Techniques for Harmonic Analysis

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Abstract-- **This paper describes the gained experience on the development and application of techniques for harmonic analysis of nonlinear power systems. These methodologies have been developed in the time, frequency and hybrid time and frequency domain frames of reference. Their application to the computation of the periodic steady state solution of different test systems is detailed, indicating their advantages and limitations in terms of efficiency, computer requirements and accuracy.**

***Index Terms*—Analysis, hybrid, nonlinear, time-varying, hybrid, periodic steady state.**

I. Introduction

IMPORTANT practical experience gathered on diverse aspects of the harmonic distortion, such as its causes, standards, mitigation, as well as its effect on the quality of power in power systems has been compiled and made available in the open literature [1-2].

Harmonic detection and harmonic prediction are currently the two main fields of the digital harmonic analysis, which allow an evaluation and diagnostics of the quality of power. The first determines and processes in real time the information of the monitored harmonic content in the network, whereas the later predicts the harmonic distortion by means of analyitical models implemented for digital simulation. To this category belong the techniques described in this contribution.

In general, harmonic simulation techniques can be identified as frequency domain, time domain and hybrid time and frequency domain methods. In the sections to follow a description is given on the conceptual and analytical details on which rely the techniques previously mentioned.

II. Methods and Algorithms

Frequency Domain. Essentially,available techniques in the frequency domain are broadly divided in current source method, iterative harmonic analysis and harmonic power flow methods.

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A. Current Source Method

The frequency response of the power network, as seen by a particular bus, is obtained injecting a one per unit current or voltage at the bus of interest with discrete frequency steps for the particular range of frequencies. The process is based on the solution of the network equation,

$$[Y]V = I \tag{1}$$

where $[Y]$ is the network admittance matrix, V is the nodal vector to be solved and I is the known vector of current injection, with only one nonzero entry.

The simplest current source method uses the sequence components frame of reference to obtain the propagation of characteristic harmonic currents by injecting ideal current sources into the power network [3]. In a later contribution, the solution of a power system is obtained directly in the phase frame of reference for three phase systems [4]. Both approaches are based on solving the entire network for each harmonic of interest, assuming harmonically decoupled circuits.

B. Iterative Harmonic Analysis (IHA)

The IHA is based on sequential substitutions of the Gauss-type. The harmonic producing device is modeled as a supply voltage-dependent current source, represented by a fixed harmonic current source at each iteration. The harmonic currents are obtained by first solving the problem using an estimated supply voltage. The harmonic currents are then used to obtain the harmonic voltages. These harmonic voltages in turn allow the computation of more accurate harmonic currents. The solution process stops once the changes in harmonic currents are sufficiently small [5-9]. One of the main advantages of the IHA method is that the power network components can be modelled in a closed form, with time domain simulation or any other forms. Distorted and non-distorted conditions can be handled with this method.

However, the narrow strability margin and slow convergence characteristic of the IHA has limited its application to the solution of practical problems in power systems. Numerical dominance of the leading diagonal of the matrix of system parameters is required to ensure convergence. This is not, however, a condition satisfied by weak or poorly damped systems or near sharply tuned resonant frequencies [5-6]. A method for improving the convergence characteristics of the IHA has been proposed [7].

C. Harmonic Power Flow Method (HPF)

The HPF method takes into account the voltage-dependent nature of power components. In general, the voltage and current harmonic equations are solved simultaneously using Newton-type algorithms [9-12].

The harmonics produced by nonlinear and time-varying components are cross-coupled. This phenomenon has has been already represented in detailed models of the synchronous machine [13-15], the power transformer [16], arc furnaces [17], TCRs [18] and the converter [19].

In [12] a harmonic domain solution process for the entire network is used where nodes, phases, harmonics and harmoni-coupling are explicitly represented. The solution is based on a linearization process around a particular operation point of nonlinear and time-varying components. Thus, a linear relationship between harmonic voltages and currents is possible; this is a valid condition only in a close neighborhood of the operation point. As a result of the linearization process, a Norton harmonic equivalent is obtained where the phase unbalance and harmonic cross-coupling effects are explicitly represented. The computation of the equivalent may not be easy and for obtaining accurate results it should be iteratively updated. The computational effort increases in direct proportion to the size of the analyzed system and to the number of harmonics explicitly represented. The unified iterative solution for the system has the form,

$$\Delta I = [Y_J]\Delta V \qquad (2)$$

where ΔI is the vector of incremental currents having the contribution of nonlinear components, ΔV is the vector of incremental voltajes and $[Y_J]$ is the admittance matrix of linear and nonlinear components. The later components are represented for each case by the computated Norton harmonic equivalent. This is a numerically robust methodology having, in addition, good convergence characteristics [12].

