Impact of Load Frequency Dependence on the NDZ and Performance of the SFS Islanding Detection Method

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***Abstract*—Sandia frequency shift (SFS) falls under the active islanding detection methods that rely on frequency drift to detect an islanding condition for inverter-based distributed generation. Active islanding detection methods are commonly tested on constant RLC loads where the load's active power is directly proportional to the square of voltage and is independent on the system frequency. Since the SFS method relies primarily on frequency to detect islanding, the load's active power frequency dependence could have an impact on its performance and the nondetection zone (NDZ). In this paper, the impact of the load's active power frequency dependence on the performance of the SFS method, during an islanding condition, is analyzed. A NDZ model that takes into account the load's frequency dependence parameter is derived mathematically and validated through digital simulation. The results show that the load's frequency dependence has a significant impact on the NDZ of the SFS method and thus is an important factor to consider when designing and testing this method.**

***Index Terms*—Distributed generation (DG), inverter, islanding detection, Sandia frequency shift (SFS).**

I. INTRODUCTION

ANTIISLANDING protection is an essential component to consider when integrating distributed generation (DG) to distribution systems. The main role of an islanding detection method is to detect accurately the moment of islanding and then isolate the DG in a timely manner. Islanding detection methods could be classified into three main groups which include passive, active and communication based [1]–[3]. Passive methods rely on setting an upper and lower threshold on a certain measured parameter, for example, frequency or voltage, to detect an islanding condition [1]–[4]. In active methods, the interface control design is modeled such that a certain system parameter is forced to drift once an islanding condition occurs and thus facilitating islanding detection [5], [6]. Recently, new active methods, relying on injecting disturbances, were proposed to detect an islanding condition [6], [7]. In [6], the proposed method relies on injecting a negative sequence current and measuring the corresponding negative sequence voltage variation to detect islanding. In [7], the current angle signal is distorted by injecting a low amplitude sinusoidal waveform and measuring the corresponding voltage deviation. Communication-based methods rely on sending and receiving signals between different protective devices to detect islanding. Active methods are considered the most attractive option since active methods are less expensive than communication based and have smaller nondetection zone (NDZ) than passive methods. NDZ could be defined as the loading conditions for which an islanding detection method would fail to detect islanding in a timely manner [8]. Recently, hybrid passive-active islanding detection methods combining advantages of both approaches were proposed in [9]–[11].

Sandia frequency shift (SFS) falls under the frequency drift active methods which also includes active frequency drift (AFD) [12], automatic phase shift, and slip mode frequency shift (SMS) [13]. The NDZ of active methods, relying on frequency drift, was analyzed in [14] and [15]. The SFS method was proven to be one of the most effective methods with a small NDZ. Islanding detection methods, and their NDZ, were developed and tested on constant RLC loads [1]–[9], [11]–[18]. In [19], the effect of the load's frequency dependence on the operation of one of the passive methods, over/under voltage protection and over/under frequency protection, was analyzed, and it was concluded that the load's frequency dependence has an impact of the NDZ and islanding detection capability of this method [19].

Commonly in power system transient analysis, the load frequency dependence is taken into account and has a major effect on the frequency deviation [20]–[23]. This has not been taken into consideration in the design of active methods such as the SFS method. The SFS method was tested on constant RLC loads which were assumed to be the hardest loading condition to detect [15]. Loads, on a distribution system, vary in characteristic depending on the type (residential, commercial or industrial) as well as season and weather [21]. In [21], typical load frequency dependence parameters were given for various types of loads. The majority of the loads operate close to unity power factor with the active power frequency dependence parameter varying from 0 to 3 [20].

In this paper, the performance of the SFS method is tested taking into account the load's frequency dependence. The NDZ for the SFS method is derived mathematically to demonstrate

Manuscript received May 24, 2009; revised July 31, 2009; accepted September 15, 2009. Date of publication October 6, 2009; date of current version December 10, 2010.

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Digital Object Identifier 10.1109/TIE.2009.2033482

TABLE I
TYPICAL LOAD FREQUENCY DEPENDENCE PARAMETER

Load Type	k_{pf}
3–phase Air condition	0.98
Water Heater	0
Clothes Washer	3
Fluorescent lights	1
Fan motors	2.9
Agricultural pump	5

the effect of load frequency dependence parameter on islanding detection. The inverter-based DG as well as the islanding detection method is modeled on PSCAD/EMTDC and simulation results are presented to verify the mathematical analysis. This paper is organized as follows: Section II derives the mathematical expression used to model the NDZ. Section III analyzes the effect of load frequency dependence on the performance of the SFS method. Section IV provides simulation results to verify the mathematical analysis. Lastly, conclusions are drawn in Section V.

