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Electric Power Systems Research 77 (2007) 170–180

ELECTRIC POWER SYSTEMS RESEARCH

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Characteristics of vector surge relays for distributed synchronous generator protection

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Received 12 September 2005; received in revised form 17 February 2006; accepted 17 February 2006

Abstract

This work presents a detailed investigation on the performance characteristics of vector surge relays used to detect islanding of distributed synchronous generators. A detection time versus active power imbalance curve is proposed to evaluate the relay performance. Computer simulations are used to obtain the performance curves. The concept of critical active power imbalance is introduced based on these curves. Main factors affecting the performance of the relays are analyzed. The factors investigated are voltage-dependent loads, load power factor, inertia constant of the generator, generator excitation system control mode, feeder length and *R*/*X* ratio as well as multi-distributed generators. The results are a useful guideline to evaluate the effectiveness of anti-island schemes based on vector surge relays for distributed generation applications.

Keywords: Distributed generation; Islanding detection; Synchronous generators; Vector surge relays; Vector shift relays

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1. Introduction

Distributed generation has recently gained a lot of momentum in the power industry due to market deregulation, technological advances, governmental incentives and environment impact concerns [1–3]. An important requirement for the connection of synchronous generators to distribution networks is the protection system capability of islanding detection. Islanding occurs when a portion of the distribution system becomes electrically isolated from the remainder of the power system, yet continues to be energized by distributed generators. This is also known as loss of mains or loss of grid [3]. Failure to trip islanded generators can lead to a number of problems to the generator and the connected loads. The current industry practice is to disconnect all distributed generators immediately after the occurrence of islands [4,5]. Typically, a distributed generator should be disconnected within 200–400 ms after loss of main supply. In order to achieve such a goal, each distributed synchronous generator must be equipped with an islanding detection device. The common devices used for this purpose are the modified versions of the under/over voltage and under/over frequency relays. Among them, devices based on variations of frequency have been recognized as the most reliable option by the industry so far. Representative examples of such relays are the rate of change of frequency relay (ROCOF) and the vector surge relay (VSR), which is also known as vector shift or voltage jump relay [1–3]. However, it has been well recognized that such relays tend to fail when the mismatch or imbalance between the generation and the load in the islanded system is small. As more and more distributed generators are added to utility systems, it has become clear that a good understanding on the operating characteristics of these relays is important. The results can be very useful for utility engineers to evaluate the reliability and robustness of a given distributed generation anti-islanding scheme.

The objective of this paper is to present our investigation results on this subject. The concepts of detection time versus active power imbalance curve and critical active power imbalance are proposed to characterize the relay performance. Since vector surge relays have been widely used by the industry, it is selected as the study subject in this paper. However, the proposed method can be applied to other types of anti-islanding relays as well.

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doi:10.1016/j.epsr.2006.02.011

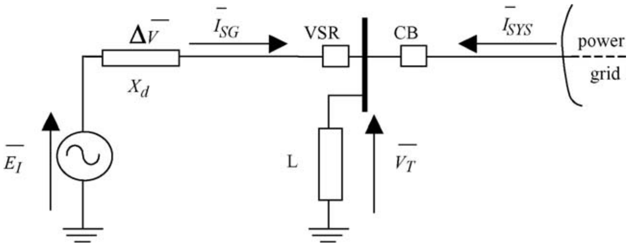

Fig. 1. Equivalent circuit of a synchronous generator in parallel with utility.

This paper is organized as follows. The principle of vector surges relays is explained in Section 2. The detection time versus active power imbalance curves and the concept of critical active power imbalance are discussed in Section 3. The main factors affecting the performance of vector surge relays are investigated in Section 4. The factors investigated are voltage-dependent loads, load power factor, inertia constant of the generator, generator excitation system control mode, feeder length and *R*/*X* ratio as well as multi-distributed generators. Finally, in Section 5, the main conclusions are analyzed.

