Power Quality Studies Using the ATP Package

Juan A. Martinez, *Member, IEEE*

***Abstract*—Several techniques have been used to simulate power disturbances, quantify their impact and analyze mitigation devices. The ATP is a general purpose tool that has been extensively applied in power quality studies. This paper presents a scope of power quality studies for which this tool can be used. The document includes also a short introduction to its main capabilities and a description of three illustrative examples.**

***Index Terms*—Power Quality, Power Distribution, Modeling, Simulation.**

I. INTRODUCTION

The term power quality is used to describe disturbances that can lead to equipment misoperation [1], [2]. A broad definition of power quality would also include voltage unbalance in multi-phase networks, and dielectric selection in equipment. With the new deregulation era, power quality goals are also expanding the definition of reliability [3].

Although most power equipment can operate with relatively wide variations in voltage, current and frequency, the proliferation of electronic equipment, like computers, digital clocks or adjustable speed drives, sensitive to these variations, has increased the concern of utilities and their customers.

Power disturbances can have a very adverse effect on costumer equipment; many of these effects are well known and documented [4], [5]. Standards are being continuously updated and developed to define, characterize and evaluate power quality disturbances, and to provide measures for mitigating their effects [6].

Digital simulation is a very effective mean to perform power quality studies. Several techniques have been developed to simulate and analyze power quality problems using a digital computer. These techniques are based on transformed methods [7], frequency-domain methods [8], [9], and time-domain methods [10]. Among the most popular tools based on a time-domain technique are the EMTP (ElectroMagnetic Transients Program) and like [11], [12]. These programs can be used in power quality studies to predict the waveform and magnitude of power disturbances, analyze the influence of system and component parameters on their propagation, validate models of power system equipment, or test and design mitigation techniques.

This paper presents the application of the ATP version of the EMTP. ATP is an acronym that stands for Alternative Transients Program [13]. Several tools are presently available to help ATP users; they can be integrated in a single package that can be customized for a specific application.

The document is an updated version of some previous works by the same author [14], [15], [16]. It includes a summary of ATP capabilities and solution methods, an introduction to the type of studies that can be performed with this package, an overview of its applications in power quality studies, and three illustrative examples.

II. POWER QUALITY DISTURBANCES

A. Characterization

Phenomena that can cause power quality disturbances are many, and they can be originated from several sources. An important effort has been made by the power industry and international associations to classify and characterize these phenomena. A first classification might distinguish between steady state and transient problems. Variations of the first group are characterized by a waveform distortion, that is, a deviation from the ideal waveform at power frequency. The most common power quality problems included in this group are harmonics, interharmonics, notches and noise.

The term transient is generally used to denote a transition from one steady state to another. Transient power quality problems are characterized by their frequency spectrum and duration. They can be classified into two subcategories: impulsive and oscillatory. There are, however, other power quality variations, such as sags and swells, in which transient events are involved, although they are frequently characterized as steady state variations.

Table I shows a summary of the most important power quality disturbances, their causes, their impact, and the techniques for mitigating their effects.

B. Requirements of Simulation Tools

It is widely recognized that digital simulation has many benefits. In power quality studies, it can be useful

- to understand how disturbances propagate into the network
- to determine waveform distortion caused by different types of sources
- to quantify the impact of some disturbances
- to test and design mitigation techniques
- for educational purposes [17].

Taking into account the nature of power quality disturbances, their sources and the behavior of the power network, several basic capabilities are required on simulation tools:

TABLE I
POWER QUALITY DISTURBANCES

TYPE OF DISTORSION	DURATION	METHOD OF CHARACTERIZING	CAUSES	IMPACT	POWER CONDITIONING SOLUTIONS
Harmonics	Steady state	Harmonic spectrum Harmonic distortion	Nonlinear loads Solid-state switched loads	Overheating of equipment Relay misoperation Insulation breakdown	Active and passive filters Current waveshaping
Phase-unbalance	Steady state	Unbalance factor	Single-phase loads	Overheating	Static var systems
Interruptions	-------------	Duration	Faults Equipment failure Maintenance	Equipment shutdown	Backup generators UPS Energy storage technologies
Notches	Steady state	Duration Magnitude	Adjustable speed drives	Misoperation of digital clocks Communication interference	Isolation inductances Capacitor banks
Voltage flicker	Steady state	Variation magnitude Frequency of occurrence Modulation frequency	Arc furnaces Intermittent loads Motor starting	Misoperation of servomotors	Static var systems Static compensator
Sags/Swells	Transient	Magnitude Duration Rms vs. time	Remote faults Motor starting	Equipment shutdown Misoperation of sensitive loads	UPS Energy storage technologies Dynamic voltage restorer
Oscillatory transients	Transient	Waveform Peak magnitude Frequency range	Switching of line, cables, capacitors and loads	Damage of electronic equipment Insulation breakdown	Filters Isolation transformers Surge arresters
Impulsive transients	Transient	Rise time Peak magnitude Duration	Lightning Electrostatic discharge	Insulation breakdown	Shielding Surge arresters
Noise	Steady state/ Transient	Magnitude Frequency spectrum	Improper ground Solid-state switched loads	Misoperation of microprocessor-based equipment	Adequate ground Filters

1) *Frequency-domain solution method*, to analyze harmonic propagation, identify resonance conditions, and design filters.
2) *Time-domain solution method*, to analyze those variations of transient nature and determine their impact.
3) *Accurate modeling*, to represent the power network and disturbance sources, with capabilities to model nonlinear and frequency-dependent behaviors.
4) *Multi-level modeling*, to allow users the representation of different parts of a system using different approaches.
5) *Numerical stability*, to avoid run-off problems and oscillations at discontinuities.
6) *Postprocessing capabilities*, to depict simulation results and quantify the impact of power quality variations.
7) *Interface to external programs*, to take advantage of capabilities available in other software tools.

III. THE ATP PACKAGE

A. Solution Methods and Main Capabilities

This tool was originally developed for simulation of electromagnetic transients in power systems. A transient simulation is carried out with a fixed time step selected by the user, using the trapezoidal rule of integration and the Bergeron's method. However, the program can also be used to perform AC steady state calculations and calculate harmonic power flows. Solution methods to solve systems with nonlinear components have been also implemented [11].

The package can represent control systems and interface them with an electric network, using two different options: TACS and MODELS [13].

Several non-simulation routines are available to support the use of some components. For instance, they can be used for the computation of line and cable parameters or the derivation of a coupled RL matrix aimed at representing a multi-phase, multi-winding transformer.

Presently, the ATP package is integrated by at least three tools: ATPDraw [18], a graphical preprocessor for creating/editing input files; TPBIG, the main processor for transients and harmonics simulations; one postprocessor for plotting simulation results. ATPDraw is an interactive Windows-based program that can act as a shell for the whole package; however, users can control the execution of all programs integrated in the package from ATPDraw. Standard components are supported by this tool.

Since most of the capabilities that have expanded the applications of the package are implemented in TPBIG, the rest of this document will describe features of this tool only; by default they will be referred as ATP features.

Fig. 1 shows a schematic diagram of the connectivity between simulation capabilities, supporting routines, external programs and all types of files.

B. New Capabilities

The implementation of new capabilities during the last few years have expanded ATP applications. The results derived from a simulation are not always the target of a run. Instead these results can be used to perform a sensitivity analysis, adjust component parameters, or select power components (arresters, fuses,...). The result provided by the program could be the type of arrester needed at a specific location, the dependence of a voltage with respect to a parameter of the system, or the density function of voltage sags in a network. Therefore, a case can be simulated several times before deactivating the program, the parameters of the system under simulation can be changed according to a given law, some components can be either disconnected or activated, and some calculations can be carried out by external programs.

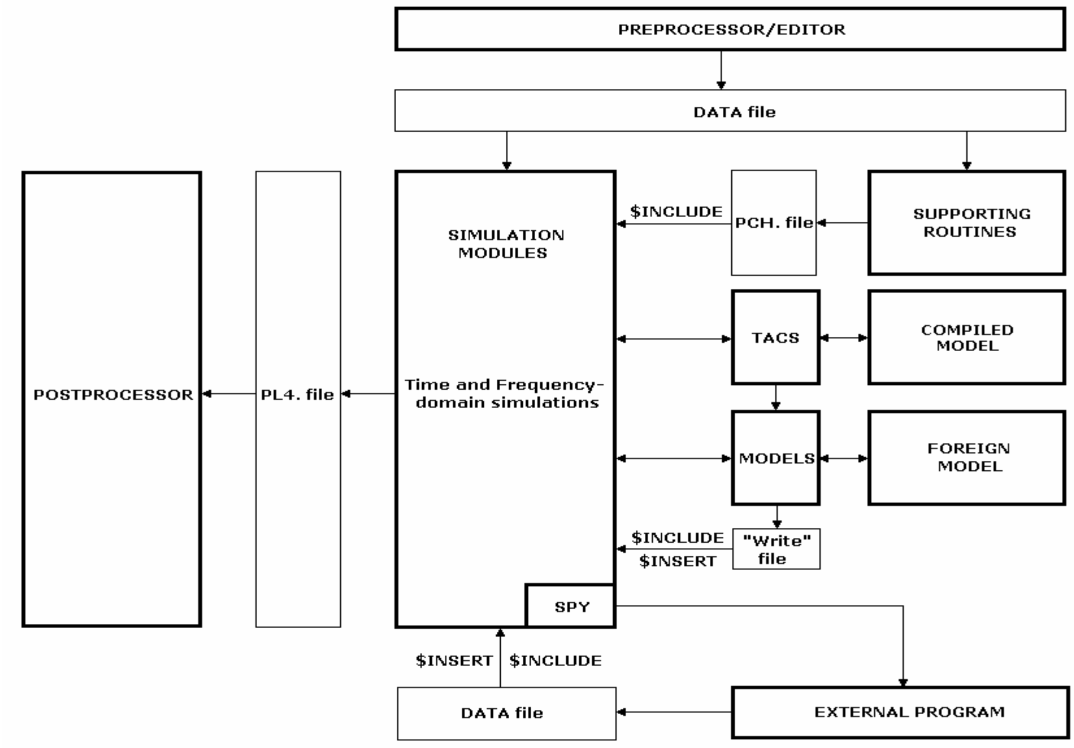


Fig. 1. Simulation modules and supporting routines.

The ATP package is based on the following concepts [19]:
1) _Multiple run option_: A case can be simulated many times while changes are introduced into the system at every run. This option, known as Pocket Calculator Varies Parameters (PCVP), can be used to perform statistical and sensitivity studies.
2) _Open system_: A link to external programs/tools can be established before, during and after a simulation to take advantage of the capabilities of these tools and to add or test new capabilities. This option can be used, for instance, to link the ATP to MATLAB and take advantage of its features, or to run a custom-made program that can derive the parameters of a power component using a data conversion procedure not yet implemented in the package.
3) _Data symbol replacement_: $PARAMETER is a declaration that can be used to replace data symbols of arbitrary length prior to a simulation. Three replacement modes can be applied: simple character replacement (one string is replaced by other of the same length), mathematical replacement (string is replaced by a number deduced from a mathematical formula), integer serialization (used to encode strings within a DO loop).
4) _Data module_: ATP-coded templates can be used to simplify the usage of power components and extend modeling capabilities to more complex equipment [20]. With the new Windows-based environment, custom-made models are represented by a module and its associated ATPDraw icon. Their development relies on the routine Data Base Module; however, other ATP capabilities can be used to perform simple calculations with module arguments, to decide what parts of a module can be activated at a given run, or what parts should remain sleeping.
5) _Interactivity_: Several simulation modules will be usually involved in a general procedure. Interactivity between them is critical as calculations will be performed in several modules. The interface between a power system and a control section to pass variables in both senses has been a feature since the earliest development of control capabilities. However, it has been the possibility of passing also parameters what has added flexibility to some of the capabilities described above and increased the type of applications.
6) _Model editor_: Some simple rules and new capabilities (TO SUPPORTING PROGRAM option, DO loops, string replacement) can be used to develop a data file aimed at representing the code of a component taking into account the transient process to be simulated and the information available.

IV. Power Quality Applications

EMTP-like programs are suitable tools for analyzing the effects of disturbances and techniques aimed at mitigating them. The application of these tools in power quality studies were discussed in [14] and [15], where the following areas were analyzed

a) Modeling of power system components and sources of power quality problems.
b) Simulation of the effects of power quality disturbances.
c) Analysis and design of mitigation techniques.
d) Postprocessing of simulation results.
e) Development of custom-made models and simulation tools.

A summary of the most important studies is presented in the subsequent sections. Readers are referred to [14] for more details.

A. Power Quality Studies

1) Frequency-domain simulations

The ac steady state solution of linear networks for a single frequency is obtained using nodal admittance equations

$$[Y][V] = [I] \quad (1)$$

being elements of *[Y]*, *[V]* and *[I]* complex phasor values.

Two options, Frequency Scan (FS) and Harmonic Frequency Scan (HFS) are also based on this solution method. FS is used to obtain the driving point impedance at a particular node versus frequency, detect resonance conditions and design filter banks. HFS will be generally used for analyzing harmonic propagation in power networks. Certain components are frequency-dependent, but their models are not yet available in the ATP package; however, users can develop custom-made models to meet modeling requirements.

2) Time-domain simulations

The trapezoidal rule is used to convert the differential equations of the network components into algebraic equations involving voltages, currents and past values. These algebraic equations are assembled using a nodal approach

$$[G][v(t)] = [i(t)] - [I] \quad (2)$$

where *[G]* is the nodal conductance matrix, *[v(t)]* is the vector of node voltages, *[i(t)]* is the vector of current sources, and *[I]* is the vector of "history" terms.

The conductance matrix is symmetrical and remains unchanged since the integration is performed with a fixed time-step size. The solution of the transient process is then obtained using triangular factorization.

Two methods are used to solve nonlinear networks.

- Pseudo-nonlinear representation of power components: the conductance matrix is changed and retriangularized whenever the solution moves from one straight-line segment to another.
- Compensation: nonlinear elements are represented as current injections that are superimposed to the solution of the linear network after this solution has been computed; this approach is usually very efficient but it is limited to only one nonlinear component per isolated subnetwork.

In switching operations, the trapezoidal rule acts as a differentiator and introduces sustained numerical oscillations, which can be mitigated by placing snubber (RC) circuits in parallel with switches.

A time-domain solution method can be used to perform different types of power quality studies.