In a more recent contribution [20] a Newton-Raphson method is proposed based on the instantaneous power balance formulation for the representation of linear and non-linear loads.

D. Time Domain

In principle, the periodic behaviour of an electric network can be obtained directly in the time domain by integration of the differential equations describing the dynamics of the system, once the transient response has died-out and the periodic steady state obtained [21]. This Brute Force procedure [22] may require of the integration over considerable periods of time until the transient decreases to negligible proportions. It has been suggested only for the cases where the periodic steady state can be obtained rapidly in a few cycles [6]. This is usually the case of systems where ideal sources are assumed and are, in addition, sufficiently damped. In this formulation, the general description of nonlinear and time-varying elements is achieved in terms of the following differential equation,

$$\dot{x} = f(x,t) \qquad (3)$$

where x is the state vector of m elements.

The inefficient solution of (3) based on a conventional numerical integration process such as the Runge-Kutta has limited its application to obtain the periodic steady state solution of electric systems with nonlinear and time-varying components, even though in the absence of numerical instability this process leads to the “exact” solution [22].

Fast Convergence to the Limit Cycle (Steady State)

A technique has been used to obtain the periodic steady state of the systems without the the computation of the complete transient [23]. This method is based on a solution process for the system based on Newton iterations. In a later contribution [24], techniques for the acceleration of the convergence of state variables to the Limit Cycle based on Newton methods in the time domain have been introduced with the purpose of removing the severe limitations and computational inefficience of conventional Brute Force methods to obtain the periodic solutions in power systems.

Fundamentally, to derive these Newton methods it is assumed that the periodic steady state solution $x(t)$ of (3) is *T*-periodic and can be represented as a Limit Cycle for x_k in terms of other periodic element of x or in terms of an arbitrary *T*-periodic function, to form an orbit. Before reaching the Limit Cycle the cycles of the transient orbit are very close to it. Their position is apropiately described by their position in the Poincaré Plane [22]. A single cycle “maps” its starting point x^i to its final point x^{i+1} and also maps, from a Base Cycle [24], a segment of perturbation Δx^i to Δx^{i+1}. All the mappings close to the Limit Cycle are quasi-linear, so that a Newton method can be used to obtain the starting point x^∞ of the Limit Cycle.

It is posible to take advantage on the linearity taking place in the neighborhood of a Base Cycle if (2) is linearized around a solution $x(t)$ from t_i to t_{i+T}, yielding the variational problem,

$$\Delta\dot{x} = J(t)\Delta x \qquad (4)$$

where $J(t)$ is the *T*-periodic Jacobian matrix.

Note that (4) allows the application of Newton type algorithms to extrapolate the solution to the Limit Cycle, obtained as [24],

$$x^\infty = x^i + C(x^{i+1} - x^i) \qquad (5)$$

where

$$C = (I - \Phi)^{-1} \qquad (6)$$

In (5) x^∞, x^i and x^{i+1} are the vectors of state variables at the Limit Cycle, beginning and end of the Base Cycle respectively, and in (6) *C*, *I* and Φ are the iteration, unit and identification matrices, respectively.

This technique has been successfully applied to the modeling in the time domain of components such as the synchronous machine [25], the power transformer [26], arc furnaces [27], TCRs [28], TSCs [29] and TCSCs [30].