2. Principle of vector surge relays

When a synchronous generator is operating in parallel with a distribution network, as depicted in Fig. 1, there is a voltage drop ΔV between the terminal voltage V_T and the generator internal voltage E_I due to the generator current I_{SG} passing through the generator reactance X_d. Consequently, there is a displacement angle between the terminal voltage and the generator internal voltage, whose phasor diagram is presented in Fig. 2(a). In Fig. 1, if the circuit breaker CB opens, due to a fault for example, the system composed by the generator and the load *L* becomes islanded. At this instant, the synchronous machine begins to feed a larger load (or smaller) because the current I_{SYS} provided by (or injected into) the power grid is abruptly interrupted. Consequently, the angular difference between V_T and E_I is suddenly increased (or decreased) and the terminal voltage phasor changes its direction, as shown in Fig. 2(b). Analyzing such phenomenon in the time-domain, the instantaneous value of the terminal voltage jumps to another value and the phase position changes, as depicted in Fig. 3, where the point *A* indicates the islanding instant. This behavior of the terminal voltage is called vector surge or vector shift. It is possible to verify that the cycle duration also changes. Vector surge relays are based on such phenomena [3].

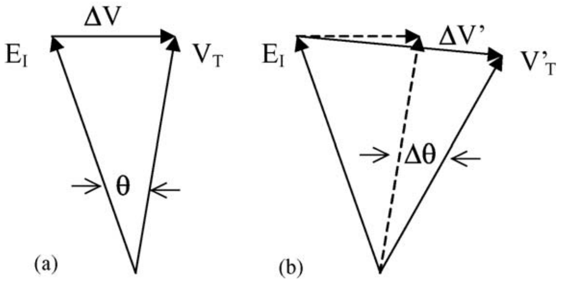

Fig. 2. Internal and terminal voltage phasors: (a) before the opening of circuit breaker and (b) after the opening of circuit breaker.

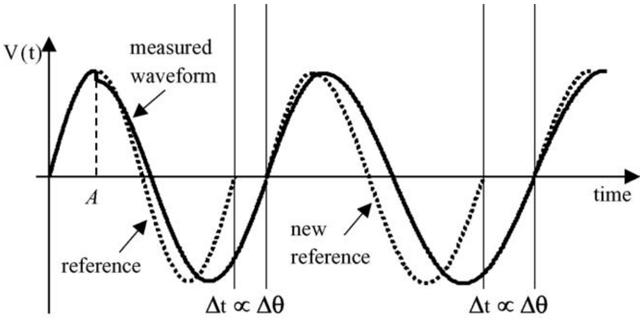

Fig. 3. Voltage vector surge and vector surge relay cycle-by-cycle measurements.

Vector surge relays available in the market measure the duration time of an electrical cycle and start a new measurement at each zero rising crossings of the terminal voltage. The current cycle duration (measured waveform) is compared with the last one (reference cycle). In an islanding situation, the cycle duration is either shorter or longer, depending on if there is excess or deficit of power in the islanded system, as shown in Fig. 3. This variation of the cycle duration results in a proportional variation of the terminal voltage angle $\Delta\theta$, which is the input parameter of vector surge relays. If the variation of the terminal voltage angle exceeds a pre-determined threshold α, a trip signal is immediately sent to the circuit breaker. Usually, vector surge relays allow this threshold to be adjusted in the range from 2° to 20° [3]. Another important characteristic available in these relays is a block function by minimum terminal voltage. If the terminal voltage drops below an adjustable level threshold $V_{\min}$, the trip signal from the vector surge relay is blocked. This is to avoid, for example, the actuation of the vector surge relay during generator start-up or short-circuits.

3. Determination and analysis of the performance curves

In this section, the determination and analysis of the detection time versus active power imbalance curves, i.e. the performance curves, are discussed. In this paper, the performance curves are obtained by using repeated dynamic simulations. The pre-islanding active power imbalance is gradually varied from 1 to 0 pu, referred to the MVA rating of the generator, by changing the generation–load profile in the islanded system. For each active power imbalance level, dynamic simulation is conducted, the detection time is determined once that the relay activation criterion is met and then the curves are plotted.

In this work, the network components were represented by three-phase models. Distribution feeders were modeled as series RL impedances. Transformers were modeled using *T* circuit. The synchronous generators were represented by a sixth-order three-phase model in the d*q* rotor reference frame [6]. The generators were considered equipped with an automatic voltage regulator, which was represented by the IEEE-Type 1 model. The mechanical power was considered constant, i.e. the primer mover and