- Transients simulations: Transient events are usually associated to lightning and power equipment switching. In power quality studies, a transient simulation can be useful to analyze switching overvoltages, voltage sags, notching, flicker or noise, and to design mitigation devices. Modeling guidelines for transients simulations using EMTP-like tools have been published elsewhere [21], [22].
- Harmonics simulations: The ac steady state solution method cannot be applied in the presence of non-linear components or variable topology circuits, which can produce steady-state harmonics. Other approaches should be then considered. The simplest one is known as "brute force": the system is started from standstill and the simulation is carried out long enough to let the transients settle down to steady-state conditions. This approach can have a very slow convergence if the network has components with light damping. A more efficient method is to perform an approximate linear ac steady-state solution with nonlinear branches disconnected or represented by linearized models. Another alternative is based on the "start again" feature: using a "brute force" initialization, the solution is saved once the system reaches the steady-state, later runs can be started at this point. As for the representation of harmonic source, several approaches can be considered:
  - a voltage or current injection through an equivalent source composed of the harmonic spectrum of the load
  - a switching function, used to represent the terminal characteristics of a converter, which appears as a current source, seen from the power network
  - a detailed representation of the harmonic source; for instance, a complete model of a static converter and its control unit.

3) Sensitivity analysis

A sensitivity analysis is performed to evaluate the variation of a variable caused by changes of one parameter. This type of analysis is very useful when one or more parameters cannot be accurately specified. A sensitivity analysis will determine for which range of values a parameter is of concern. This type of analysis is based on the combination of two ATP options, Pocket Calculator Varies Parameters (PCVP) and $PARAMETER. PCVP allows users to repeat a case as many times as desired, $PARAMETER can be used to change a network parameter between a range of values.

4) Monte Carlo simulations

Some power quality disturbances are characterized by parameters that can be statistically described. A Monte Carlo simulation is a numerical procedure applied to problems involving random variables. Statistical switching has been a built-in capability of most transients programs for many years; however, some statistical studies cannot be performed with this capability. PCVP combined with other ATP capabilities, e.g. MODELS, can be used to perform any type of Monte Carlo simulations not covered by statistical switches.

B. Development of Custom-Made Models

Several models needed in power quality studies are not available in the ATP, e.g. an arc furnace model for flicker studies. However, many capabilities of the ATP package can be used to develop custom-made models. In power quality studies, these models can be classified into four different groups: disturbances, power components, mitigation devices, measuring devices [20].

As mentioned above, Data Base Module is a supporting routine that can be used for the development of integrated modules or to create component modules, which will be inserted in a data file by means of an INCLUDE statement with a very simple grammar. Data modules are generally used to simplify the use of power components and extend modeling capabilities to more complex equipment.

More powerful modules can be developed when combined with $PARAMETER, since simple calculations can be performed with module arguments and internal module variables using a pseudo-Fortran language.

C. Development of Custom-Made Tools

Several approaches can be considered for developing custom-made tools using capabilities of the ATP and other software tools. For instance, MATLAB capabilities can be used to perform very specific calculations using an interactive link to the transients program. When using the ATP, the interface is made via MODELS and a foreign model, see diagram depicted in Fig. 1. An interesting tool for analysis of distribution networks based on capabilities of both MATLAB and an electromagnetic transients program was presented in [23].

A different approach is shown in Fig. 2, a custom-made program, based on a high-level language, i.e. C or BASIC, is developed to perform a specific type of studies leaving the transient calculation and some plotting tasks on the ATP package.

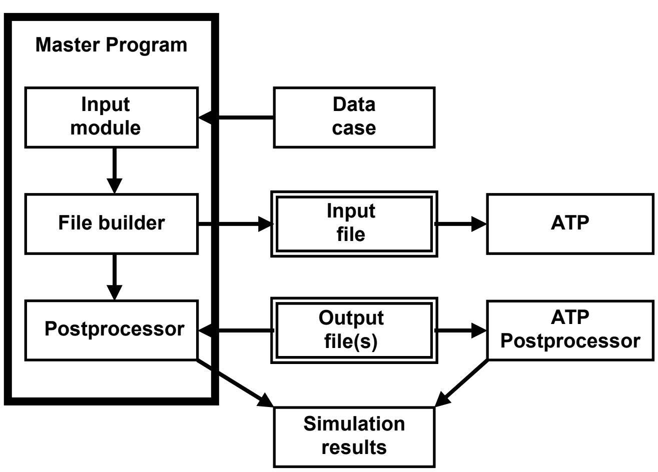


Fig. 2. Scheme of a custom-made tool.

V. Illustrative Examples

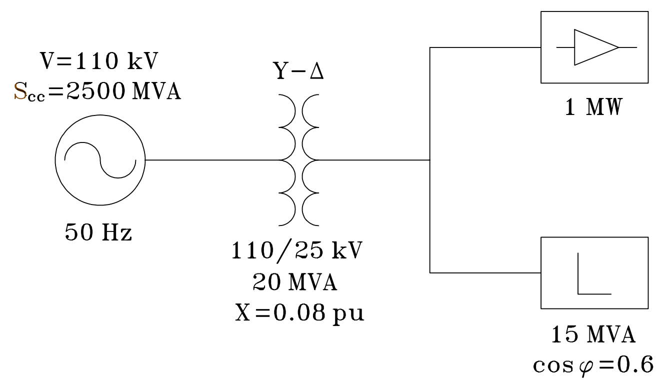
To illustrate the type of power quality studies that can be performed with this package, three case studies are described in the subsequent sections. They are based on most of the capabilities presented above.

A. Harmonic Resonance

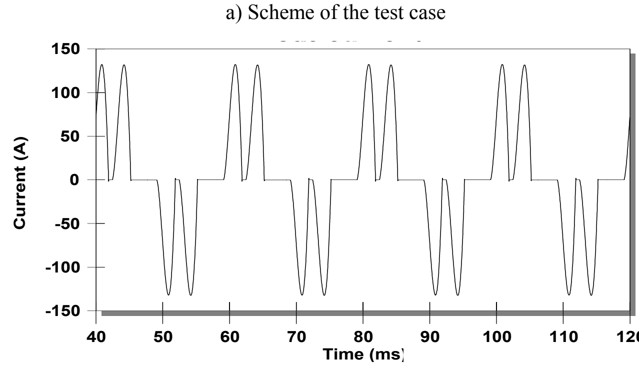
Fig. 3a shows a three-phase linear load, paralleled by a diode bridge, fed from the medium voltage side of a step-down transformer. A 12 MVAr capacitor bank is to be placed at the point of common coupling (PCC) to improve the power factor. After installing the capacitor bank, a resonance problem could be originated due to the presence of harmonic currents injected by the diode rectifier, see Fig. 3.b.

The transient simulation with the capacitor installed at the PCC confirmed that resonance would occur and the capacitor bank could be damaged. However, this problem can also be predicted by performing a frequency scan of the system. Fig. 3.c shows that resonance would be originated if a fifth harmonic (250 Hz) current was injected into the network.

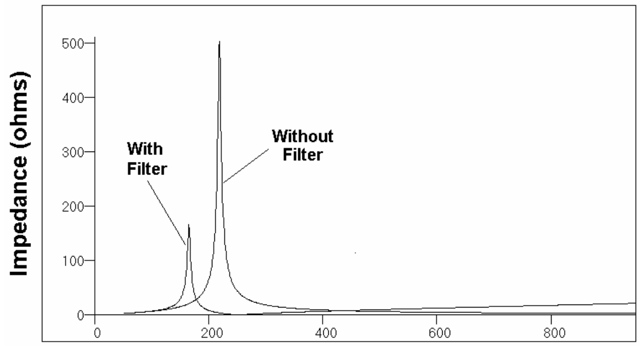
It is well known that this harmonic is present in the ac current of a diode rectifier. The problem can be solved by installing a passive filter instead of a capacitor bank. The frequency responses with and without the passive filter are also shown in Fig. 3c. The filter can be used for both improving the power factor and avoiding resonance.



a) Scheme of the test case



b) Diode bridge current



c) Frequency response

Fig. 3. Harmonic resonance study.

B. Prediction of Voltage Sags

The Monte Carlo method is a widely used technique for analyzing multidimensional complex systems. It can be used for solving both stochastic and deterministic problems, although the first type is the most usual one. This technique is based on a iterative procedure that is repeated using in every new step a new set of values of the random variables involved in the process, being these values generated according to the probability density function associated to each variable. The goal of a Monte Carlo solution is to obtain the response of a system to some stochastic input variables. Sampling is iteratively repeated until convergence is achieved. If the realization of the random input variables is generated by a proper sampling procedure, the solution converges as $n \rightarrow \infty$, being n the number of samples and $1/sqrt(n)$ the rate of the statistical error convergence to zero.

A procedure for prediction of voltage sags in power networks based on the Monte Carlo method has been developed taking advantages of ATP capabilities [24]. The procedure assumes that sags are due only to faults caused within the distribution network. Voltage sags will be characterized by the remaining voltage and the duration.

The developed procedure can be summarized as follows. The test system is simulated as many times as required to achieve the convergence of the Monte Carlo method. Every time the system is run, fault characteristics are randomly generated using the following distributions:

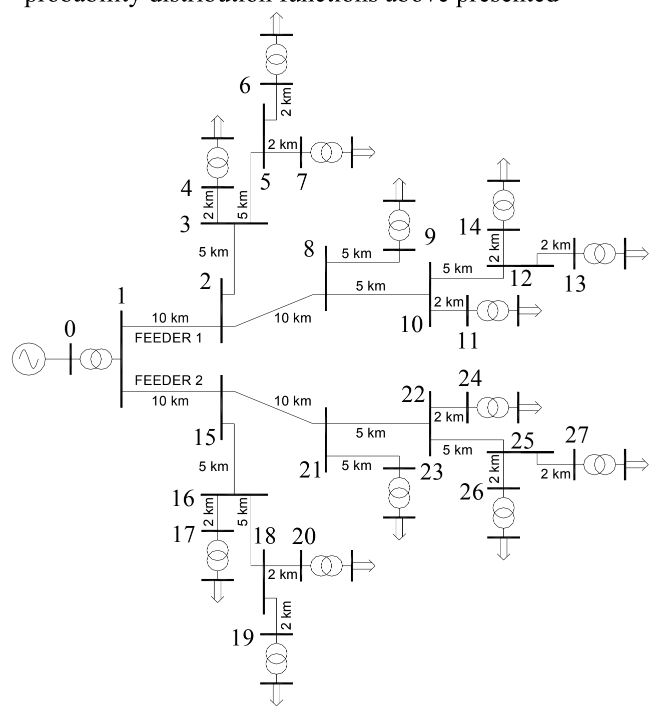
- The fault location is selected by generating a uniformly distributed random number, since the probability of fault is the same for any point of the distribution system.
- The fault resistance has a normal distribution, with a mean value of 10 Ω, and a standard deviation of 1 Ω.
- The initial time of the fault is uniformly distributed between 0.04 and 0.06 s.
- The duration of the fault has a normal distribution, with a mean value of 0.06 s, and a standard deviation of 0.01 s.
- The probabilities of each type of fault are as follows: LG = 80%, 2LG = 17%, 3LG = 0%, LL = 2%, 3L = 1%.

The fault impedance has been modeled as a constant resistance; however, its representation is a difficult subject since the fault arc varies with time and depends on the type of fault. The value used in this study is an average of the expected values for each type of faults.

Fig. 4 shows the scheme of the test system, it is a medium size distribution network with two feeders and 27 nodes. The lower voltage side of the substation transformer is grounded by means of a zig-zag reactor of 75 Ω per phase.

A constant impedance model has been chosen for representing power demands. It is a very usual representation in EMTP studies; however, a more accurate model should be considered for some voltage sag studies, e.g. voltage sag index calculations. Among those custom-made modules that were developed for this study, it is worth mentioning those dedicated to perform special features, namely

- a module for generating random variables, according to the probability distribution functions above presented



HV equivalent: 110 kV, 1500 MVA, X/R = 10
Substation transformer: 110/25 kV, 20 MVA, 8%, Yd
Distribution transformers: 25/0.4 kV, 1 MVA, 6%, Dy
Lines: $Z_{1/2} = 0.61 + j0.39$, $Z_0 = 0.76 + j1.56$ Ω/km

Fig. 4. Diagram of the test system.

- a three-phase distribution line model that can be separated into two sections of different length to allow the insertion of the randomly-generated fault
- a module for monitoring and recording voltage sag characteristics at the selected nodes.

The following information was recorded at every run:

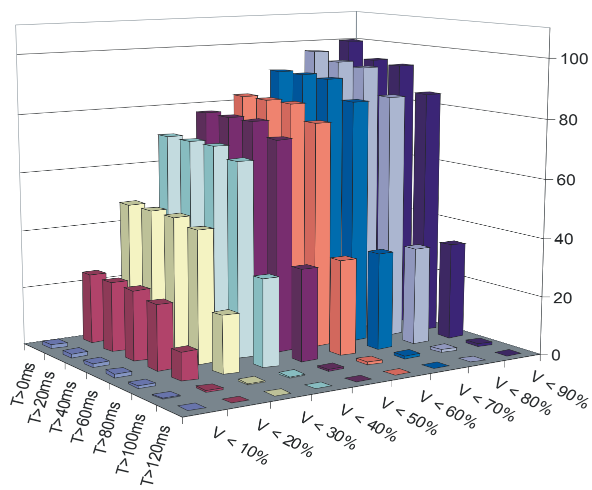
- the characteristics of the fault (location, initiation time, duration, resistance, faulted phases, type of fault)
- the characteristics of the sags (remaining voltage, duration) on every phase of the selected nodes.

Once the procedure is finished, the recorded information is manipulated to obtain the voltage sag density function and the number of sags per year.

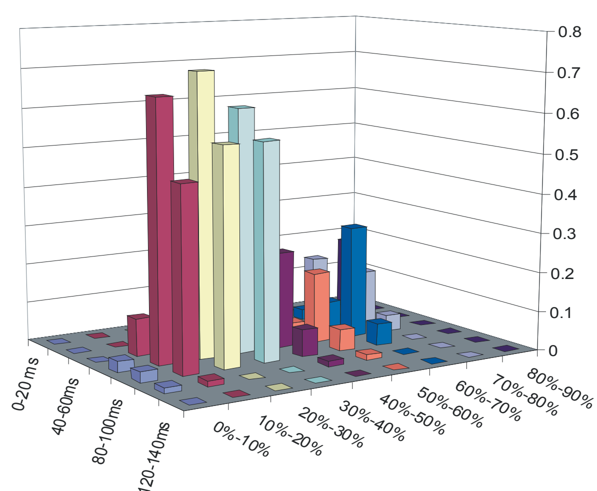
Several criteria can be used to decide when the convergence of the Monte Carlo simulation is achieved. For instance, the convergence can be determined by checking the error between a few points of the cumulative probability curve of all random variables against the theoretical values, or by checking the confidence level.

The test system was simulated 1000 times. If it is assumed that 12 short-circuits are caused per year and 100 km of overhead lines, as the network has 114 km, then 1000 runs equal the performance of the network during 73 years.

