactive power compensation
- S: load break switch used for switching capacitor C on/off
- The DG is represented by a directly connected wind farm composed of three squirrel cage induction generators (SCIG), each with 3 MW rating, connected to the 25 kV system through a 25,000/690 V interfacing transformer

2.2. Single-phasing operation without the presence of DG

In a passive vertically integrated distribution system, i.e., without DG units, single-phasing can be detected easily, as the current of the lost phase drops to zero, whereas the currents in the other two healthy phases remain almost the same. This task is usually accomplished using a current-unbalance relay. A typical relay (Multilin 469) trips after two seconds if the average current is more than 25% of the full load current, and the current in one phase is approximately zero. This situation can be simulated by opening the circuit breaker CB4 to disconnect the DG and opening phase A in the midpoint of line L1. The currents drawn by load 3 and seen by CB 5 are shown in Fig. 2.

2.3. Single-phasing operation in the presence of DG

In this case, the DG unit is connected to the system (CB 4 is closed), and as in the previous case, a single-phasing situation is simulated by opening phase A at the midpoint of line L1. Consequently, the phase A current in the line drops to zero. However, the backfeed current from the DG unit will support the current in the lost phase, and the phase A current seen by the load to be protected (load 3) is not equal to zero, as shown in Fig. 3, hence masking the single-phasing condition. As a result, using traditional current-unbalance relays (such as the Multilin 469) in conjunction with CB5 to detect single-phasing, in the presence of DG, is no longer effective.

However, as shown in Fig. 3, the current waveforms initiated at the onset of the single-phasing condition are characterized by an