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A hybrid time–frequency approach based fuzzy logic system for power island detection in grid connected distributed generation

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ABSTRACT

A new time–frequency approach for power island detection in distributed generation systems is presented in this paper, using a hybrid fast variant of the S-Transform (ST) algorithm and a fuzzy expert system. The fast S-Transform algorithm with different types of frequency scaling, band pass filtering and interpolation techniques, results in significantly reduced computational cost, than the conventional S-Transform approach. The relevant spectral features of negative sequence voltage and current signals obtained from the distributed generation (DG) system terminals are extracted from the time–frequency matrix, obtained through fast ST. These features are used as inputs to a fuzzy expert system (FES), to distinguish between an islanding or non-islanding event, over a variety of operating conditions of the DGs including the change of system configurations, power imbalance, etc. The accuracy and response time of this new approach is compared with several well-known techniques (including time–frequency transform based methods), by applying it on both standard and existing distribution networks.

1. Introduction

Due to the growing importance of clean energy in comparison with conventional energy production from fossil fuels, DG systems are gradually becoming more popular all over the world. DGs comprise of conventional and renewable energy sources like solar, photovoltaic (PV), wind turbines, fuel cells, small-scale hydro, tidal and wave generators, micro-turbines, etc.; these are interconnected with power utility, supplying a portion of the total power to the connected loads at the distribution voltage level. Further, the DG systems exhibit high energy efficiency, low environmental impacts, and improve power quality of the distribution network. However, the steady state and dynamic behavior of the DGs affect their connection on existing utility network giving rise to control, protection and power quality problems [1–4]. Islanding is one such problem, in which a distribution system becomes electrically isolated from the rest of the power system, but continues to be energized by DGs connected to it [5,6]. According to IEEE Std. 1547-2003 [7], an islanding detection relay should instantly disconnect the DG, within 2 s of formation of a power island.

Several islanding detection techniques have been reported in recent years, and the general approach is to measure system parameters such as changes in voltage, frequency and harmonic distortion (passive techniques), which show significant deviation during grid disconnection or the detection of system parameter changes in the islanded DGs by introduction of small disturbances (active techniques) to the DG network. Such islanding detection techniques [8–10] include Over and Under frequency detection, rate of change of frequency (ROCOF) and voltage vector shift (VVS) based techniques [5,6,8–10]. An islanding detection technique must be reliable and fast in response. However, some passive islanding detection methods [5,6,8–10] not only exhibit slow response, but also give rise to false tripping signals.

Amongst the time–frequency approach, Wavelet Transform (WT) and S-Transform (ST) based methods have been previously used for islanding detection [11–14]. The wavelet based approach [11] uses wavelet coefficients exceeding a predetermined threshold to distinguish between islanding and non-islanding events, within a certain time limit. Although Discrete Wavelet Transform (DWT) is the most favoured time–frequency approach for power system protection [15] and power island detection [11–14], it suffers from inaccuracies due to the presence of sub harmonics, decaying dc components and noise in the current signals. On the other hand ST is a powerful tool for power signal disturbance assessment [16,17], but it involves high computational overhead, of the order of $O(N^2 \log N)$ using the entire data window for the signal. Thus, the conventional ST is not suitable for real-time applications, unless its speed is significantly increased. Although there have been some attempts to reduce the computational overhead for the calculation of discrete ST, the one presented recently [18] holds significant promise, where the discrete ST is treated as a

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special case of Generalized Fourier family transform (GFT). The GFT algorithm combines down sampling and signal cropping to produce a discrete fast ST. Such a scheme removes the retrieval of the unwanted information, thereby limiting the computational requirements. Computational complexity of such a Discrete Fast S-Transform (DFST) is $O(N \log N)$ in optimal conditions.

Thus, this paper principally proposes a new islanding detection method based on DFST which not only shows fast response, but which is also highly reliable. The computational overhead and calculation time of the new algorithm is substantially lesser than the widely used conventional ST used for islanding detection in [14], which is shown subsequently. Both the negative sequence voltage and negative sequence current are measured at the DG location, which are used as inputs to the DFST processing module resulting in features like spectral energy and standard deviation of the negative sequence voltage and negative sequence current at different frequency levels. For detecting power islands, the features from DFST showing significant fluctuations are given as inputs to the Fuzzy Rule-Based classifier, using trapezoidal membership functions (MFs) for classification of a non-islanding and an islanding event. The remaining paper is organized as follows: Section 2 describes the Discrete Fast S-Transform, while Section 3 addresses the DFST-based power island detection scheme. Section 4 depicts the feature extraction, while Section 5 presents the Fuzzy Rule-Based classifier. The simulation results and operation of the islanding detection scheme are depicted in Section 6. In Section 7, a detailed comparison of the proposed approach with various existing methods is presented. Lastly, the conclusions are drawn in Section 8.