Fig. 5a and 5b depict the cumulative voltage sag density function and the number of sags per year that result at phase "A" of Node 4, see Fig. 4, after 1000 runs. Both charts give the probability of characteristic intervals. They have been deduced considering only those cases for which the retained voltage was equal or smaller than 90% of the rated voltage.



a) Sag density function



a) Number of sags per year

Fig. 5. Prediction of voltage sags – Node 4, Phase A.

C. Voltage Sag Mitigation

Voltage sags in distribution networks can be compensated by means of a dynamic voltage restorer (DVR). A typical DVR consists of a PWM converter, for smooth generation of voltage waveforms, a passive filter for harmonic cancellation and a transformer in series with the feeder.

The goal of the restoration is not only to compensate for voltage magnitude, but for phase shift too. Several compensation schemes can be considered: compensation for the difference between the sag and the pre-sag voltages, and the so-called in-phase injection, whose goal is to compensate for voltage magnitude only.

Fig. 6 shows the scheme of the test case. The system has been reduced to a three-phase controlled voltage source, a sensitive load and the DVR, placed between the source and the load. The voltages supplied by the sources can be controlled by the user to represent sags and swells on each phase at the input side of the DVR transformer.

Simple low frequency models were used to represent all components. The load is assumed to behave as a linear constant impedance. A very detailed model of the converter was created in which semiconductors were modeled as ideal switches. Snubber circuits were placed in parallel with semiconductors to avoid numerical oscillations. The control unit was modeled using TACS capabilities.

The strategy to control gate signals is aimed at achieving compensation of both voltage magnitude and shift, and is based on the following principles [25]

- System currents and voltages at both sides of the DVR are measured.
- 'αβ' transform is applied to voltages and currents.

$$\begin{bmatrix} S_\alpha \\ S_\beta \\ S_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (3)$$

- A new transformation is performed to obtain the 'dq' components.

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} Cos\,\theta & Sen\,\theta \\ -Sen\,\theta & Cos\,\theta \end{bmatrix} \cdot \begin{bmatrix} S_\alpha \\ S_\beta \end{bmatrix} \quad (4)$$

- Voltage compensation in 'dq' values is determined for positive and negative sequence voltages.
- The values deduced above are those required at converter side of the transformer terminals; voltages to be obtained at the converter terminals are deduced by taking into account the filter effect.
- Compensation voltages at each converter phase are obtained by applying antitransforms, first from 'dq' to 'αβ' values, and then to 'abc' values.
- Finally, gate signals are determined by using a PWM control strategy.

Fig. 7 shows some simulation results from two different cases

- In the first one, the characteristics of voltage sags (retained voltage, duration, phase jump) are the same at each phase on the input side of the DVR
- In the second case, swells are caused in two phases and a sag in the third one; the phase jump is different for each phase.

It is evident form the plots showing the voltages at the load terminals that the output voltages of the DVR remain practically the same as before the event, and only a small transient overvoltage is produced at the beginning and the end of the DVR performance for the second case.

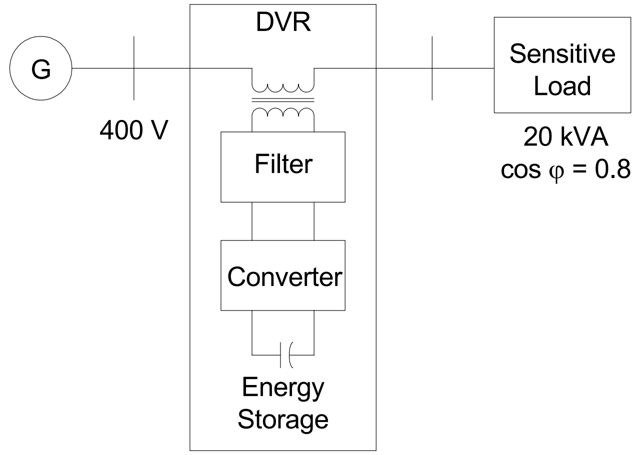
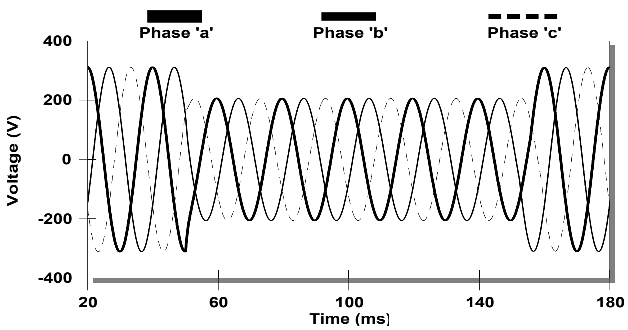
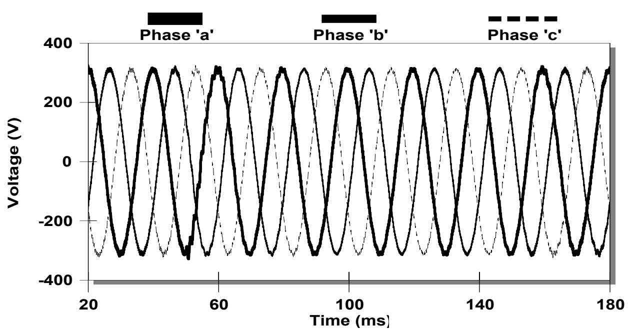


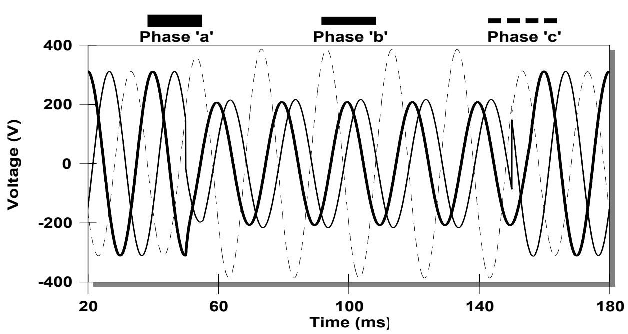
Fig. 6. Mitigation of voltage sags. Scheme of the test case



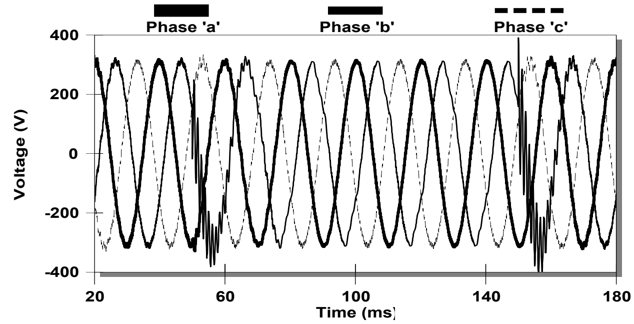
a) Case 1 : DVR input voltages



b) Case 1 : DVR output voltages



c) Case 2 : DVR input voltages



d) Case 2 : DVR output voltages

Fig. 7. Simulation of a Dynamic Voltage Restorer.

VI. CONCLUSIONS

EMTP-like tools are widely used in power quality studies. This paper has presented the application of the ATP version to this field. The capabilities implemented in this tool during the last few years have expanded its application to studies not previously covered, e.g. sensitivity analysis or Monte Carlo simulations. This package can be customized for specific applications by either creating new modules or by interfacing it to other tools.

VII. REFERENCES

[1] G.T. Heydt, "Electric power quality: A tutorial introduction," *IEEE Computer Applications in Power*, vol. 11, no. 1, pp. 15-19, January 1998.
[2] R.C. Dugan, M.F. McGranaghan and H.W. Beaty, *Electrical Power Systems Quality*, McGraw-Hill, 1996, New York.
[3] D. Sabin and A. Sundaram, "Quality enhances reliability," *IEEE Spectrum*, vol. 33, no. 2, pp. 34-41, February 1996.
[4] IEEE TF on the Effects of Harmonics on Equipment (V.E. Wagner, Chairman), "Effects of Harmonics on Equipment," *IEEE Trans. on Power Delivery*, vol. 8, no. 2, pp. 672-680, April 1993.
[5] A. Domijan et al., "Directions of research on electric power quality," *IEEE Trans. on Power Delivery*, vol. 8, no. 1, pp. 429-436, January 1993.
[6] *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519, 1992.
[7] G.T. Heydt and A.W. Galli, "Transient power quality problems analyzed using Wavelets," Paper 96 SM 456-4 PWRD, presented at the *1996 IEEE PES Summer Meeting*, July 28 - August 1, Denver.
[8] J. Arrillaga, B.C. Smith, N.R. Watson and A.R. Wood, *Power System Harmonic Analysis*, John Wiley, 1997.
[9] Tutorial on "Harmonics Modeling and Simulation," IEEE Power Engineering Society, TP-125-0, 1998.
[10] H.W. Dommel, "Techniques for analyzing electromagnetic transients," *IEEE Computer Applications in Power*, vol. 10, no. 3, pp. 18-21, July 1997.
[11] H.W. Dommel, *ElectroMagnetic Transients Program. Reference Manual (EMTP Theory Book)*, Bonneville Power Administration, Portland, 1986.
[12] J.A. Martinez-Velasco (Ed.), *Computer Analysis of Electric Power System Transients*, IEEE Press, 1997.
[13] Can/Am Users Group, *ATP Rule Book*, 1998.
[14] J.A. Martinez, "Power quality analysis using electromagnetic transients programs," *Proc. of 8th ICHQP*, October 14-16, 1998, Athens.
[15] J.A. Martinez, "Power quality studies using electromagnetic transients programs," *IEEE Computer Applications in Power*, vol. 13, no. 3, pp. 14-19, July 2000.
[16] J.A. Martinez, "The ATP package. An environment for power quality analysis," *Proc. of 9th ICHQP*, October 1-4, 2000, Orlando.
[17] A. Abur and M. Kezunovic, "A simulation and testing laboratory for addressing power quality issues in power systems," Paper PE-070-

PWRS-0-2-1998, presented at the *1998 IEEE PES Winter Meeting*, February 1-5, Tampa.

[18] H.K. Høidalen, L. Prikler and J.L. Hall, "ATPDraw - Graphical preprocessor to ATP, Windows version," *Proc. of IPST'99*, June 20-24, 1999, Budapest.

[19] J.A. Martinez and J. Martin-Arnedo, "The ATP package. New capabilities and applications", *Med Power 2002*, November 4-6, 2002, Athens.

[20] J.A. Martinez and J. Martin-Arnedo, "EMTP modular library for power quality analysis," *IEEE Budapest Power Tech'99*, August 29-September 2, 1999, Budapest.

[21] CIGRE Working Group 33-02, "Guidelines for Representation of Network Elements when Calculating Transients," 1990.

[22] A. Gole, J.A. Martinez-Velasco and A.J.F. Keri, "Modeling and Analysis of System Transients Using Digital Programs," IEEE PES Special Publication, TP-133-0, January 1999.

[23] K. Vu et al., "Simulation tool for distribution-system modeling, analysis and algorithm testing," *Proc. of IPST'97*, pp. 446-451, June 22-26, 1997, Seattle.

[24] J.A. Martinez and J. Martin-Arnedo, "Voltage sag stochastic prediction using an electromagnetic transients program," submitted for publication in *IEEE Trans. on Power Delivery*.

[25] J. Martin-Arnedo, J.A. Martinez-Velasco and T. Iannucci, "Simulación de un acondicionador dinámico de tensión," (in Spanish), *Revista Iberoamericana del ATP*, vol. 3, no. 3, October 2001.

VIII. Biography

Juan A. Martinez was born in Barcelona (Spain). He is Profesor Titular at the Departament d'Enginyeria Elèctrica of the Universitat Politècnica de Catalunya. His teaching and research interests include Transmission and Distribution, Power System Analysis and EMTP applications.

A ROBUST MARKOV-LIKE MODEL FOR THREE PHASE ARC FURNACES

F. Chen V. V. Sastry S. S. Venkata K. B. Athreya

Department of Electrical & Computer Engineering **Department of Mathematics /Statistics**
Iowa State University
Ames, IA 50011-3060

Abstract: -- A novel approach of modeling a nonlinear, highly time varying load such as an Electric Arc Furnace (EAF) is presented in this paper. First and second order Markov-like models are formulated to compare their effectiveness in the evaluation of the stationary nature of the process and the possibility of predicting the state variable such as arc current at least one step in advance. It is seen that the statistical behavior of the EAF data is stationary with respect to time by comparing certain characteristics of the two data sets derived from the empirical frequency distributions. A second order Markov-like model is proved to be very effective in the prediction of EAF current to a good degree of accuracy. The predictor is the most probable value of the immediate future, given the present and the immediate past for each step of prediction.

Keywords: Electric Arc Furnace, Markov-like Models, Load Model, Transition Matrix, Prediction

1. INTRODUCTION

The Electric Arc Furnace (EAF) is very common in the steel manufacturing industry to melt scrap and pre-reduced metals. Since it is a large, highly unbalanced, nonlinear and time varying load, the influence of EAF on power quality is of great concern to power systems engineers. The fact that arc-length is time variant and the movement of scrap is random, it makes the current waveform look erratic. Voltage fluctuation, which is usually associated with a voltage flicker, is caused by the EAF current. For these reasons, the arcing process is assumed to be statistical in nature [1]. As a consequence, the EAF load can not be adequately represented by a deterministic dynamic model.

The EAF is such an electrically chaotic load in nature that accurate modeling of it is necessary to evaluate and mitigate its deleterious impact on a power system. In fact, a lot of work has been reported in this area. The approaches using related v-i characteristics, in which arc length, arc voltage and arc current are expressed by empirical formulas, were presented in [3,4]. The authors of ref. [5] proposed a flicker compensation technique using stochastic and sinusoidal time varying laws. The EAF current is also considered as a deterministic chaotic system by Tan et al. al [6]. Most of these models are in time domain while the authors of ref. [7] employed a frequency domain method to analyze the harmonic EAF current. Varadan et al. al [8] suggested that a single phase arc furnace model should be adequate to represent a three phase EAF circuit.

An alternative and new approach proposed in this paper is to model the EAF system as a Markov-like sequence based on ref. [9,10]. It is shown that this approach makes it possible to simulate the EAF behavior accurately. Developments in statistics and applied probability suggest that a suitable Markov-like model may fit a wide range of discrete-valued time series very well, in particular for dynamic data [9,10,11,12]. Thus the observed and recorded waveforms of an EAF system and other phenomena can be seen as nonlinear, dynamic time series, which may behave chaotically. In the following sections, the procedures for developing a first order and second order Markov-like models from field data in time series format are described. Nomenclature is defined as well. Then, the two models are evaluated by comparing the simulation results with actual current data. The paper also discusses the effectiveness of the one-step-ahead prediction approach using the results derived from the second order Markov-like modeling. The quality of the prediction is tested by comparison with real data. Simple statistical analysis is also used for this purpose.