II. NDZ WITH FREQUENCY DEPENDENT LOADS

The NDZ of an islanding detection method could be represented in the $\Delta P - \Delta Q$ (active power mismatch–reactive power mismatch), $L - C_{\mathrm{norm}}$ (load inductance–load normalized capacitance), or $Q_f - f_r$ (load quality factor–load resonance frequency) plane [8], [14], [15]. In this paper, the $\Delta P - \Delta Q$ is implemented and new equations are derived, for modeling the NDZ that take into account the active power frequency dependence. The load is represented by a parallel inductance (L), capacitance (C), and a resistance (R) that is frequency dependent to model active power frequency dependence. The load characteristic can depend on the season, class (residential, commercial, or industrial) and composition of the load (air conditions, lighting, electric heating, and motor loads). For example, the typical active power load frequency dependence parameter for a residential electrical heating load during the summer and winter are 0.7 and 1, respectively [21]. Typical load frequency parameters could be found in [21].

Generally, in order to determine the load parameters, measurement, and data acquisition devices are installed at the load terminal. These devices measure voltage and frequency deviations during a disturbance event. The corresponding variation in load active and reactive power is measured, and the load model is estimated by fitting the data to the assumed model. Table I presents the active power load frequency dependence values for various types of loads [20].

In general, the load's active and reactive power can be modeled in terms of R, L, and C as follows:

$$P = (P_o + \Delta P)\left(\frac{V}{V_o}\right)^{NP}(1 + k_{\mathrm{pf}}(f - f_o)) = \frac{3V^2}{R} \tag{1}$$

$$Q_L = (Q_o + \Delta Q) = \frac{3V_o^2}{\omega_o L} \tag{2}$$

$$Q_C = Q_o = 3V_o^2 \omega_o C \tag{3}$$

where P, Q_L, and Q_C represent the load's active, inductive reactive, and capacitive reactive three phase power, respectively, and ΔP and ΔQ represent the active and reactive power mismatch, respectively. The term NP represents the load's voltage dependence parameter which will be set equal to two while k_{pf} represents the load's frequency dependence parameter. The parameters V, V_o, and ω_o represent the system operating voltage, system nominal voltage, and system nominal frequency in radians per second, respectively. The parameters f and f_o represent the system frequency and nominal frequency, respectively. To represent the NDZ in terms of ΔP, the load and DG power are equated as follows:

$$P_{\mathrm{DG}} = P_{\mathrm{Load}}. \tag{4}$$

The DG is designed to operate as a constant current-controlled source. For the SFS method, the DG phase angle is expressed as follows:

$$\phi_{\mathrm{DG}} = -\frac{\pi}{2}\left(cf + k(f - f_o)\right) \tag{5}$$

where cf and k represent the parameters of the SFS islanding detection method. The SFS method relies on injecting a slightly distorted current waveform in order to drift the frequency beyond the frequency relay threshold values presented in the IEEE standards [17], [24], [25]. This is accomplished by chopping the current waveform, through the parameter cf, and introducing zero periods which will in turn affect the DG phase angle. In addition to cf, the DG phase angle is designed to be dependent on the system frequency by introducing another factor "k" [14], [15]. By referring to (4), the active power balance equation could be expressed as follows:

$$3VI_{\mathrm{rated}}\cos\phi_{\mathrm{DG}} = (P_o + \Delta P)\left(\frac{V}{V_o}\right)^{NP}(1 + k_{\mathrm{pf}}(f - f_o)) \tag{6}$$

where I_{rated} is the DG rated output current. Equation (6) can be further simplified as shown in

$$\frac{P_o}{\cos\phi_{\mathrm{DG|rated}}} V\cos\phi_{\mathrm{DG}} = (P_o + \Delta P)\left(\frac{V}{V_o}\right)^{NP}(1 + k_{\mathrm{pf}}(f - f_o))\,V_o \tag{7}$$

$$\frac{\Delta P}{P_o} = \frac{\cos\phi_{\mathrm{DG}}}{\left(\frac{V}{V_o}\right)^{NP-1}(1 + k_{\mathrm{pf}}(f - f_o))\cos[\phi_{\mathrm{DG|rated}}]} - 1. \tag{8}$$

Equation (8) represents the main equation for determining the active power mismatch term for modeling the NDZ. It can be seen that the NDZ will be dependent on k_{pf}. The reactive power mismatch can be found by equating the DG and load reactive power as follows:

$$3VI_{\mathrm{rated}}\sin\phi_{\mathrm{DG}} = Q_L - Q_C = \frac{3V^2}{\omega L} - 3V^2\omega C. \tag{9}$$