E. Hybrid Methods

The fundamental advantages of the frequency and time domains are used in the hybrid methodology [24-25], where the power components are represented in their natural frames of reference, e.g., the linear in the frequency domain and the nonlinear and time-varying in the time domain. The Fig. 1 illustrates the conceptual representation of the hybrid methodology. The voltages V at the load nodes where the nonlinear components are connected are iteratively obtained. Starting from estimated V values, the currents I_L for the linear part are computated for each harmonic h using the harmonic admittance matrix $[Y_k]$, which includes non-linear load effects. For the nonlinear part, V is taken in the time domain as the periodic function $v(t)$ to obtain $i(t)$, which is then transformed to I_N in the frequency domain. In convergence $\Delta I = I_L + I_N$ tends to zero. The iterative solution for the entire system has the form,

$$\Delta I = [Y_k]\Delta V \tag{7}$$

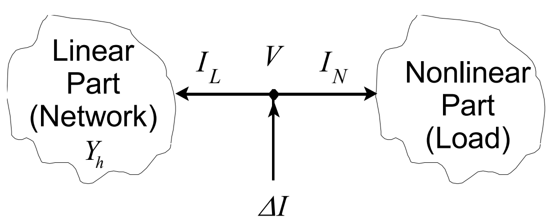


Fig. 1 System seen from load nodes

F. Parallel Processing.

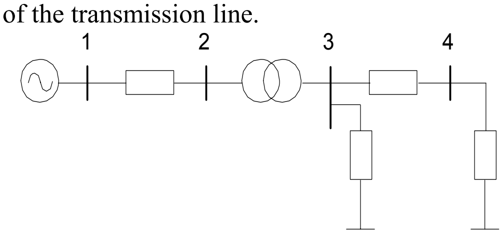
The methods and algorithms described in the previous sections are based on different frames of reference.; each of them having associated a particular computational efficiency. There is a common characteristic between these techniques: all of them are based on a conventional sequential computer solution. In recent contributions [31-33], parallel processing technology [34-35] has been applied to further enhance the efficiency of harmonic simulation techniques. The basic idea is to solve a large problem by splitting it-up into several small tasks, which are simultaneously solved to obtain a final overall solution of the original problem. Preliminary results on harmonic analysis indicate that the application of parallel processing considerably improves the efficiency reducing the computational effort required by conventional sequential solution techniques.

III CASE STUDIES

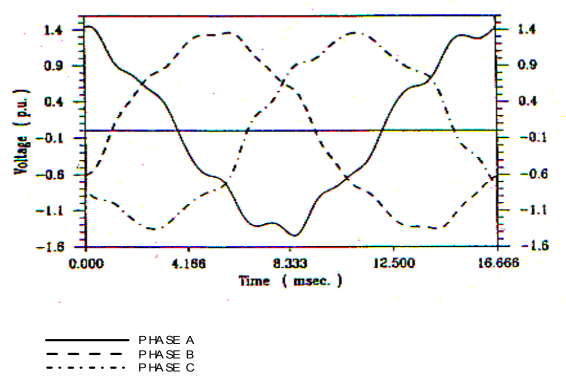
A. Application of the Harmonic Domain

The Harmonic Domain is applied to the solution of the practical Jaguara-Taquaril transmission system [6], modified to incorporate a load to the end of the 398 km transmission line, as illustrated in Fig. 2(a). Detailed three-phase models in the Harmonic Domain of the synchronous generator, the power transformer and the transmission line have been used. The details on the analytical formulation and test data are given in [15]. The generator model incorporates the stator-rotor harmonic interaction and magnetic saturation effects [15]. The transformer model takes into account a multilimb (3 o 5) magnetic core where the saturation phenomenon is represented [11]. Besides, the harmonic coupling and winding electrical connections effects are incorporated. The transmission line is represented with a frequency dependent model where long line effects are taken into account [36].

The Fig. 2(b) illustrates the response obtained at node 4. The distorted voltage waveforms and their harmonic content shown in Fig. 2(c) describe the combined effects of the intrinsic system unbalance, saturation and harmonic interaction between stator-rotor in the generator, transformer saturation, magnetic core (3 limbs), electrical configuration (grounded star-delta), frequency-dependence and long line effects of the transmission line.