2. MODEL DEVELOPMENT

The development of the proposed models is based on ideas from Markov's theory [9,10,12,13,14]. The application of a first order Markov-like model is discussed at first in detail. Then these ideas are extended to a second order Markov-like model. The formulation of the model involves steps i) to viii) in the following in relation to Fig. 1, which represents a typical arc current waveform.

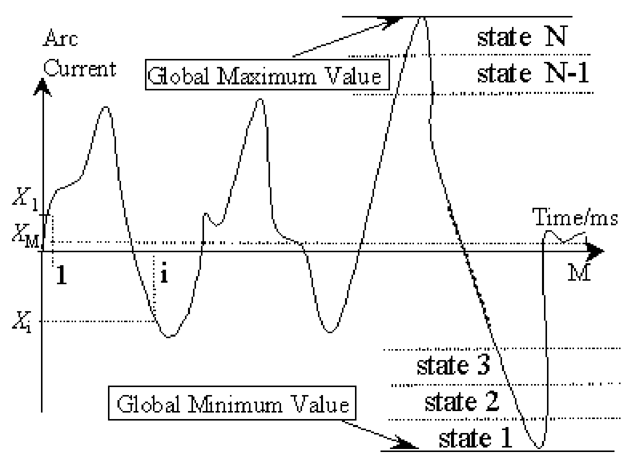


Fig. 1 Illustration of states used in Markov-like model

Step i) The global minimum and maximum values of the variable (arc current or voltage, etc.) under study over the interval of observation are identified.

Step ii) All the values of the data from the global minimum to maximum are divided into a finite number (say N) of intervals such as state 1, state 2, … state N (see Fig. 1).

Step iii) Given the time series $\{X_j: j=1, 2,\ldots M\}$ with its state space $S=\{1, 2, \ldots. N\}$, define

$\delta_{kj} = 1$ if $X_j \in$ state k
$\delta_{kj} = 0$ if $X_j \notin$ state k (1)

Then the frequency of visits to state k called Empirical Frequency Function (EFF) is

$$\pi_k = \frac{1}{M}\sum_{j=1}^{M}\delta_{kj} \quad (2)$$

Also define the Empirical Cumulative Distribution Function (ECDF)

$$F_k = \sum_{j=1}^{k}\pi_j \quad (3)$$

It equals proportion of visits to less than or equal to state k during the time period {1, 2, … M}

Step iv) The frequency of transition from state k to *l* in one step is

$$\pi_{kl} = \sum_{j=1}^{M-1}\delta_{kj}\delta_{l(j+1)} / \sum_{j=1}^{M}\delta_{kj} \quad (4)$$

It is the ratio of the number of transitions from state k to *l* to the number of visits to state k in the data.

π_{kl} is an estimate of one step transition probability $P\{X_{i+1} \in \text{state } l \mid X_i \in \text{state } k\}$ for the first order chain $\{X\}$. Note that for each state k, $\{\pi_{kl} : l=1,2 \ldots.N\}$ estimates the transition probability distribution of the next state given that the current state is k. This will be useful in making the prediction of the future state given the present state.

Step v) The frequency of transitions from state h to k and then to *l* in one step is

$$\pi_{hkl} = \sum_{j=1}^{M-2}\delta_{hj}\delta_{k(j+1)}\delta_{l(j+2)} / \sum_{j=1}^{M-1}\delta_{hj}\delta_{k(j+1)} \quad (5)$$

and it is an estimate of one step transition probability $P\{X_{i+1} \in \text{state } l \mid X_i \in \text{state } k, X_{i-1} \in \text{state } h\}$ for the second order chain $\{Y_i=(X_i,X_{i+1})\}$,

Step vi) If $\pi_{kl} \approx \pi_{hkl}$ for all *h*, then the chain is approximately a first order Markov chain. Otherwise, find the third order transition frequency π_{ghkl}

$$\pi_{ghkl} = \sum_{j=1}^{M-3}\delta_{gj}\delta_{h(j+1)}\delta_{k(j+2)}\delta_{l(j+3)} / \sum_{j=1}^{M-2}\delta_{gj}\delta_{h(j+1)}\delta_{k(j+2)} \quad (6)$$

and check if $\pi_{ghkl} \approx \pi_{hkl}$ for all *g*. If so, it is approximately a second order Markov chain.

Step vii) The second order chain *Y* is Markov-like but with state space S×S, the Cartesian product of S with itself. This should make the estimate of conditional distribution of the future given the present sharper, thus reduce the level of uncertainty. If necessary one could go to a third or higher order Markov-like chain *Z*, where one records three or more consecutive *X* values instead of two consecutive values.

Step viii) In addition to the above Markov-like modeling, it is also useful to give simple statistical summaries of the data such as the mean, variance and the empirical distribution.

The application of the above procedure to some EAF data is described below.

3. MARKOV-LIKE MODEL APPLICATIONS

Actual EAF data are used to test the models that have just been introduced in section 2. This EAF is a 50 MVA three-phase ac unit which is connected to a 34.5 kV bus behind a specially designed EAF transformer rated at 100 MVA. Twenty seconds of historical arc current and voltage data of phase A is utilized to build the model. A first order Markov-like model is proposed first for description of the concept in section 3.2. Then the second order Markov-like model for accurate modeling and prediction is discussed in section 3.3.

3.1 First Order Markov-like Model

To illustrate, the arc current data are divided into two independent sets. One could compute the estimates of the transition probability matrix from every data set, then use these estimates to simulate and compare the simulation results and the original data with each other to validate the model. The results from the first order Markov-like model are shown in Figs. 2 to 3 and Table 1. The upper part of Fig. 2 is the plots of the Empirical Frequency Function (EFF) π_k for the two actual data sets and their simulation results. Since the data are very close to each other, expanded look within a small interval (states 25 to 35) for these EFFs is shown in the lower part of Fig. 2. Fig. 3 shows the Empirical Cumulative Distribution Function (ECDF) F_k of the corresponding EFFs of Fig. 2. Again, to make the figure clearer, Fig. 3 also gives an expanded look for states 25 to 35 in the lower part. Table 1 indicates the mean and variance indices of the original and simulated current data.

It can be easily seen that the EFFs for the two actual data sets in Fig. 2 are very much alike, and the simulation results are almost the same as the original actual data so that in the figure they are overlapped. In fact, during the simulation, even when the initial condition is changed, the results did not have much variation. It can also be seen that, means are the same for the original and simulation data sets. Their variances are also very close to each other. One may deduce from the simulation results that the transition matrix is a natural parameter of this system. It appears as well that the statistical behaviors of the EAF current are stationary with respect to time from the similarities in characteristics for the two data sets. The statement can also be confirmed by observing the ECDFs of the two data sets along with their simulation results given in Fig. 3.

The same procedure is carried out on the EAF voltage and the corresponding EFFs are shown in Fig. 4. An expanded view is shown for states 25 to 35 in the lower part of this figure, just as in the case of processing EAF current. Since the EFFs are closer to each other than those from the EAF current, the model seems even more accurate for EAF voltage. This is to be expected because the waveform of the EAF voltage is not so irregular as the EAF current. The statistical indices for the two data sets are almost the same, as it is shown in Table 2. Accordingly, specific attention is paid to the EAF current only in the subsequent sections.

3.2 Second Order Markov-like Model

The short-term and long-term predictions of the variable based on the present and past data are of practical interest and value to power engineers. Using the first order Markov-like model, the empirical frequencies of the states help in predicting future averages. Also, the estimated transition probability matrix helps prediction of the immediate future value given the present value. Some parts of the result file consisting of transition matrix are shown in Table 3. Since the matrix is sparse, only nonzero elements are recorded in a format of $\{\pi_{kl}$: its value$\}$. For instance, the first line of data indicates that if the current state is 1, it has a high probability (π_{11}=0.9000) to stay in this state in the next step. This transition matrix is good for a long-term prediction from the earlier analysis, i.e., the simulation results fit with the original data. However, it is found to be not good enough for short-term prediction. For example, in state 41, it has positive probability to enter each of the states 39, 40, 41, 42 and 43. While all of the probabilities are below 0.40, as can be seen from Table 3, one can not predict the next value with accuracy and confidence. The problem of finding a better model for an accurate prediction is now addressed.

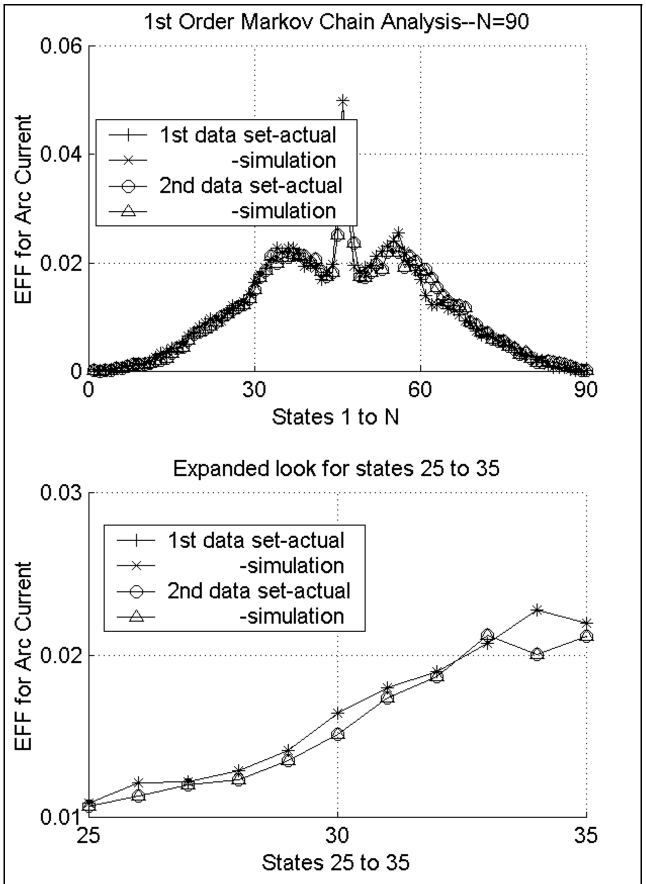


Fig. 2 EFFs for actual arc current from a first order Markov-like model N=90

3.2.1 Concept

For short-term prediction, the transition probability estimates are not sharp (i.e., not very close to 1 or 0) in the first order Markov-like model. This leads one to consider a second order Markov-like model, where a vector $Y_i=(X_{i-1},X_i)$ is recorded for each time point. The first order Markov-like model, as it is shown in the upper part of Fig. 5, does not distinguish between increasing and decreasing trend. On the other hand, a second order Markov-like model does distinguish between increasing and decreasing trend, as shown in the lower part of Fig. 5. Also, most of the transition probabilities are close to 1 or 0, as shown in Table 4. This property makes it effective in short-term prediction, i.e., given current state value Y_i in Y chain, the value of Y_{i+1} can be estimated with higher accuracy.

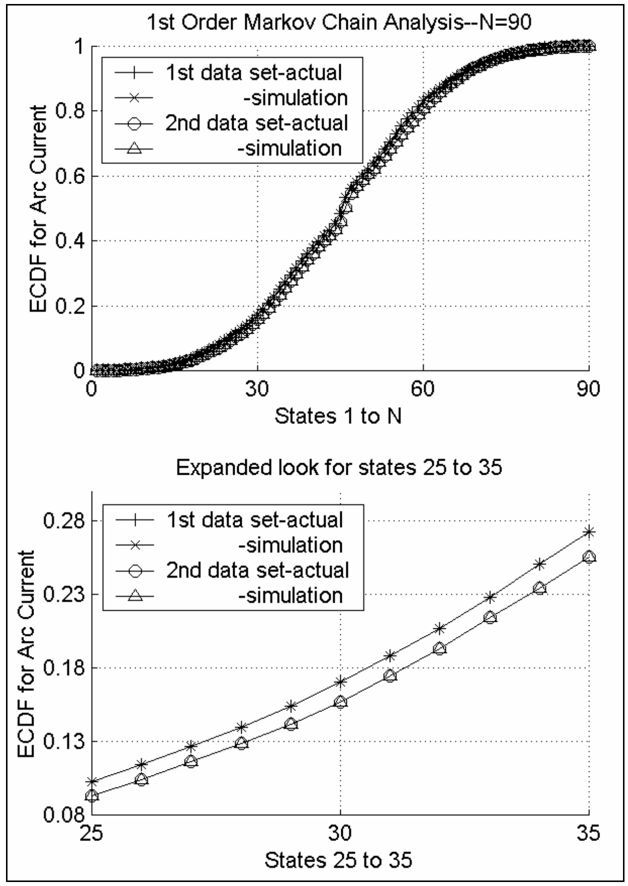


Fig. 3 ECDFs for actual arc current from a first order Markov-like model N=90

Table 1 Statistical indices of the states for original current data and simulation results

Data sets		Mean	Variance
Original data	First set	0.011111	0.000087
	Second set	0.011111	0.000084
Simulation result	First set	0.011111	0.000086
	Second set	0.011111	0.000084

The transition matrix for the second chain $\{Y_i\}$ is similar to that of first order Markov-like model, the dimension is double powered. That is to say, if the state number is set to be 50, for a first order Markov-like model the transition matrix is of the dimension (50×50), while for a corresponding second order Markov-like model, it is of the dimension (50×50)×(50×50)=(2,500×2,500). In Table 4, part of the matrix is also listed in the format of $\{\pi_{hkl}$: its value$\}$, while the chain is defined as $Y_i=(X_{i-1},X_i)$. The results are very satisfactory. Most of transition probabilities are larger than 0.9 or less than 0.1. In many states the probabilities are 1 or 0. Therefore one can predict the value of the arc current at the next step with a high level of confidence. For instance, when the present state is (1,2), one can estimate with reasonable certainty that it will enter state (2,2) according to the transition matrix (vide Table 4). As mentioned earlier, the fact that the estimates of the second order one-step transition probabilities are sharper than those of the first order one-step transition probabilities suggests that the underlying time series is not a first order Markov chain. Nevertheless, this methodology provides accurate prediction of a seemingly chaotic time series.

