Application of Duffing Oscillators for Passive Islanding Detection of Inverter-Based Distributed Generation Units

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***Abstract*—Regarding the safety and reliable operation of modern distributed generation (DG) systems, an expert diagnosis apparatus is required to distinguish between different events. One of the crucial requirements in DG safe operation is the "islanding detection." In this paper, a new passive islanding detection method, based on the application of the Duffing oscillators, is suggested for the first time and tested under different network conditions. The method is designed to detect the changes on point of common coupling frequency by identifying the transformation of the Duffing oscillator from "chaotic state" to "great periodic state" and vice-versa. The simulations results, carried out by MATLAB/Simulink, are used to validate the performance of the proposed method. It is shown that the proposed method has excellent accuracy within a minimum detection time, even with the presence of high noise to signal ratios.**

***Index Terms*—Chaos, distributed generation (DG), duffing equation, islanding, voltage source converter.**

I. Introduction

ISLANDING operation of distributed-generation (DG) units usually occurs when the power supply is disconnected from the main utility but the DG keeps supplying power into the network. Failure to trip the DG during islanding may produce several negative impacts on DG equipment and utility power systems. The DG unit should detect the islanding and disconnect the DG unit in a timely manner to avoid damages [1], [2]. The main part of islanding detection is to accurately discern the moment of islanding and isolate the DG from the distribution network (DN) in minimum time. Unintentional islanding of DG may result in power-quality (PQ) issues, interference with grid protection devices, and low safety for consumers. It should be mentioned that some researchers are investigating the situation in which the DG has the ridethrough capability and is authorized to energize the load after islanding [3]–[6]. This option can add more complexity to the control system and costs as well.

In general, islanding detection methods are categorized into three main groups; namely: passive, active, and communication-based methods [7]. Passive islanding detection methods estimate the moment of the islanding using different measurements at the PCC. This benefit of passive methods is wane due to the fact that it is not easy to rely only on system parameters (e.g., voltage and frequency) for accurate detection of the islanding instant. Differentiating the system contingencies and transients from those of islanding events is not easy. Setting upper and lower thresholds can help to discriminate between the islanding and grid-connected conditions. However, this results in large nondetection zones (NDZs). For example, the over/underfrequency protection method uses upper and lower frequency thresholds. Sometimes, the load closely matches the DG capacity. In this case, the amount of the frequency or voltage deviation will not be sufficient to trigger the islanding detection system. NDZ is defined by the load consumption and power generation conditions that cause failure to detect islanding in a timely manner. Passive islanding detection methods mostly suffer from large NDZs [8], [9]. Several passive islanding detection methods are available like: undervoltage/overvoltage protection (UVP/OVP) and underfrequency/overfrequency protection (UFP/OFP) [9]; rate of change of active power [10], [11]; rate of change of frequency (ROCOF) [12], [13]; rate of change of frequency over power [14]; voltage and power factor changes [15]; phase jump detection [16]; as well as voltage unbalance and total harmonic distortion [17].

Unlike passive islanding detection methods, active islanding detection schemes make a perturbation into the voltage-source converter (VSC) output current by injecting an active signal in order to cut off the power balance between DG and local load consumption [18]. Hence, it becomes easy to detect the islanding condition. The main advantage of these methods over passive detection methods is their relatively small NDZ [9]. However, most active schemes have disadvantages of complex structure, and PQ degradation, to some extent. Some renowned active methods include slide-mode frequency shift (SMS) [19], active frequency drift (AFD) [20], and Sandia frequency shift (SFS) [21]. Communication-based methods rely on sending and receiving signals between different measurement units and protection apparatus to detect islanding. A comprehensive survey on different islanding detection methods can be found in [7].

This paper proposes a new passive islanding detection method, which has a tiny NDZ and excellent accuracy. The proposed method is based on a virtue of signal processing using Duffing oscillators. The Duffing equation is applied because it is one of the classic nonlinear systems that has been extensively studied [22]–[24]. The basic idea is that a small periodic signal in a noise can be detected by the Duffing oscillator via a transition from the "chaotic motion" to "great periodic motion"

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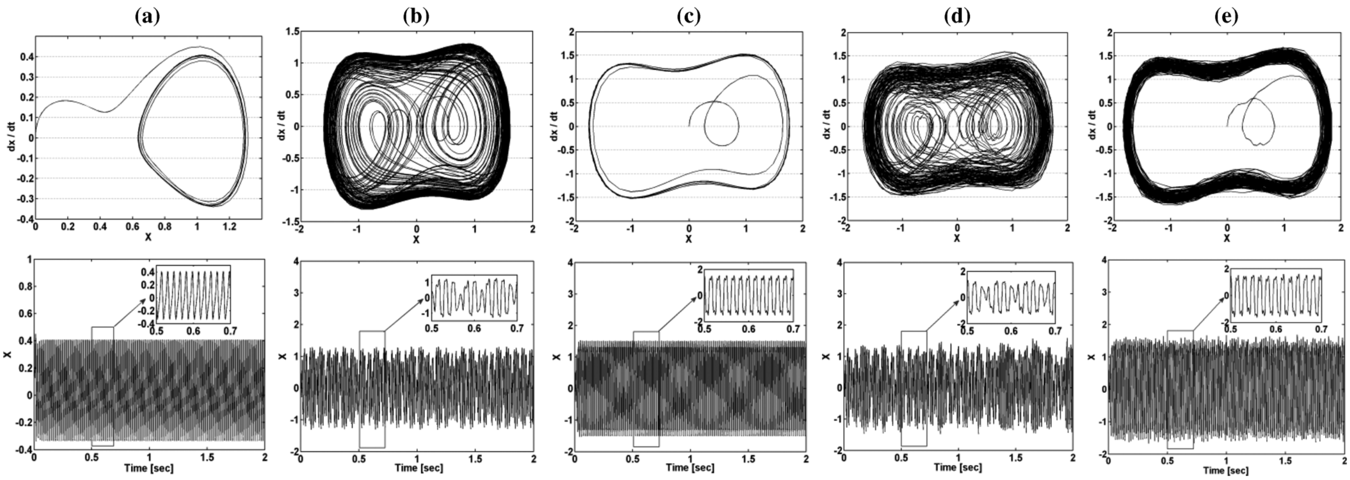