(a)



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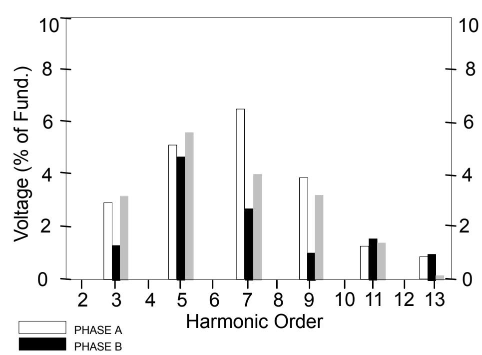


(c)

Fig. 2. (a) Test system 1; (b) Voltajes at node 4; (c) Voltaje harmonic content at node 4

B. Application of Techniques for the Acceleration to the Limit Cycle.

The Fig. 3 illustrates the case of a 3 node network with magnetizing branches and arc furnaces connected at nodes 2 and 3 respectively, two shunt capacitors and three transmisión lines. The dynamic of the system is represented by eleven ordinary differential equations The source is assumed sinusoidal of *1.0 p.u.* in amplitude. The Limit Cycle is located within a maximum error of 10^{-10} *p.u.*

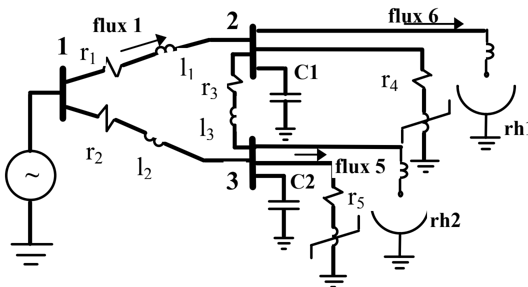
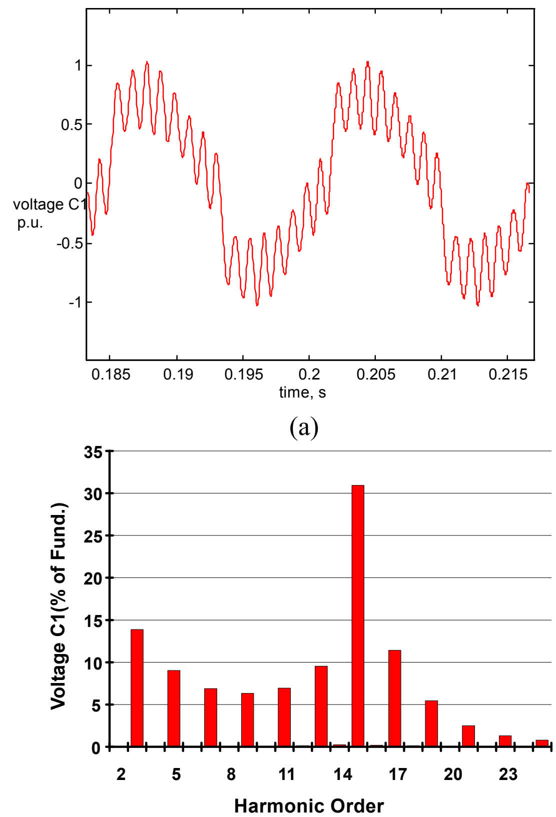


Fig. 3 Test system 2.

The periodic steady state of the system is obtained in 79 periods (cycles) of time (NFC) using the Brute Force method (BF) and in 56 using the Newton methods for the acceleration of the convergence to the Limit Cycle based on the Direct Approach (DA) and Numerical Differentiation (ND) procedures, respectively [24], see Table 1. The voltage through capacitor C1 and its harmonic content are illustrated by Figs. 4(a) and (b), respectively. A considerable harmonic distortion is observed in the capacitor voltage, see Fig. 4(a), mainly produced by the strong harmonic injection coming from the arc furnaces. For this particular case large amounts of higher harmonics are produced, as observed from Fig. 4(b) where the 15th harmonic is around 30% of the fundamental

***Table 1.** Errors during convergence of DA y ND.*

NFC	Brute Force	DA Method	ND Method
8	2.0454e-002	2.0454e-002	2.0454e-002
20	6.6126e-004	9.4284e-003	9.4284e-003
32	2.7154e-005	4.2512e-005	4.2510e-005
44	1.1015e-006	8.6676e-010	8.6957e-010
56	4.4521e-008	8.4932e-015	1.1643e-014
:	:		
79	9.4800e-011		



(a)

(b)

Fig. 4. Voltage and harmonic content in capacitor C1.(a) Voltage v_{C1}; (b) Harmonic content.