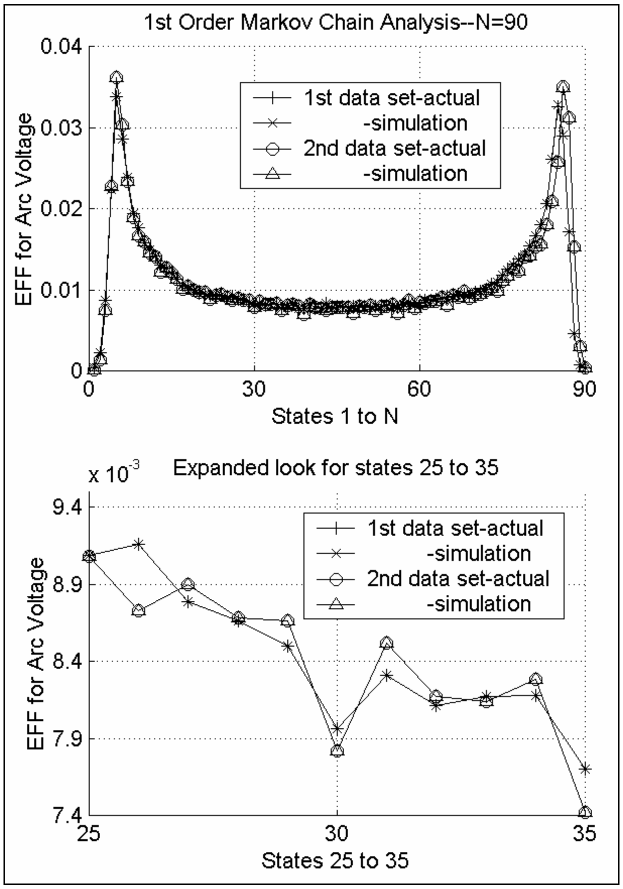


Fig. 4 EFFs for actual arc voltage from a first order Markov-like model N=90

Table 2 Statistical indices of the states for original voltage data and simulation results

Data sets		Mean	Variance
Original data	First set	0.011111	0.000037
	Second set	0.011111	0.000038
Simulation result	First set	0.011111	0.000037
	Second set	0.011111	0.000038

3.2.2 EFF Figures from Data and Simulation

Only the EAF current is processed using a second Markov-like model since it changes more abruptly. The results are shown in Fig. 6. It should be stressed that while the number of the state N is 50 in this case, in a second order Markov-like model, the states have been arranged as the sequence of (1,1), (1,2), … (1,50), (2,1), (2,2),… (50,50). But for convenience, the states in the x-axis are lined up into one dimension from 1 to (50*50)=2500. The data are still divided into two parts in this approach. In Fig. 6, EFFs are plotted for the two actual data sets together with their simulation results derived from a second order Markov-like model processing using transition matrix. In addition, an expanded look for states 500 to 600 is provided in the lower part of Fig. 6.

Table 3 Some elements of transition matrix for a first order Markov-like model

π_{11} : 0.9000 π_{12} : 0.1000
π_{21} : 0.1875 π_{22} : 0.6250 π_{23} : 0.1875
……
$\pi_{41,39}$: 0.0095 $\pi_{41,40}$: 0.3091 $\pi_{41,41}$: 0.3944
$\pi_{41,42}$: 0.2417 $\pi_{41,43}$: 0.0453
……
$\pi_{90,89}$: 0.1052 $\pi_{90,90}$: 0.8948

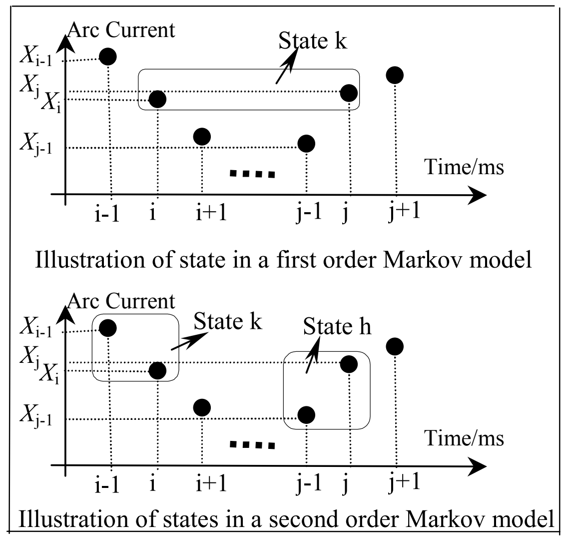


Fig. 5 Comparison of states in first and second order Markov-like model

Table 4 Some elements of transition matrix for a second order Markov-like model

π_{111} : 0.921053 π_{112} : 0.078947
π_{122} : 1.000000
π_{211} : 1.000000
……
$\pi_{27,28,28}$: 0.897181 $\pi_{27,28,29}$: 0.102819
$\pi_{28,26,26}$: 1.000000
……
$\pi_{50,49,49}$: 1.000000
$\pi_{50,50,49}$: 0.076923 $\pi_{50,50,50}$: 0.923077

It may be observed that the EFFs from the two actual data sets and simulation results are really similar. This suggests that EFFs and ECDFs from the actual data show the statistical characteristics when the sample data are large enough. It may not be the case if a small sample of data is selected. Statistical indices such as mean and variance are also included in Table 5. Their similarities in values also show that this model is effective.

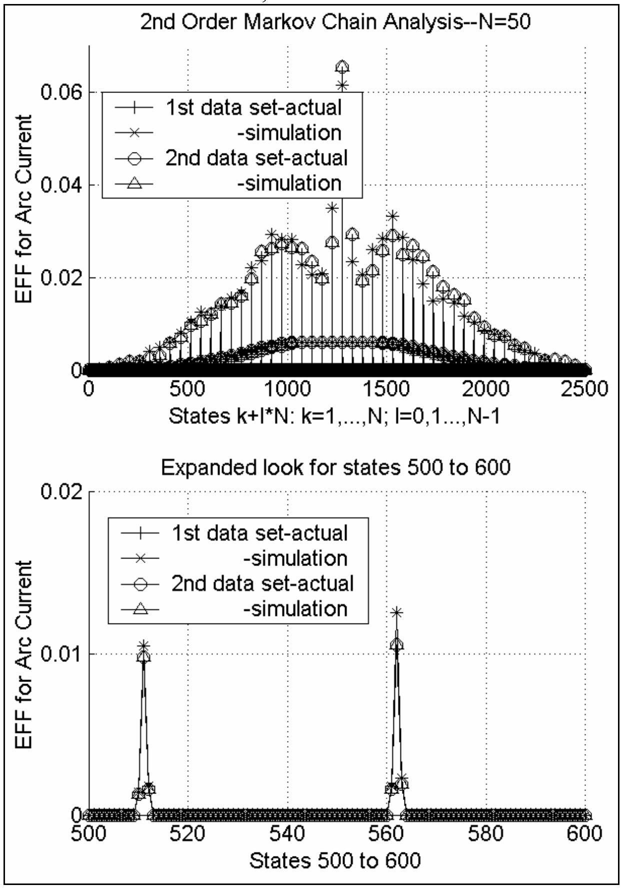


Fig. 6 EFFs for actual arc current from a second order Markov-like model N=50

Table 5 Statistical indices of the states for original current data and simulation results

Data sets		Mean	Variance
Original data	First set	0.0004	0.000007
	Second set	0.0004	0.000008
Simulation result	First set	0.0004	0.000007
	Second set	0.0004	0.000008

Based on these results, it is suggested that the transition matrix is a key parameter of the model for the following reasons:
1) The transition matrix reflects the dynamic characteristics of the system, and it is flexible for prediction.
2) The precision of prediction is high in this model, as it shall be demonstrated in the next section.

4. ONE-STEP-AHEAD PREDICTION

Ten seconds of additional actual data are selected for comparison with the results from one-step-ahead prediction by the second order Markov-like model. When predicting, given the state of $Y_i=(X_{i-1},X_i)$, one can search from the transition matrix and identify the state with maximum conditional probability in the next step. Then the time domain value corresponding to that state is recorded as the estimate $\hat{X}_{i+1}$. The results can be achieved by following the same procedures for ten seconds. Fig. 7 gives 200 points of predicted data along with the actual testing data. It shows that the difference between the actual and predicted data at every time step is very small. A second order Markov-like model is applied in the same way to the predicted data as to the actual data. The EFFs from the result are shown in Fig. 8. These are close to those in Fig. 6. It is also the case in Table 6, where for predicted data the statistical indices of mean and variance are compared with those derived from the actual data. This suggests that the model is very effective for short and long term predictions.

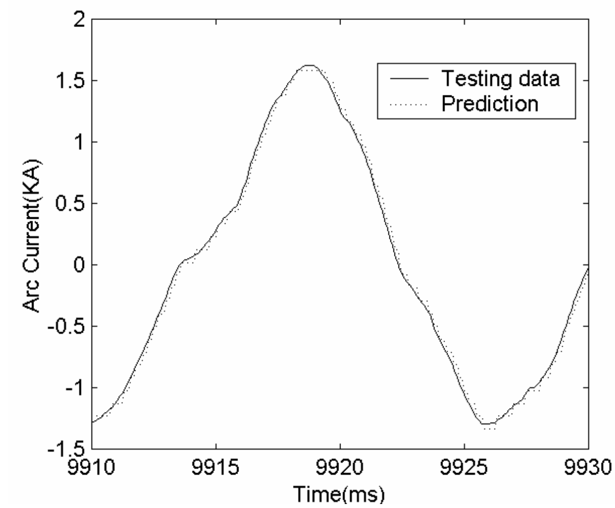


Fig. 7 Waveforms for a part of the predicted and related actual arc current

5. CONCLUSIONS

Based on the Markov-like Modeling of the EAF current/voltage data as detailed in sections 3 and 4, one is able to draw the following conclusions.

i) From a deterministic point of view, the EAF time series $\{X_i$: i=1, 2, … M$\}$ look quite chaotic and nonlinear. However, from the Markov-like modeling point of view, there is a remarkable regularity.

ii) The Empirical Frequency Function, Empirical Transition Frequencies and other time averages exhibit consistency over time. Thus observing the first part of the data set it is possible to make prediction about various time averages for the following data sets. For a long-term time average prediction of this kind, the first order Markov-like model for $\{X\}$ is quite adequate.

iii) In short-term prediction, the second order Markov-like chain Y is better. It is found that the calculated probabilities based on Y are sharp, i.e., very close to 1 or 0. Hence it is better for accurate prediction than the first order ones. This suggests that the first order time series $\{X\}$ is not Markovian and yet the methodology provides a relatively accurate prediction scheme. Thus the procedure is statistically robust. In some cases, it maybe necessary to use a third or higher order Markov-like model, but at the expense of increased computation.

iv) In all, it appears that the Markov-like modeling is a very effective alternative to analyze the dynamics of an EAF system and other kinds of discrete-valued time series with similar behaviors.

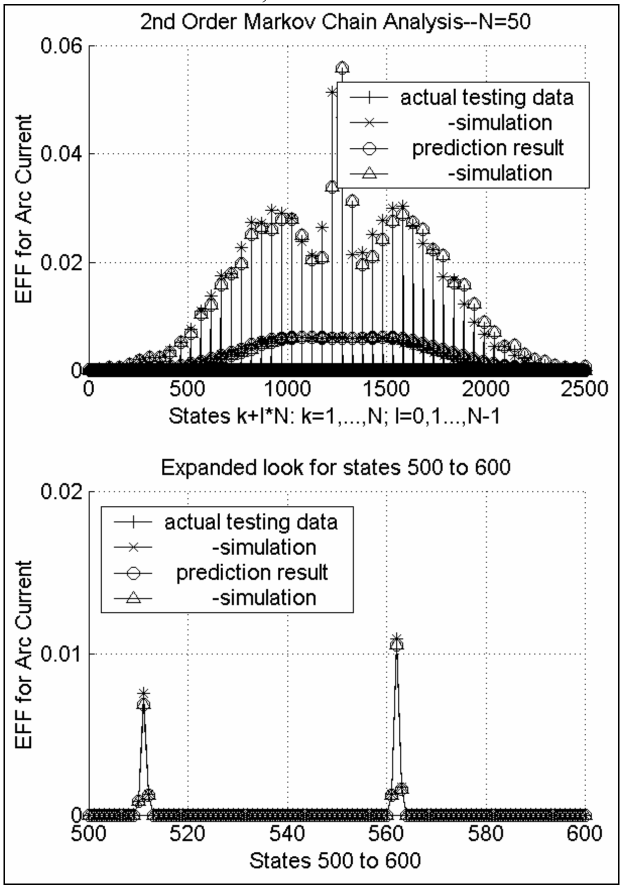


Fig. 8 EFFs for the predicted current from a second order Markov-like model N=50

Table 6 Statistical indices of the states for actual and predicted data

Data sets	Mean	Variance
Predicted data	0.0004	0.000008
Actual data	0.0004	0.000008

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] M.S. Sarshal, R.M. Iravani, "Analyses of Harmonic and Transient Phenomena Due to Operation of an ac Arc Furnace", *Iron and Steel Engineer*, April 1996, pp78-82.

[2] H. Schau, D. Stade, "Mathematical Modeling of Three Phase Arc Furnace", *Proceedings of IEEE International Conference on Harmonics in Power Systems*, vol. l., Bologna, September 21-23, 1994, pp 422-428.

[3] G.C. Montanari, M. Loggini, A. Cavallini, L. Pitti, D. Zaninelli, "Arc Furnace Model for the Study of Flicker Compensation in Electric Networks," *IEEE Transactions on Power Delivery*, vol. 8, no. 4, 1994, pp.2026-2036.

[4] R.C. Dugan, "Simulation of Arc Furnace Power Systems", *IEEE Trans. on Industry Applications*, vol. IA-16, no. 6, November 1980, pp813-818.

[5] G. Manchur and C.C. Erven, "Development of a Model for Predicting Flicker from Electric Arc Furnace", *IEEE Trans. on Power Delivery*, vol. 7, No. 1, January 1992, pp. 416-426

[6] M.V. Tan, P. Varaiya, F. Wu, "Bifurcation, Chaos, and Voltage Collapse in Power Systems," *Proceedings of the IEEE*, vol. 83, no. 11, Nov. 1995, pp. 1484-1496.

[7] G. Majordomo, L.F. Beites, R. Asensi, M. Izzeddine, L. Zabala and J. Amantegui, "A New Frequency Domain Arc Furnace Model for Iterative Harmonics Analysis", *IEEE Trans. on Power Delivery*, vol. 12, no. 4, October 1997, pp.1771-1778.

[8] S. Varadan, E.B. Makram and A.A. Girgis, "A New Time Domain Voltage Source Model for an Arc Furnace Using EMTP", *IEEE Trans. on Power Delivery*, vol. 11, no. 3, July 1996, pp. 1685-1691.

[9] K.B. Athreya, "Random Iterations: An Alternative to Deterministic Chaos Approach to Modeling", Preprint, *Department of Mathematics*, Iowa State University, 1999

[10] K.B. Athreya and G. Atuncar, "Kernel Estimation for Real Valued Markov-like Chains, Sankhya", *The Indian Journal of Statistics*, 1009, Vol. 60, Series A, Part 1, pp.1-17,1998

[11] A.M. Stankovic and E.A. Marengo, "A Dynamic Characterization of Power System Harmonics Using Markov Chains", *IEEE Trans. On Power Systems*, vol. 13, no.2, May 1998,pp. 441-448

[12] I.L. MacDonald and W. Zucchini, Hidden Markov-like and Other Models for Discrete–valued Time Series, First edition, *Chapman & Hall*, London, 1997

[13] W. F. Stewart, Introduction to the Numerical Solution of Markov-like Chain, *Princeton University Press*, Princeton, New Jersey, 1994.

