Electrical Power and Energy Systems 36 (2012) 18–30

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Estimation of power quality indices in distributed generation systems during power islanding conditions

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ARTICLE INFO

Article history:
Received 12 July 2011
Received in revised form 22 October 2011
Accepted 29 October 2011
Available online 10 December 2011

Keywords:
Power quality indices
Total harmonic distortion
Sequence voltages and currents
Power measurements
Distributed generation
Islanding condition

ABSTRACT

This paper presents a new, fast Modified Recursive Gauss–Newton (MRGN) method for the estimation of power quality indices in distributed generating systems during both islanding and non-islanding conditions. A forgetting factor weighted error cost function is minimized by the well known Gauss–Newton algorithm and the resulting Hessian matrix is approximated by ignoring the off-diagonal terms. This simplification produces a decoupled algorithm, for the fundamental and harmonic components and results in a large reduction of computational effort, when the power signal contains a large number of harmonics. Numerical experiments have shown that the proposed approach results in higher speed of convergence, accurate tracking of power signal parameters in the presence noise, waveform distortion, etc., which are suitable for the estimation of power quality indices. In the case of a distribution network, power islands occur when power supply from the main utility is interrupted due to faults or otherwise and the distributed generation system (DG) keeps supplying power into the network. Further, due to unbalanced load conditions the DG is subject to unbalanced voltages at its terminals and suffers from increased total harmonic distortion (THD). Thus, the power quality indices estimation, along with the power system frequency estimation will play a vital role in detecting power islands in distributed generating systems. Extensive studies, both on simulated and real, benchmark hybrid distribution networks, involving distributed generation systems reveal the effectiveness of the proposed approach to calculate the power quality indices accurately.

1. Introduction

The quality of electric power has become an increasing concern for electric utilities and their customers over the last decade. Poor power quality is attributed due to the various disturbances like voltage sag, swell, impulsive, and oscillatory transients, multiple notches, momentary interruption, harmonics, and voltage flickers. Moreover, the recent advances in sustainable energy systems like the solar, wind and microturbine, and their induction to a low voltage microgrid has necessitated correct monitoring of power quality problems. In order to improve the quality of electrical power, it is customary to continuously record the disturbance waveforms using power-monitoring instruments. Further, with increased interest in electric power network restructuring under deregulation and the use of distributed generators in power distribution networks in a microgrid environment has necessitated the estimation of PQ indices, according to IEEE Std. 1459-2000 [1]. Also, the PQ indices need to be evaluated in the recent spurt of activities in the area of sustainable energy systems like the wind, photovoltaic, and fuel cell, in which significant amounts of time-varying harmonics are generated along with the frequency variations.

Distributed generation (DG) units [2–6] are rapidly increasing and most of them are interconnected with distribution network to supply power into the network as well as local loads. Various types of distributed generation systems like photovoltaic, wind farms, fuel cells, and micro turbines, are being used to alleviate the need for clean power, to offset the environmental concerns and supply the much needed power to remote areas. Use of DGs with the existing power distribution network, may improve the quality of power by minimizing the power quality disturbances and also reduce the peak loads, eliminating the requirement for reserve margin. A cluster of DGs can supply power to the grid as well as to the local loads and thus, require a careful analysis of their protection and safety problems during faults and islanding conditions. When power supply from the main utility is interrupted due to fault and other reasons and DG maintains the power supply to the distribution network, a situation like power islanding occurs, which causes negative impacts on the DG; without fast detection of the island, the DG may be lost. Thus, it is very important to identify the power island and disconnect the DG from the distribution system, as quickly as possible.

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doi:10.1016/j.ijepes.2011.10.019

Nomenclature

A_r amplitude of the rth harmonic component
ϕ_r phase of the rth harmonic component
w_r angular frequency of the rth harmonic component
v random noise
k time instant
r harmonic component
N harmonic order
λ forgetting factor
e estimation error
ξ variable forgetting factor-based cost function
V_{ar}, V_{br}, V_{cr} phase voltages of the rth harmonic component
I_{ar}, I_{br}, I_{cr} phase currents of the rth harmonic component
V_r^+, V_r^-, V_r^0 sequence voltages of the rth harmonic component
I_r+, I_r^-, I_r^0 sequence currents of the rth harmonic component
P_r^+, P_r^-, P_r^0 sequence powers of the rth harmonic component
$V_{ubk,rms}, I_{ubk,rms}$ root mean square values of voltage and current for an unbalanced system
$V_{ub,THD}, I_{ub,THD}$ equivalent total harmonic distortion factors for voltage and current
$S_{1ap}, S_{tap}, S_{nap}, S_{hap}$ fundamental, total, non-fundamental and harmonic apparent powers
D_{ubV}, D_{ubI} voltage and current distortion powers
P, Q total 3-phase active and reactive power
PF effective power factor
PQ power quality
FFT fast fourier transform
RDFT recursive discrete fourier transform
LMS least mean squares
EKF extended Kalman filter
PLL phase-locked loop