C. Application of the Hybrid Methodology.

The hybrid methodology has been successfully applied to obtain the periodic steady state solution of larger systems [24]. However, to date the analysis has been restricted to single phase systems, such as IEEE test systems of 14, 30, 57 and 118 nodes [37]. In Table 2 are reproduced the results obtained and reported in [24] for the 118 node test system. Three nodes are indicated where nonlinear loads of the type of the magnetizing branch of a transformer are connected. The convergence was obtained in four iterations to meet a criterium for convergence of 10^{-6} *p.u.*

***Table 2.** Harmonic voltages, IEEE-118 test system.*

Harmonic	Node 7	Node 107	Node 118
1	0.98913	0.99158	0.95101
3	2.637e-03	2.305e-03	1.786e-03
5	3.294e-05	1.265e-04	6.060e-05

D. Application of Parallel Processing

The Table 3 gives the relative efficiency achieved with the solution obtained for test system 2 with the sequential and the parallel computation using PVM with the ND method. For this test case seven computers were used; one taking the role of the master processor (797 MHz) and six of the slave processors (794 MHz). All computers have installed the UNIX operative system.

The relative efficiency is computed as [38],

$$E_{relative} = \frac{T_1}{T_P} \quad (7)$$

where,

T_1 execution time with one processor

T_P execution time with P processors

Note from Table 3 that the use of a slave processor is equivalent to the sequential solution process. The relative efficiency increases with the number of slave processors used. For the analyzed case the use of four slave processors results on a relative efficiency improvement varying between 1.0 and 1.7336 with respect to the sequential solution using 512 time steps per period, whereas for 4096 time steps per period this variation goes from 1.0 to 1.8520.

Table 3 *Sequential vs parallel solution comparison using PVM*

Number of Slave Processors	Time steps per period			
	512	1024	2048	4096
1	1.0	1.0	1.0	1.0
2	1.3911	1.4444	1.4583	1.4369
3	1.6121	1.7096	1.7455	1.7250
4	1.7336	1.8227	1.8596	1.8520

Table 4 gives the relative efficiency achieved with the solution obtained with the sequential and parallel computation of the ND method using the multithreading platform. For this case a 797 MHz computer with two processors was used. This computer has installed the UNIX operative system. It can be noticed that there is a significant increase on the relative efficiency with the use of two threads, e.g. from 1.0 to 1.4824 with 512 time steps per period and from 1.0 to 1.5081 with 4096 time steps per period. However, the efficiency remains nearly constant with additional threads.

Table 4 *Sequential vs parallel solution comparison using threads*

Number of threads	Time steps per period			
	512	**1024**	**2048**	**4096**
1	1.0	1.0	1.0	1.0
2	1.4444	1.4461	1.4449	1.4430
3	1.4824	1.4878	1.4933	1.5005
4	1.4824	1.4911	1.5000	1.5073
⋮	⋮	⋮	⋮	⋮
11	1.4824	1.4977	1.5033	1.5081

III. CONCLUSIONS

A description has been given on the fundamentals of the techniques for the harmonic analysis in power systems, developed in the frames of reference of frequency, time and hybrid time-frequency domain, respectively. The details on their formulation, potential and iterative process has been given.

In general Harmonic Power Flow methods are numerically robust and have good convergence properties. Howerver, their application to obtain the non-sinusoidal periodic solution of the power system may require the iterative process of a matrix equation problem of very high dimensions.

Conventional Brute Force methodologies in the time domain for the computation of the periodic steady state in the power system are in general an inefficient alternative which, in addition, may not be sufficiently reliable, in particular for the solution of poorly damped systems. The potential of the Newton techniques for the acceleration to the Limit Cycle has been illustrated. Their application yields efficient time domain periodic steady state solutions.

The principles of the hybrid methodology of solution have been given and its potential has been indicated for the solution of larger single phase systems. It is an interesting alternative of solution in merit to its ability to represent the system components in their natural frame of reference, leading to efficient, robust periodic steady state time solutions for the complete network. To date it has been successfully applied to the solution of single phase systems, being in progress its application to the periodic steady state solution of practical three phase systems.

Preliminary results on the application of parallel processing in harmonic analysis indicate that this technology can substantially enhance the original computer efficiency of existing harmonic simulation techniques. This is a field in need of further investigation.

IV. ACKNOWLEDGMENT

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