[14] W. Charytoniuk, M.S. Chen and P. Van Olinda, "Non Parametric Regression Based Short-term Load Forecasting", *IEEE Trans. on Power Systems*, vol. 13, no. 3, Aug 1998, pp. 725-730.

8. BIOGRAPHIES

Krishna B. Athreya obtained his Ph.D. in mathematics from Stanford University in 1967. He is currently a professor at Iowa State University with a joint appointment in the department of mathematics and statistics. He holds the title of distinguished professor in the college of Liberal Arts and Science. He is a fellow of the Institute of Mathematical Statistics, USA and the Indian Academy of Science, Bangalore, and an elected member of the International Statistical Institute. He has co-authored with P. Ney a book on Branching Process (1972), Springer-Verlag, co-edited three other books, has over 100 research papers. His research interests include Branching Process, Markov Chains, Stochastic Modeling and Mathematical Statistics.

Feng Chen was born in P. R. China and there he received his B.Eng. and M.S. Degree from Huazhong University of Science & Technology, Wuhan, in 1995 and 1998 respectively. Then he obtained his Ph.D. from Iowa State University in 2002. Currently he works as a staff engineer at General Electric Network Solutions. His interests are mainly distribution system, non-linear system modeling, protection and EMS software.

Vedula V. Sastry received the Ph.D. degree in 1968 from Indian Institute of Technology, Kharagpur , India and there after he had been a teacher, research and consultant during his tenure with Indian Institute of Technology, Madras for 3 decades. From August 1998 to August 2002, he was an Adjunct Professor at Department of Electrical & Computer Engineering, Iowa State University, Ames, USA. He is currently a Principal Engineer at United Technologies Research Center CT, USA. He is an elected Fellow of Indian National Academy of Engineering, New Delhi and Sen. Member of IEEE, New York.

S.S. Venkata is presently Professor and Palmer Chair of Electrical and Computer Engineering Department at Iowa State University, Ames, Iowa. His research interests include power quality and reliability, power electronic applications to power systems, automated distribution system planning and automation, intelligent applications to power systems, six-phase transmission, protection, and education. He has served as consultant to several utilities and industries. Dr. Venkata is a Fellow of the IEEE. He is also a member of Tau Beta Pi, Sigma Xi, and Eta Kappa Nu, and several IEEE committees and subcommittees. He is a registered professional engineer. He has published and presented more than 170 papers and is co-author of Introduction to Electric Energy Devices (Prentice Hall, 1987). In 1996 he received the Outstanding Power Engineering Educator Award from the IEEE Power engineering Society. He received his B.S.E.E and M.S.E.E from India. He received his Ph.D. from the University of South Carolina, Columbia in 1971. He taught at the University of Massachusetts, Lowell for one year, West Virginia University, Morgantown for seven years, and at the University of Washington, Seattle for 17 years.

Techniques for Harmonic Analysis

A. Medina, *Senior Member, IEEE*

***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.

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,

$$[Y]V = I \qquad (1)$$

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].

A. Medina is with the Facultad de Ingeniería Eléctrica, División de Estudios de Posgrado, U.M.S.N.H., Morelia, Michoacán, MEXICO (email: amedina@zeus.umich.mx)

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,

$$\Delta I = [Y_J]\Delta V \tag{2}$$

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,

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

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,

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

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],

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

where

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

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,

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

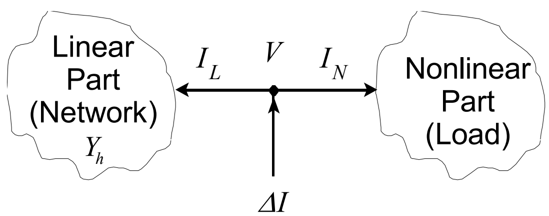


Fig. 1 System seen from load nodes

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.

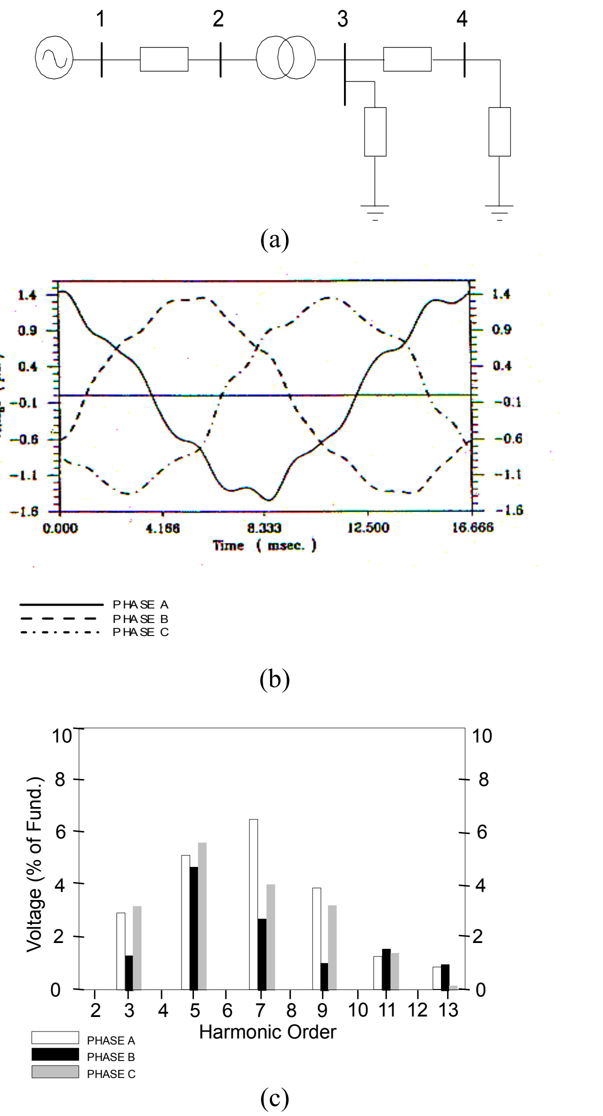


Fig. 2. (a) Test system 1; (b) Voltajes at node 4; (c) Voltaje harmonic content at node 4

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.*

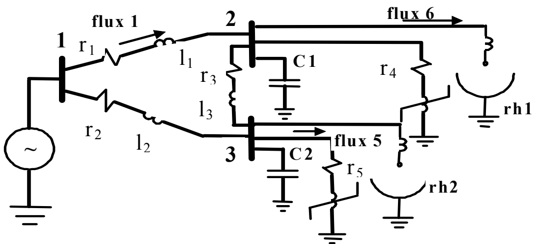
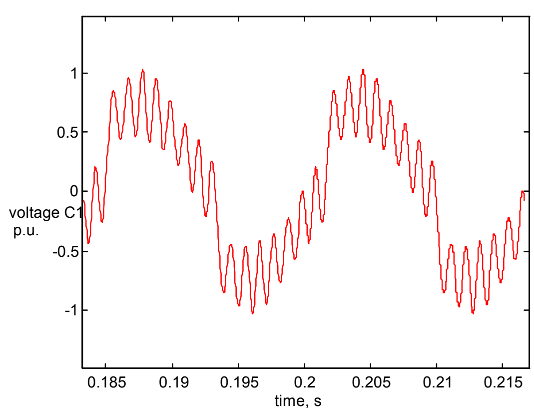


Fig. 3 Test system 2.

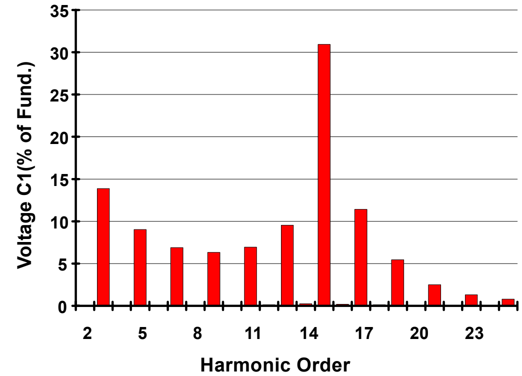
The periodic steady state of the system is obtained in 79 periods (cycles) of time (NFC) using the Brute Force method (BF) and in 56 using the Newton methods for the acceleration of the convergence to the Limit Cycle based on the Direct Approach (DA) and Numerical Differentiation (ND) procedures, respectively [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],

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

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

IV. 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. However, 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.

V. ACKNOWLEDGMENT

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VI. REFERENCES

[1] J. Arrillaga, D.A. Bradley, P.S. Bodger, *Power System Harmonics*, John Wiley and Sons, 1985.

[2] M.H.J. Bollen, *Understanding Power Quality Problems*, IEEE Press, 2000.

[3] A.A. Mahmoud, R.D. Schultz, "A Method for Analyzing Harmonic Distribution in A.C. power Systems", *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-101, No. 6, PP. 1815-1824, 1982.

[4] T.J. Demsem, P.S. Bodger, J. Arrillaga, "Three Phase Transmission System Modelling for Harmonic Penetration Studies", *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-103, No. 2, pp. 310-317, Feb. 1984.

[5] C.D. Callaghan, J. Arrillaga, "Convergence Criteria for Iterative Harmonic Analysis and its Application to Static Convertors", in *Proc. 1990 IEEE/ICHPS IV International Conference on Harmonics in Power Systems*, Budapest, Hungary, October 4-6, pp. 38-43.

[6] H.W. Dommel, A Yan, S. Wei, "Harmonics from Transformer Saturation", *IEEE Trans. on Power Systems*, Vol. PWRD-1, No. 2, pp. 209-214, Apr. 1986.

[7] C.D. Callaghan, J. Arrillaga, "A Double Iterative Algorithm for Iterative Harmonic Analysis and Harmonic Flows at ac-dc Terminals", *Proc. of the IEE*, Vol. 136, No. 6, 1989, pp. 319-324.

[8] V. Sharma, R.J. Fleming, L. Niekamp,"An Iterative Approach for Analysis of Harmonic Penetration in Power transmission Networks", *IEEE Trans. on Power Delivery*, Vol. 6, No. 4, pp. 1698-1706, Oct. 1991.

[9] B.C. Smith, J. Arrillaga, A.R. Wood, N.R. Watson, "A Review ofIterative Harmonic Analysis for AC-DC Power Systems", *IEEE Trans. on Power Delivery*, Vol. 13, No. 1, pp. 180-185, Jan. 1998.

[10] D. Xia, G.T. Heydt, "Harmonic Power Flow Studies, Part I – Formulation and Solution, Part II – Implementation and Practical Application", *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-101, pp. 1257-1270, June 1982.

[11] W. Xu, J.R. Marti, H.W. Dommel "A multiphase harmonic load flow solution technique", *IEEE Trans. on Power Systems*, vol. PS-6, pp. 174-182, Feb. 1991.

[12] J. Arrillaga, A. Medina, M.L.V. Lisboa, M.A. Cavia, P. Sánchez, "The Harmonic Domain a Frame of Reference for Power System Harmonic Analysis", *IEEE Trans. on Power Systems*, Vol. 10, No. 1, pp. 433-440, Feb. 1995.

[13] W.W. Xu, J.R. Marti, H.W. Dommel, "A Synchronous Machine Model for Three-Phase Harmonic Analysis and EMTP Initialization", *IEEE Trans. on Power Systems*, Vol. 6, No. 4, pp. 1530-1538, Nov. 1991.

[14] A. Semlyen, J.F. Eggleston, J. Arrillaga, "Admittance Matrix Model of a Synchronous Machine for Harmonic Analysis", *IEEE Trans. on Power Systems*, Vol. PWRS-2, No. 4, pp. 833-840, Nov. 1987.

[15] A. Medina, J. Arrillaga, J.F. Eggleston, "A Synchronous Machine Model in the Harmonic Domain", *in Proc. IEEE ICEM92 International Conference on Electrical Machines*, Manchester, UK, pp. 647-651.

[16] A. Medina, J. Arrillaga, "Generalised Modelling of Power Transformers in the Harmonic Domain", *IEEE Trans. on Power Delivery*, Vol. 7, No. 3, July 1992, pp. 1458-1465, Sept. 1992.

[17] E. Acha, A. Semlyen, N. Rajakovic, "A Harmonic Domain Computational Package for Nonlinear Problems and its Application to Electric Arcs", *IEEE Trans. on Power Delivery*, Vol. 5, No. 3, pp. 1390-1397, July 1990.

[18] E. Acha, J.J. Rico, S. Acha, M. Madrigal, "Harmonic Domain Modelling of the Three Phase Thyristor-Controlled Reactors by Means of Switching Vectors and Discrete Convolutions", *IEEE Trans. on Power Delivery*, Vol. 11, No. 3, pp. 1678-1684, 1996.

[19] B.C. Smith, A. Wood, J. Arrillaga, "A Steady State Model of the AC-DC Converter in the Harmonic Domain", *IEE Proc. Generation, Transmission and Distribution*, Vol. 142, No. 2, pp. 109-118, 1995.

[20] M. Madrigal, E. Acha, "A New Harmonic power Flow Method Based on the Instantaneous power Balance", *in Proc. of the 10th IEEE/ICHQP International Conference on Harmonics and Quality of Power*, Rio de Janeiro, Brazil, October 6-9, 2002.

[21] H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks", *IEEE Trans. on Power Apparatus and Systems*,Vol. PAS-88, No. 4, pp. 388-399, April 1969.

[22] T.S. Parker, L.O. Chua, *Practical Numerical Algorithms for Chaotic Systems*, Springer-Verlag, 1989.

[23] T.J. Aprille, T.N. Trick, "A Computer Algorithm to Determine the Steady State Response of Nonlinear Oscillators", *IEEE Trans. on Circuit Theory*, Vo. 9, No. 4, pp. 354-360, 1972.

[24] A. Semlyen, A. Medina, "Computation of the Periodic Steady State in Systems with Nonlinear Components Using a Hybrid Time and Frequency Domain Methodology", *IEEE Trans. on Power Systems*, Vol. 10, No. 3, pp. 1498-1504, Aug. 1995.

[25] O. Rodríguez, A. Medina, "Fast Periodic Steady State Solution of a Synchronous Machine Model in Phase Coordinates Incorporating the Effects of Magnetic Saturation and Hysteresis", *in Proc. 2001 IEEE PES Winter Meeting*, Vol. 3, January 28 – February 1, 2001, Columbus, Ohio, USA, pp. 1431-1436.