Fig. 1. Duffing oscillator in the phase plane and $x - t$ diagram. (a) Small periodic motion. (b) Chaotic motion. (c) Great periodic motion. (d) Chaotic motion additional Gaussian noise. (e) Great periodic motion-added Gaussian noise.

and vice-versa. The accuracy of the method is tested under a variety of conditions, including load switching, different load quality factors, and imbalance loading conditions. The sensitivity analysis of the presented method to the noise and comprehensive investigation on the NDZ of the method is also studied in this paper.

This paper is organized into the following sections: the next section illustrates the fundamental principle of Duffing oscillators. Section III presents the system under study. The proposed islanding detection method is discussed in Section IV. The performance of the presented method is evaluated in Section V and the paper ends with conclusions in Section VI.

II. Duffing Oscillators

Chaos describes the complex behavior of a nonlinear deterministic system. The first description of a chaotic process was made in 1963 by Lorenz [23]. Generally, a nonlinear dynamic system has four states: 1) the fixed point; 2) the periodic motion; 3) the chaotic motion; and 4) the quasiperiodic motion (great periodic motion). The basic idea of the signal detection scheme based on chaotic oscillators is that a small periodic signal in noise can be detected by the Duffing oscillator via a transition from chaotic motion to periodic motion.

The normal form of the Duffing equation is as follows:

$$\frac{d^2x}{dt^2} + \delta\frac{dx}{dt} - x + x^3 = \gamma\cos(t) \tag{1}$$

where δ is the damping ratio, the term "$-x + x^3$" represents the nonlinear restoring force, and $\gamma\cos(t)$ is the periodic driving force. Assuming $y = dx/dt = \dot{x}$, we have [22]

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= -\delta y + x - x^3 + \gamma\cos(t). \end{aligned} \tag{2}$$

If δ is fixed, then as γ varies from small to large, the system state varies from small periodic motion [Fig. 1(a)] to chaotic motion [Fig. 1(b)] and, at last, to the great periodic motion [Fig. 1(c)] [22] and [24].

If $\gamma = \gamma_c$ (γ_c refers to the critical value), then the system is in the critical state (chaos, but about to change to the periodic motion). The to-be-detected signal (D_f) can be viewed as a perturbation of the main sinusoidal driving force $\gamma\cos(t)$ (the reference signal). Although noise may be intense, it can only affect the local trajectory on the phase plane diagram, without causing any phase transition [Fig. 1(d) and (e)] [22]. In order to use (2) to detect weak signals with different frequencies, some frequency transformation should be applied. Considering $t = \omega\tau$, we have [22]

$$\begin{aligned} x(t) &= x(\omega\tau) = x^*(\tau) \\ \frac{dx(t)}{dt} &= \frac{1}{\omega}\frac{dx(\omega\tau)}{d\tau} = \frac{1}{\omega}\frac{dx^*(\tau)}{d\tau} \\ \frac{d^2x(t)}{dt^2} &= \frac{1}{\omega^2}\frac{d^2x(\omega\tau)}{d\tau^2} = \frac{1}{\omega^2}\frac{d^2x^*(\tau)}{d\tau^2}. \end{aligned} \tag{3}$$

Substituting (3) into (2), omitting the subscript $*$ of $x^*(\tau)$, and adding the input signal [22], we obtain

$$\begin{aligned} \dot{x} &= \omega y \\ \dot{y} &= \omega(-\delta y + x - x^3 + \gamma_c\cos(\omega\tau) + \text{Input}) \end{aligned} \tag{4}$$

where

$$\text{Input} = S(\tau) + \sigma(\tau) = a\cos\left((\omega + \Delta\omega)\tau + \varphi\right) + \sigma(\tau). \tag{5}$$

where $\sigma(\tau)$ is the Gaussian noise, $\Delta\omega$ is the frequency difference, and φ is the primary phase difference. In this paper, the fourth-order Runge–Kutta algorithm is used to solve the Duffing equation. Therefore, the system is a discrete dynamic system by nature. The dynamics of the discrete system are similar, but slightly different from the original continuous system. There is truncation error (discretization error) involved in a Runge–Kutta algorithm. It exists even with high precision arithmetic, because it is caused by truncation of the infinite Taylor series to form the algorithm [22]. Truncation error depends on the step size used, and the dependence is especially distinct, when the system is strongly nonlinear.

In this paper, $\delta = 0.5$ and $h = 10^{-5}$ (step size) were assumed and the value of γ_c was fixed at 0.81.