Islanding detection [2–6], Alaboudy and Zeineldin [28] usually employs methods to monitor the system parameters like the voltage magnitude and phase, frequency and its rate of change, impedance, and power output. from the DG terminal or pattern recognition approaches, employing wavelet transform or S-transform. In general, after loss of the main power supply system, the DG has to supply power to the rest of the connected distribution network, and the connected loads. This operation creates some loading changes on the DG and the single phase loads on the system, producing unbalance and harmonic voltages and currents, contributing to THD [6]. Additionally, the load changes and unbalancing can cause the generation of negative sequence voltages [6], currents, and power, necessitating the monitoring the power quality indices during islanding and also during non-islanding conditions (like fault conditions, which may or may not occur with grid islanding).

Due to the increased importance of PQ problems in the distribution networks, it has become imperative to estimate the various power quality indices to assess its impact and devise methods to mitigate them. Numerous methods for assessing power quality are available and among them, the FFT is used commonly for the extraction of harmonics. Unfortunately, the FFT suffers from leakage and picket fence effects and provides erroneous measurements if the PQ waveforms are contaminated with noise. Some of the widely used techniques include LMS algorithm based adalines and neural networks [7–9], recursive least squares [10,11], Recursive Newton Type Algorithm [12–14], Gauss–Newton methods [15–17], Kalman and unscented Kalman Filter [18–21], etc. Also, the newly presented techniques include iterative loop approach [22], vector transformations [23], on-line methods [24,25] have been presented for estimating power signal parameters under time varying and distorted conditions. The EKF and its variants suffer from an incomplete of knowledge about the statistical properties of the power quality waveforms and also the choice of covariances depends on trial. Large computational overhead occurs, in the presence of a large number of harmonic components, say upto the 64th harmonic.

Amongst all these methods, the LMS based adaline is the simplest, but the estimation of frequency is difficult to handle under time varying situations. Also, both the recursive Newton and Gauss–Newton methods become computationally involved, with increased order of harmonics in the signal and high sampling rate. Further, the recursive Newton method computes the PQ signal frequency only, whereas the recursive Gauss–Newton algorithm (RGN) assumes that the PQ signal frequency is known and estimates the amplitude and phase of the sinusoid, of only the fundamental. Therefore, there is a need for an algorithm to estimate simultaneously, the PQ signal parameters and commonly used PQ indices such as RMS values of voltage, and current, the PF, THD, sequence components for active and reactive powers.

In this paper, a computationally less involved and very fast, Modified Recursive Gauss–Newton algorithm (MRGN) is presented for power quality assessment. Further, the PQ indices are estimated, using the definitions specified in the IEEE standard [1], mentioned earlier. The speed of the MRGN is due to certain assumptions and approximations used in the conventional RGN algorithm. Further, the algorithm also takes into account, the time varying nature of the power signals like the sudden changes in amplitude, phase angles, and frequency of the fundamental and harmonic components, which results in fast convergence to true values with significant accuracy. Using extensive studies, the superiority of this algorithm over the LMS, RDFT and other well known techniques has been shown. Further, the paper is organized as: After the introduction in Section 1, Section 2 presents a detailed signal model, which includes fundamental and harmonics, embedded in noise. In this section, the new fast MRGN algorithm is also presented, for the signal model described in the beginning. After computing the various voltage and current parameters, estimation of PQ indices including sequence voltages and currents are presented in Section 3. Section 4 considers several test cases and provides results, which exhibit robustness of accuracy and convergence in the presence of high measurement noise. Lastly, concluding remarks are given in Section 5.

2. Power signal model and the new fast MRGN algorithm

The Gauss–Newton method is used to estimate the parameters of a time varying power signal, by minimizing a priori estimation error between the observed signal and the estimated one, in the least square sense. An exponentially weighted error cost function is minimized, using an unconstrained optimization technique resulting in a Hessian matrix, which is suitably manipulated to yield a recursive decoupled formulation of the MRGN algorithm. All the parameters of the time varying power signal are estimated with very little computational overhead due to the decoupled nature of the algorithm. The Gauss–Newton algorithm has the computational simplicity of the normal gradient technique and speed of convergence of the Newton algorithm.

The observed power, voltage or current signal is assumed to comprise of the fundamental and harmonics of order N and is represented in discrete form by,