Electric Power Systems Research 154 (2018) 515–527

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Sensitivity analysis of method for harmonic state estimation in the power system

Vedad Bečirović[a,*], Ivica Pavić[b], Božidar Filipović-Grčić[b]

[a] Faculty of Electrical Engineering, University of Sarajevo, Zmaj od Bosne bb, 71000 Sarajevo, Bosnia and Herzegovina
[b] Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, 10000 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 31 May 2017
Accepted 28 July 2017

Keywords:
Power systems
Power quality
Harmonic estimation
Kron reduction matrix
Optimization evaluation genetic algorithms
Sensitivity analysis

ABSTRACT

In this paper, a new algorithm for harmonic state estimation in power systems is represented. The algorithm is based on node voltage method, Kron reduction matrix, modeling of power system in frequency domain using phase values and optimization genetic algorithm. The algorithm uses measured voltage and current harmonics as an input data, with partially known data about transmission network. Algorithm estimates RMS and angle values of voltage harmonics in the unmonitored part of power system. Sensitivity analysis of proposed algorithm was conducted on a case study of 110 kV transmission network. Admittance matrix of power system is identified by using genetic algorithm with an accuracy of 0.5%, while an error of harmonic voltage estimation is lower than 1.129%.

1. Introduction

PSs represent the most complex techno-economical systems of today. For an efficient management of PS, basic requirement is efficient monitoring. High demanding life standards, application of optimization processes to improve efficiency, productivity and cost effectiveness of PSs are reasons why increasing number of PSs nowadays work near stability limit.

Current situation and future activities in the field of PQ are topics of concern of numerous working groups, research centers and science gatherings. In the papers [1–3] authors have presented a detailed overview of PQ monitoring. They concluded that harmonic monitoring represents a very important factor for cost effective techno-economical functioning of a PS. PQ monitoring at one point of PS gives information solely about PQ at the monitored point. On the other hand, estimation of PQ parameters in PS gives a global picture of PQ in observed PS. References [4,5] contain overview of methods, procedures and algorithms of PQ estimation in PS.

At the beginning of 70's a term “harmonic estimation” was introduced [6] and since then harmonic estimation remains topic of interest.

Causes of harmonic propagation in transmission networks, algorithm for HSE and mathematical formulation of higher harmonics in frequency domain are given in reference [7]. References [8,9] have similar approach to conducting HSE. In the reference [8] harmonics were analyzed, i.e. classic HSE, while in the reference [9] sub-harmonic state estimation was analyzed. In both references a node voltages method, Kron reduction matrix and problem solving in system of phase values were used. A proposed algorithm in references [8,9] was implemented on real PS configuration.

Most of the algorithms are based on node voltages method, however, algorithms implementing Kirchhoff's current law can be encountered as well. In the reference [10] Kirchhoff's current law was used, i.e. measurement of currents of buses. Certain simplifications were introduced and fitness function was formed. Maximum HSE error was 0.5% which is a good result.

Generally speaking, usage of LS, TLS, WLS, FDWLS and SVD in HSE represents basics of algorithms. Reference [11] used TLS and statistical approach to HSE results processing, and moreover, it discussed IEEE case study containing 14 buses. In the reference [11] for HSE were used WLS, SVD i FDWLS. Listed algorithms were implemented on two examples with real PS measurements. Furthermore, application of SVD in HSE was also explained in the reference [12,13]. By implementation of different approaches to HSE, so-called hybrid algorithms were developed, one of them being OA-HSE. OA-HSE was mathematically formulated and published in [14]. The algorithm is often cited in papers listing probability as one of the approaches to HSE. Furthermore, in reference [14], an example was given with real measurements made in PS. In the paper [15], authors used probability of certain harmonics occurrence at unmonitored PS buses in order to estimate harmonic state. Fur-

* Corresponding author.
E-mail addresses: vbecirovic@etf.unsa.ba (V. Bečirović), ivica.pavic@fer.hr (I. Pavić), bozidar.filipovic-grcic@fer.hr (B. Filipović-Grčić).

http://dx.doi.org/10.1016/j.epsr.2017.07.029
0378-7796/

Nomenclature

BGA	binary genetic algorithm
CT	current transformer
EMTP-RV	electromagnetic transient program – RV
FDWLS	fast decoupled weighted least square
GA	optimization evaluation genetic algorithms
GPS	global positioning system
HDA	harmonic domain algorithm
HS	harmonic sensitivity
HVN	height voltage networks or HV networks
LS	least square
LVN	low voltage networks or LV networks
MHS	mean harmonic sensitivity
MHVC	monitoring harmonic voltage and current – bus
MVN	medium voltage networks or MV networks
OA-HSE	observability analysis – HSE
PMU	phasor measurement unit
PQ	power quality
PS	power system
RMS	root mean square
SVD	singular value decomposition
TLS	total least squares
TVE	total vector error
VHE	voltage harmonic estimation – bus
VT	voltage transformer
WLS	weighted least square

thermore, IEEE case study containing 14 buses was discussed and criteria for HSE assessment, i.e. for HSE evaluation, were introduced in the same paper. Similarly, in 1998 paper [16] was published where concept of HSE application in PS was stated. It is interesting to compare ideas proposed in the past with their nowadays implementation. Certain proposals are today outdated in terms of new technologies.