2. Discrete Fast S-Transform

Brown et al. [18] have recently proposed the Generalized Fourier family transform (GFT) which treats ST as a special case. The GFT algorithm combines down sampling and signal cropping to produce a fast ST. The technique is based on Heisenberg's uncertainty principle, which limits the time–frequency resolution of ST and employs a tradeoff between the time resolution and frequency resolution. In ST the window width decreases at higher frequencies, with a reduction in frequency resolution; conversely the window widths are wider at low frequencies. Hence, the signal can be down sampled at low frequencies and cropped at high frequencies to result in fewer samples to be evaluated. Brown et al. [18] have employed the band pass filtering or signal cropping, in a way to relate it to frequency sampling through uncertainty principle.

2.1. Fast Fourier Transform (FFT)-based algorithm for evaluation of DFST

The Generalized S-Transform of a time varying signal $h(t)$ is obtained as:

$$S(\tau,f) = \int_{-\infty}^{\infty} h(t)\cdot w(\tau - t,f)\cdot \exp(-2\pi \mathrm{i}ft)\mathrm{d}t \quad (1)$$

where the window function $w(t, f)$ is chosen as

$$w(t,f) = \frac{1}{\sigma(f)\sqrt{2\pi}}\exp\left(-t/\left(2\cdot\sigma(f)^2\right)\right) \quad (2)$$

and $\sigma(f)$ is a function of frequency as

$$\sigma(f) = \frac{\alpha}{|f|} \quad (3)$$

Here, α is normally set to a value 0.2 for best overall performance of S-Transform, where the contours exhibit the least edge effects; for computing the highest frequency component of very short duration oscillatory transients, α is made equal to 5. The S-Transform performs multiresolution analysis on the signal, because the width of its window varies inversely with frequency. This gives high time resolution at high frequencies but, high frequency resolution at low frequencies. However, a generalized window function has a greater flexibility of generating required spectral component for fault analysis [16] and hence, it is chosen here.

Thus, the standard deviation $\sigma(f)$ is chosen as,

$$\sigma(f) = w/(a + bf^p) \quad (4)$$

where a, b are positive constants, f is the signal fundamental frequency and $w \leqslant \sqrt{a^2 + b^2}$. In (1), the usually chosen window (w) is a Gaussian one. Thus, the spread of the original Gaussian function is being varied with frequency to generate the new modified Gaussian window as,

$$w(t,f) = \frac{a + bf^p}{r\sqrt{2\pi}} e^{-\frac{(a+bf^p)^2 t^2}{2k^2}}, r \leqslant \sqrt{a^2 + b^2} \quad (5)$$

The discrete version of (1) is obtained as,

$$S(j,n) = \sum_{m=0}^{N-1} H[m+n]G(m,n)e^{\frac{i2\pi mj}{N}} \quad (6)$$

where

$$G(m,n) = e^{\frac{-2\pi^2 m^2 \alpha^2/(a+bf)^2}{n^2}} \quad (7)$$

and $H(m, n)$ is obtained by shifting the discrete Fourier transform of $h(k)$ by n; $H(m)$ is given by,

$$H[m] = \frac{1}{N}\sum_{k=0}^{N-1} h(k)e^{\frac{-2\pi mk}{N}} \quad (8)$$

and $j, m, n = 0, 1, 2, \ldots, N-1$.

The computation of the DFST is outlined in the following steps:

Step 1: Appropriate choice of the frequency scaling is a deciding factor for the fast computation of the algorithm. The selection of frequency scaling method is explicated below.

2.2. Dyadic scaling

This is the most common type of the frequency scaling. Here the frequency samples are chosen at an interval of $k = \{2^0, 2^1, 2^2, \ldots, 2^l\}$, $2^l < N$. where N is the total length of the time series. The frequency samples thus chosen act as the centre frequency for each band pass filter. For low frequencies the band pass filter is wider and it gets narrower as the centre frequency increases. Other than this scale, many other scales such as logarithmic scaling, can be used depending on the application. As opposed to $(N/2)$ number of time spectrum computations in the discrete S-Transform, the dyadic scale reduces it to $\log_2(\frac{N}{2})$ and the logarithmic scale reduces it to $\log_e(\frac{N}{2})$. The intermediate values in the scaling are approximated using different kinds of interpolation techniques. The choice of the interpolation technique is just a tradeoff between required precision and the computational effort in interpolating.

Step 2: Calculate the discrete Fourier Transform $H(k)$ of the signal samples $h(k)$ using FFT algorithm.

Step 3: Set the width of the band pass filter using uncertainty principle.

Since the significant frequencies in most power system disturbances lie within 3–4 kHz, the FFT of the raw signal is filtered with a band pass filter having cutoff frequency of nearly 4 kHz, and M is