[26] S. García, A. Medina, "A State Space Three-Phase Multilimb Transformer Model in the Time Domain: Fast Periodic Steady State Analysis", *in Proc. 2001 IEEE PES Summer Meeting*, Vol. 3, July 2001, Vancouver, Canada, pp. 1859-1864.

[27] A. Medina, N. García, "Dynamic Análisis of Electric Arcs Using a Time Domain Newton Technique", *in Proc. 1998 IEEE International Power Electronics Congress*, October 1998, Morelia, México, pp. 82-88.

[28] N. García, A. Medina, "Efficient Computation of the Periodic Steady-State Solution of Systems Containing Nonlinear and Time-Varying Components. Application to the Modeling of TCRs", *in Proc. of the 9th IEEE/ICHQP Internacional Conference on Harmonics and Quality of Power*, Orlando FL, USA; 2000, Vol. 2, pp. 673-678.

[29] N. García, A. Medina, "Fast Periodic Steady State Solution of Systems Containing Thyristor Switched Capacitors", *in Proc. 2000 IEEE PES Summer Meeting*, Seattle, USA; July 2000, Vol. 2, pp. 1127-1132.

[30] A. Medina, A. Ramos-Paz, C.R. Fuerte-Esquivel, "Fast Periodic Steady State of Systems Containing TCSCs", *in Proc. of the 10th IEEE/ICHQP International Conference on Harmonics and Quality of Power*, Rio de Janeiro, Brazil, October 6-9, 2002.

[31] N. Garcia, E. Acha, and A. Medina, "Swift Time Domain Solutions of Electric Systems Using Parallel Processing", *in Proc. of the Sixth IASTED International Conference*, Rhodes, Greece, July 2001, pp. 172-177.

[32] A. Medina, A. Ramos-Paz, C.R. Fuerte Esquivel, "Efficient Computation of the Periodic Steady State Solution of Systems with Nonlinear Components Applying Parallel Multi-Processing", *in Proc. 2002 IEEE PES Summer* Meeting, Chicago Il, USA, Vol. 3, pp. 1483-1487.

[33] A. Medina, A. Ramos-Paz, C.R. Fuerte Esquivel, "Periodic Steady State Solution of Electric Systems with Nonlinear Components Using Parallel Processing", *IEEE PES Power Engineering Review*, to be published.

[34] Geist, A. Beguelin, A. and Dongarra, J., *PVM: Parallel Virtual Machine, MIT Press 1994*.

[35] Sun, *Multithreaded Programming Guide*, Aug. 1997.

[36] A. Medina, "Power System Modelling in the Harmonic Domain", *PhD Thesis*, University of Canterbury, New Zealand, 1992.

[37] L.L. Freris, A.M. Sasson, "Investigation of the Load Flow Problem", *Proceedings of the IEE*, Vol. 115, No. 10, October 1968, pp. 1450-1460.

[38] I . Foster ,.: *Designing and Building Parallel Programs*, Addison Wesley, 1994.

VII. BIOGRAPHY

Aurelio Medina (SM´02) obtained his Ph.D. from the University of Canterbury, Christchurch, New Zealand in 1992. He has worked as a Post-Doctoral Fellow at the Universities of Canterbury, New Zealand (1 year) and Toronto, Canada (2 years). At present he is a staff member of the Facultad de Ingeniería Eléctrica, UMSNH, Morelia, Mexico where he is the Head of the Division for Posgraduate Studies. He is Senior Member of IEEE and is listed in the book Who's Who in the World. His research interests are in the dynamic and steady state analysis of power systems.

Monitoring Power Quality in Electric System for Transportation as basis for Probabilistic Analysis

Morris Brenna, Paolo Pinato (*), Dario Zaninelli (**), *Senior Member IEEE*

Abstract **- The paper deals with the possible implementation of probabilistic methods for defining the disturbance spectrum generated by electric traction unit sand by ac industrial supply network in different operating conditions.**

In the work, an experimental data set is used to analyze the disturbances present in the electric systems for transportation currently in use in Italy and in other European countries, based on static power conversion stations and dc supply feeders. The collected data constitute the basis for developments of a probabilistic analysis that can bring to the definition pf stochastic model for the future power quality studies in electric traction networks.

Keywords **– Electric traction, harmonic pollution, contact line, experimental survey, power quality, power electronic.**

I. Introduction

The main purpose of public transportation service is to ensure, in any operational situation, the safety and regularity of the service provided by rolling stocks. To this end, it is necessary that the harmonic disturbances generated by traction units conform to the compatibility limits with the signaling system set up for traffic control.

Electrified transport systems are complex ones; they continue to evolve, both during their design stage and during manufacturing, but also throughout their long period in service. Therefore, because of their complexity and technical developing, they are difficult to define, evaluate, or monitor in terms of reliability. The “continuity” aspects were traditionally divided from the “quality” ones, but recently, with the widespread use of electronic control devices, it is difficult to set a border between "continuity" and "quality" and this latter has become the main topic.

A system reliability decrease in terms of quality (i.e. distorted waveforms, voltage variations, frequency shifts, unbalances, electromagnetic disturbances) can cause damages as the lack of continuity of the supply or dangerous conditions. As an example the telecontrol devices are sensitive to electromagnetic phenomena, or the signaling relays could be susceptible of errors in presence of harmonic currents and voltages.

This paper aims to show a possible harmonic emission spectrum of an electrical conversion sub-station for electric traction (ESS) in the operating conditions of the transportation system.

Without impairing the general validity of the report, reference was made to the railway traction system in operation in Italy: a direct current power system supplied via overhead line with return via rails. The supply voltage has a harmonic spectrum that is influenced by the switching frequency of the switches present in the conversion system (50 Hz and its multiples) and by the presence of operating anomalies in the industrial network. In addition, harmonic components can be found associated with the train run on the system due to the drives present on board.

Going into more detail, an experimental investigation was made on the voltage and current waveforms, and therefore their harmonic pollution, depending on the type of operation in different hours for several days [1].

The collected data are a point of departure for characterizing the anomalies of the voltage waveshape present in the industrial distribution network that supplies the traction systems through a statistic model proposed in the paper [2].

At the end some interesting comments on the results obtained conclude this paper with some objective criticism on the limitations of the survey.

II. Description of the Traction System

To get the area of research and the problem it represents into perspective, it will be necessary to start with a brief description of the 3 kV dc traction system and especially of the characteristics of the harmonic emission.

A. Fixed Plant and Equipment

This research is the outcome of a technical co-operation with RFI S.p.A., the North Central Area of the Florence Infrastructure Department, who have kindly made available their instrument tests, measurements section and the railway

(*) M. Brenna and P. Pinato are with the Department of Electrical Engineering, Politecnico di Milano, Milano, Italy (email: m.brenna@polimi.it, paolo.pinato@polimi.it).
(**)D. Zaninelli is with the Department of Electrical Engineering, Politecnico di Milano, Milano, Italy (email: dario.zaninelli@polimi.it).

installations, performing the measurement campaign under the university direction.

In particular, reference and quote are relevant to experimental data recorded during the measurements performed on the ESS of Empoli (in Tuscany - Italy) which supplies the railway line between Firenze and Pisa and a part of Pisa's railway junction.

In Italy, as it is showed in Fig. 1 the ESS' are directly supplied by a station of the industrial network, or by primary High Voltage (HV) lines (66 kV, 132 kV, 150 kV) [3].

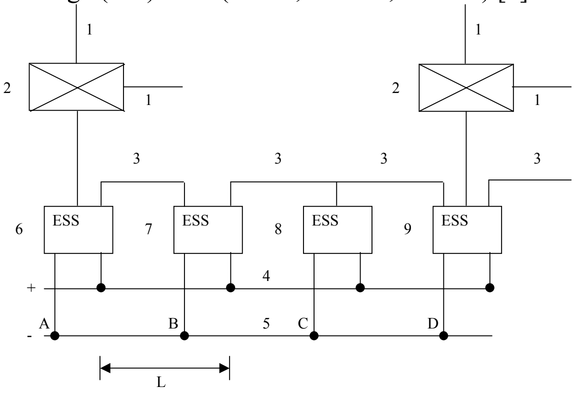

Fig. 1. Diagram of supply of a dc electric traction system. 1) HV ac lines. 2) Electric power substation of ac industrial network. 3) HV ac Primary lines of traction system. 4) Railway dc overhead lines. 5) Rails. 6-7-8-9) Substations of conversion. L) Distance among ESS'.

As regards the routes followed by the primary supply (three-phase lines) serving the Empoli's ESS of the RFI's system, these consist of a 132 kV HV line (about 5 km long).

With regards to the ac/dc conversion, there are two conversion units, each one consisting of two 132 kV / 2.75 kV transformers with load ratio-variators and a short circuit voltage equal to 7 % and a rated power of 5.75 MVA. The converters are so connected that they set up a twelve-pulse reaction, thus containing the ripple and therefore the harmonic frequency spectrum.

As regards the conversion systems, these consist of diode rectifiers; apart from these, in the secondary bus-bars of the transformers, there is a 100 kVA three-phase transformer for supplying the ac auxiliary services of the ESS.

This equipment has the following features [4]:

- 2 Graetz bridges, connected in parallel.
- Maximum rectified no-load voltage: 4 kV.
- Unit power: 5.4 MW.
- Voltage drop within the rated current: not exceeding 30 V.
- Internal short-circuit current:13 kA.
- Cooling: natural air.

Voltage drops and conversion from the ac system to dc system are not sufficient to inject into the contact line a perfectly direct current following the ripple present. To avoid disturbances to plant and equipment (in the form of noise as regards telephone lines adjacent to the contact line and, especially, due to incompatibility with the signaling circuits on the rail) and excessive heating of the traction motors, these harmonics are eliminated, or at least reduced by suitable LC passive filtering systems [4].

In this specific case, the filter used in the RFI's ESS examined here is made up as follows (Fig. 2):

Series inductor [5]:

- Rated value: 6 mH.
- Inductance variation: 0 – 20 %.
- Rated resistance at 20 °C (dc): 11 mΩ.
- Rated operating voltage (dc): 3.6 kV.
- Rated current (dc): 2.5 kA.
- Cooling: natural ventilation.
- Insulation class: F.

Parallel capacitor [6]:

- Rated value: 30 μF.
- Number of legs in parallel per filtering unit: 6.
- Number of filtering units in parallel: 3.
- Total filtering capacity: 3 x 120 μF.
- Rated operating voltage (dc): 6 kV.
- Rated current: 25 A.
- Cooling: natural ventilation.

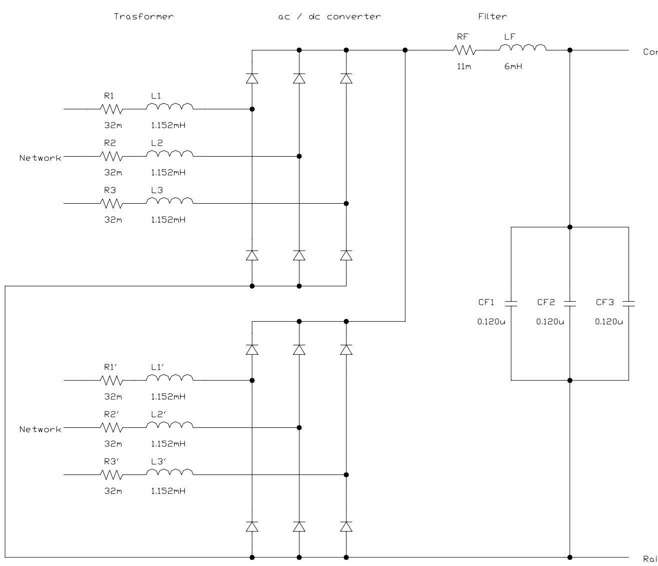

Fig. 2. Scheme of the ESS, considered for the data collection campaign.

B. *Rolling Stock*

The circuit configuration of equipment on board rolling stock is intrinsically linked with the type of supply [7].

In Italy there are several kinds of locomotives and traction units which operate on "Firenze – Pisa" railway . These ones can be listed as follows:

- Traditional or reostatic locomotives equipped with dc traction motors and system of resistors (dated on 1930 – 1960, for example FS E 646 or FS ALe 582).
- Electronic locomotives (1st generation) equipped with dc traction motor and chopper step-down (dated on 1970 – 1985, for example FS E 633, FS E 632 and

FS E 652). Direct or one stage configuration (see Fig. 3).

- Electronic locomotives (2nd generation) equipped with ac traction and inverters (dated on 1980 – 2002, for example FS ALe 426[1] or FS E 402). Indirect or two-stage configuration.

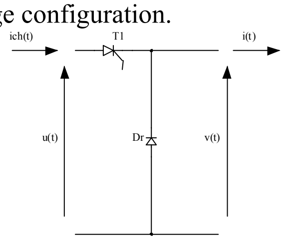

Fig. 3. Simplified diagram of an one-stage converter.

Indirect or two-stage configuration consists of two cascade converters: the input converter has a dc output that supplies an intermediate stage equipped with a filter. Downstream of this, there are the loads in general, or else those supplied by one or more choppers or inverters. This configuration is used both in setting up traction converters and for converters in the auxiliary service supply.
In the Italian railway system, the input converter is a chopper and the downstream one is an inverter (see Fig.4).

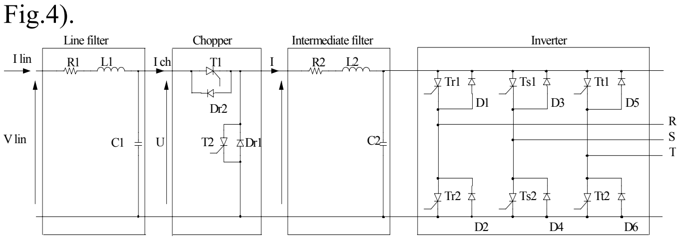

Fig. 4. Circuit diagram of a double-or two-stage converter.

III. Description of Experimental Survey

The purpose of the line measurements is to record the voltage and current harmonic spectrum on the dc side of a twelve-pulse ESS.

The line measurements consist in recording the voltage and current flowing from the dc side of a twelve-pulse ESS by means of experimental data acquisition.

The goal is to obtain a sample of data for validating a probabilistic model of the traction system in which the voltage at the contact line is set in a way that take into account the ESS operation and the trains interactions.

Voltages and currents have been recorded by means of an acquisition system with sample frequency of 10 kHz during 48 hours of operations of ESS. Each measurement set is 20 s long for a total recorded time of about 70,000 s.

The investigation on the harmonic analysis of the obtained data was limited in the frequency range between 0 Hz and 2 kHz for a good exploitation of the measurement instrumentation precision.

Thanks to the versatility of the data acquisition system it has been possible to make measurements in different operation of the ESS, at different levels of power delivered to traction line. This one can be identified by the level of the dc current of the line: high dc current value corresponds to heavy traffic on the line;low value of dc current close to zero corresponds to the “no load” condition of the ESS.