HSE is often used as a tool to identify a harmonic source. In reference [17] an algorithm was presented for harmonic source identification in PS using LS for HSE. Moreover, in [18] HSE was also used for identification of harmonic sources and time synchronized measurement. GPS technology was implemented. The problem was analyzed in system of phase values.

All previously stated algorithms assume that input data are harmonics (voltage or current harmonics) of monitored PS buses. However, measurement instruments can give measurement data in form of power per each harmonic. In reference [19], a power flow calculation method HDA in frequency domain was given. The method is based on Newton-Raphson method, Norton's theorem and Kron reduction matrix.

In reference [20], GA was used for HSE, more accurately BGA was used for SVD. This paper discusses optimal positioning of PQ monitoring devices, and moreover it uses WLS for forming fitness function. A new approach to positioning of PQ devices was presented and the approach was implemented on IEEE case study containing 14 buses [20].

Majority of algorithms proposed or used nowadays for HSE are based on PMU technology. Furthermore, in the book [21] a mathematical formulation of PMU technology is given. In reference [22,23] PMU technology, along with ridge estimation, was used for HSE. Estimation error was determined by LS and satisfying results were obtained.

Through previous analysis of relevant literature and revision of papers from 2005 [24], 2011 [25] and 2013 [26], several important factors were established for analysis in process of HSE algorithms application: (1) based on what data and how fast HSE can be conducted, and moreover, what is expected accuracy of the algorithm; (2) Mathematical formulation of the problem, i.e. on what theoretical principles the algorithm is based; (3) models of certain PS elements (transmission line, power transformer, power electronics, power sources and loads); (4) applicability of certain optimization tools; (5) analysis in different domains (frequency and time domain). Through literature analysis Frances C. Arrillaga can be singled out as first person who introduced HSE algorithm, and as a result, a majority of papers rely on Arrillaga's researches.

Research presented in this paper is a continuation of the ones shown in the reference [27]. The goal of this paper is to show a detailed mathematical description of proposed HSE algorithm, to explain its characteristics and to conduct sensitivity analysis.

2. Problem statement

Efficient operation of PS is directly related to influences of harmonic propagation in PS. Harmonic propagation throughout power network and voltage distortion are directly transmitted from transmission power network to MVN and LVN. Philosophy of management and operation of HVN with goal of PQ improvement is the basis of reliable, stable and economically feasible transmission management. Higher harmonics cause the following effects in transmission networks: additional heating and losses of PS elements (transmission lines, transformers, compensation devices), unwanted voltage distortion, interference with railway systems, increased or decreased voltage levels, increased flow of circulating currents through grounding wire, decrease of transformer rated power, interference with conventional telecommunication lines, etc.

According to the procedure for harmonic measurement shown in IEC61000-4-7 [28], it is possible to analyze harmonic content using RMS and angle measurements (harmonic phasor). Other approaches to post-processing of waveforms for determining the harmonic content exist as well, such as application of wavelet-packet transform [29]. Majority of conventional PQ monitoring devices usually measure the average RMS values of recorded waveforms, while neglecting the angle. Stated neglection is a consequence of lack of angle analysis in standard EN50160 discussing PQ. If current and voltage harmonic phasors are treated using PMU technology [21], result are synchronized harmonic phasors. Application of algorithm for PMU ensures elimination of phase error from harmonic phasors. Post-processing of voltage and current waveforms on MHVC buses (Fig. 1) is based on IEC61000-4-7 [28] and then on algorithm for PMU technology [30,21].

Certain data about PS structure are usually unknown and therefore they represent a major problem for efficient HSE. Certain HSE algorithms having high accuracy assume that matrix $[\mathbf{Y}]$ is known.

In this paper, an algorithm is proposed which is applied to the transmission network of a single voltage level. This paper has two goals of research: (1) proposed HSE algorithm should enable faster and simpler modeling of PS based on a partially known data about PS; (2) algorithm should estimate harmonics on all buses with the same accuracy.

Sensitivity analysis is applied to determine how many results are within the range of acceptable (satisfying) values in terms of global matrix $[\mathbf{Y}(h)]$ identification.

3. Harmonic state estimation

In the following chapters, an algorithm for HSE on PS buses without harmonic monitoring is mathematically and graphically described. An algorithm is based on: node voltages method, Kron reduction matrix, modeling of PS in the system of phase values,