During the measurement process a reference level of dc current is established, then when the line current reaches this level, the acquisition data system starts to record the samples of dc voltage and of dc current for 20 s and so on. Reference levels for dc current can be decided by the operator.

IV. Results of Experimental Survey

The results obtained from the measurements above described permit to characterize the interaction between the Empoli’s ESS, other ESS supplying the traction line, and the trains present on line.

The following operating conditions are considered with reference to three different cases identified by three different values of the line current (See Fig. 5).

CASE A) – High level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to 1500 A.

CASE B) – Medium level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to 500 A.

CASE C) – Low level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to < 500 A (in particular 200 A) and this case of the data acquisition is manual and not automatic as in the other cases.

Different windows of the data recorded are processed in order to evaluate the harmonic components of the traction line voltage. The amplitude of the windows is selected in 0.4 s, in this way it is possible to correctly use the Fast Fourier Transform [8], based on the sample frequency of the collected measurements.

The error on the measured harmonic components, according to the implemented instrumentation is 5 % of the measured value.

It is important to underline that the cases reported in the paper are a small picture of the total recorded data object of the survey. They are here reported as an interesting selection to show the level of the voltage harmonic pollution and to permit useful comments on the nature of the disturbances.

[1] Treno ad Alta Frequentazione" so-called T.A.F. trains, in service on the Italian Railways, now operated by Trenitalia S.p.A.

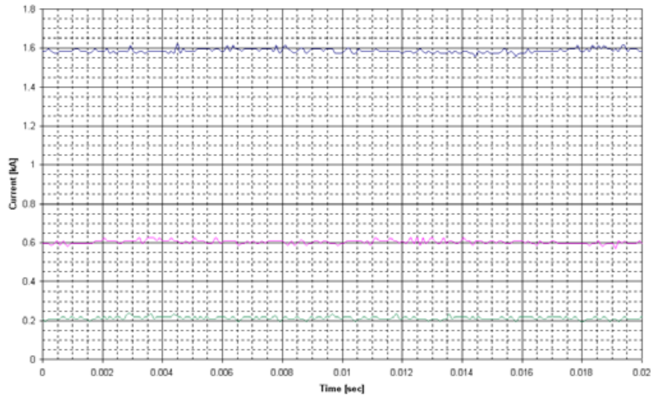

Fig. 5. Traction line current delivered by the Empoli's ESS with three different levels of the reference dc current. Case A: 1500 A – Case B: 500 A – Case C: 200 A.

Table 1 shows the results of the harmonic analysis [9] of the line voltage in the three cases of operation listed above. In the Table 1 only the components greater than 0.15 % of the rated dc voltage (3 kV) are reported. This because the acquisition system was not provided by signal filtering devices and harmonic components with amplitudes lower than that threshold are not worthy of consideration.

TABLE 1
HARMONIC ANALYSIS OF THE VOLTAGE IN THE 3 CASES OF OPERATION. THE AC COMPONENTS ARE EXPRESSED AS RMS VALUE

f [Hz]	LINE VOLTAGE Case A [V]	LINE VOLTAGE Case B [V]	LINE VOLTAGE Case C [V]
0	3820	3718	3879
25	-	0.4	-
50	8.2	8.3	17.1
65	-	0.4	-
70	1	-	-
75	0.82	0.37	0.7
100	0.6	0.6	0.4
150	4.7	4.7	3.2
300	1.5	1.0	1.0
600	-	-	0.4
1040	-	0.46	-

V. COMMENTS ON EXPERIMENTAL DATA

The results reported in Table 1 show frequency components of the line voltage concentrated at the low frequency values. In particular the component at the 50 Hz frequency of the ac main network that supplies the ESS, is the highest in term of amplitude.

The presence of these components are associated to asymmetrical distribution of currents during the switching periods of the switch branches in the converters.

The presence of the characteristic frequencies of the 12 pulse ac–dc converter (300 Hz and its multiple) are limited by the presence of the passive LC filters, described in Section II, on the dc side of the ESS. These filters are very effective also for frequencies over 300 Hz as testified by the limited values of these components reported in Table 1.

It is interesting to note the presence of voltage components at frequencies that do not have an immediate theoretical explanation these latter are due to different phenomena.

- Currents of signaling system which ensures the safety and the regularity of the flow of railway traffic.
- Physical phenomenon of electric arcs between pantography and overhead line. In this case the magnitude of harmonic disturbance depend on speed of train and on electric energy absorption when the separation happens.
- Physical phenomenon of beats[2] among converters on board of rolling stock.
- Physical phenomenon of beats between converter on board of a train and the ones of ESS.
- Physical phenomenon of beats among converters of different rolling stocks supplied by the same ESS.
- Induced disturbances by electric industrial network supplying the ESS's voltage.

VI. STATISTICAL MODEL

The next goal in the research project is the study of the performance of the traction power quality by means of a statistical model [10].

The resolution algorithm presents the following steps:

- STEP 1. Determination of the sample mean [11]of the voltage amplitude for each kth frequency, random variable A_k, which is present in the harmonic spectrum of the overhead line's voltage

$$\overline{(A_k)_m} = \frac{1}{n} \cdot \sum_{i=1}^{n} A_{ik} \text{ ,}$$

in which the index i represents the ith observation of the voltage amplitude at the kth frequency.

The sample mean represents the best estimator of the expected value:

$$\mu_k = E[A_k] = \int_{-\infty}^{+\infty} x \cdot f_{A_k}(x) dx \text{ ,}$$

in which $f_{A_k}(\cdot)$ represent the probability density of the random variable.

- STEP 2. Determination of the "concentration" of observations around the expected value. The variance (central moment of inertia of the probability masses) of the random variable A_k

$$VAR[A_k] = E\left[(A_k - E[A_k])^2\right],$$

[2] They may be defined as the composition, or rather interference, of the harmonics generated by individual converters when in operation: the result is a harmonic spectrum involving a multitude of frequencies.

is estimated by the unbiased sample variance:

$$S_{A_k}{}^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(A_{ik} - \overline{(A_k)_m} \right)^2 ,$$

- STEP 3. Determination of the covariance between the random variables A_k and A_h (harmonic voltage at the k^{th} and h^{th} frequency) defined as:

  $$COV[A_k, A_h] = E[(A_k - E[A_k]) \cdot (A_h - E[A_h])].$$

  The best unbiased estimator for the above quantity is:

  $$S_{A_k A_h}{}^2 = \frac{1}{n-2} \cdot \sum_{j=1}^{n} \sum_{i=1}^{n} \left(A_{ik} - \overline{(A_k)_m} \right) \left(A_{jh} - \overline{(A_h)_m} \right).$$

  It is thus possible to estimate the covariance matrix associated with the totality of the harmonic voltage observations recorded.

$$\Sigma = \begin{bmatrix} VAR[A_1] & & & COV[A_1, A_m] \\ & & COV[A_h, A_k] & \\ & COV[A_k, A_h] & VAR[A_j] & \\ COV[A_m, A_1] & & & VAR[A_m] \end{bmatrix}$$

  The estimator for Σ is:

$$\overline{\Sigma} = \begin{bmatrix} S_{A_1}{}^2 & & & S_{A_1 A_m}{}^2 \\ & & S_{A_h A_k}^2 & \\ & S_{A_k A_h}{}^2 & S_{A_j}{}^2 & \\ S_{A_m A_1}{}^2 & & & S_{A_m}{}^2 \end{bmatrix}$$

  It may be noted that this matrix can involve a considerable computing effort, given that from n observations and m voltage harmonics we have a covariance matrix whose dimension is m^2 and with $m + \frac{m^2 - m}{2}$ quantities to determine.

- STEP 4. Representation of the frequencies present in the emission spectrum of the ESS, amplitudes of the voltage harmonics recorded, and the number of observations associated in a hypothetical space – see Fig.6.

  It is presumed that that the probability density function represented by the dc voltage emission spectrum in of the ESS, harmonic by harmonic, occurs according to normal distribution; in addition, it is assumed that the measuring program on the RFI S.p.A. installations may confirm the experimental data recorded in the course of research [2], that is that the associated Gaussian curve reaches its maximum near the value indicated for each harmonic, possibly in the absence of symmetry in respect of the expected of each distribution.

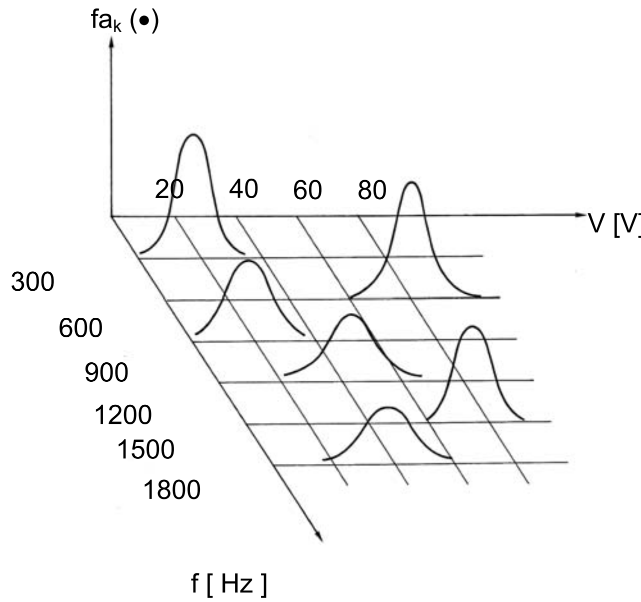

Fig.6. Diagram of the harmonic spectrum. The probability density of the corresponding voltage amplitude random variable is shown at each frequency.

- STEP 5. Should the statistical survey, starting with the experimental recordings, characterize normal probability distribution function for each voltage harmonic, use of the deterministic model for the rolling stock, a linear link between input (voltage of the contact line) and output (harmonic emission in terms of current) would make it possible to obtain a probabilistic representation of the analytical type of the disturbances generated.

  If, on the other hand, it were not possible to have a Gaussian representation of the voltage harmonics on the overhead line and/or by adapting a more detailed analysis of the working of equipment on board trains, the problem would become non-linear, so that the statistical model would have to be implemented. From the latter it would be necessary to obtain series of numerical simulations (MONTECARLO method), being a sample from n observations of the m voltage harmonics recorded, in such a way as to define the most consistent emission spectrum profile.

  Subsequently, it would be necessary to start on a new series of numerical simulations of the deterministic model, representing the rolling stock [7], in order to check on compliance with compatibility as between the traction systems and other equipment under various operating conditions, as previously done with the "real case" in Fig. 7 and reported on in the subsequent section.

Concerning to the accuracy of the probabilistic model, it is possible to underline the following comments.
While deterministic model determines the exact outcome with a math tolerance that depends on deterministic equation accuracy, the probabilistic one determines the probabilities of the possible outcomes. The solution of the equations in probability model brings to a set of average values and

relevant standard deviations for the harmonic present in ESS' voltage.

The probability values and average ones for a random quantity can be found experimentally by computing the relevant frequencies and the sample means in a large number of outcomes of random experiments.

The accuracy of the probabilistic factors is associated to the correspondence of the probability density curves to the standard ones where the "average value" and the "deviation" are defined in mathematical way. The error related to this approximation of the probability density of the random variable $f_{A_k}(\cdot)$ are reported in [10].

VII. Conclusions

The spread of power electronics in the area of electric traction makes it necessary to determine instruments and establish methods for assessing the harmonic content of the currents absorbed by electronic converters, which are the cause of susceptibility to the disturbances to which signaling circuits and more generally, the electrical and non-electrical equipment present in the vicinity of the traction system, are prone.

The present paper is a part of a more general research project that is aiming at an accurate model of electric traction system, especially about fixed plants.

The final purpose is to realize a total model of the traction supply system able to describe the behavior of ESS in randomly operating conditions.

This paper has focused attention on the evaluation of harmonic pollution in the traction line voltage and current waveforms. Recourse was made to experimental research aimed at determining the dc voltage waveshape that may statistically occur on any railway line subjected to heavy traffic.

The future developments of this research will include the setting-up of a statistical model of the traction system. As has been shown, this aspect is of considerable importance, given that the regulations governing compliance with compatibility between the traction circuit and the signaling system have also tended to define stochastic values.

VIII. References

[1] P. Pinato, D. Zaninelli "Harmonic Disturbances in Electric Traction System Overhead Lines." illustrated to "10th INTERNATIONAL CONFERECNE ON HARMONICS AND QUALITY OF POWER - ICHQP 2002", Rio de Janeiro (Brazil), 7th – 10th October 2002

[2] E. Battistini, P. Pinato, D. Zaninelli, "Probabilistic Method for disturbance analysis in electric traction systems". Proceeding of the PMAPS 2002 - Probabilistic Methods Applied to Power Systems 2002, Napoli (Italy), 23rd – 26th September 2002.

[3] F. Perticaroli, "Electric systems for transportation" (in Italian), Casa Editrice Ambrosiana, Milano (Italy), January 2001.

[4] Technical standard FS IE.TE/124 "Technical standard for I.E. service for supplying feeders of "A" type, stabilized by controlled switches with only busbar at EES and E.T stations." (in Italian), Roma (Italy), 1981.

[5] Technical standard FS E.006 "Technical standard for supplying aluminum reactors for conversion ESS filters, with 6 mH inductance and dc current of 1.8 kA (CAT. 785/686) and of 2.5 kA (CAT. 785/687) for rated dc voltage of 3.6 kV" (in Italian), Roma (Italy), 1989.

[6] Technical standard FS A.002 "Technical standard for supplying smooting capacitors of 30 μF e 6 kV for filters of electric conversion EES" (in Italian), Roma (Italy), 1988.

[7] D. Cavalloni, L. Gagliardi, P. Pinato, L. Varalli, D. Zaninelli "Design criteria of passive filters for power electronics converters used in electric traction". Proceeding of the 9th IEEE International Conference on Harmonics and Quality of Power ICHQP, Orlando (USA), 1st – 4th October 2000.

[8] A.V. Oppenheim, R.W, Schafer "Digital Signal Processig" Prentice-Hall, Inc., Englewood Cliffs, N.J. (USA) – 1975.

[9] MATLAB Version 6.0 0.88 - Release 12, The Mathworks, Inc., 22nd September 2000.

[10] A. Papoulis "Probability, Random Variables and Stochastic Processes", McGraw – Hill, New York (USA), 1977.

[11] A. Leon – Garcia "Probability and Random Processes for electrical Engineering", Addison – Wesley Publishing Company, Don Mills – Ontario (CANADA), 1989.

IX. Biographies

Morris Brenna received the M.S. degree in Electrical Engineering from the Politecnico di Milano, Italy, in 1999, and Ph.D. degree at the Dipartimento di Elettrotecnica of the Politecnico di Milano in 2003. His current research interests include power electronics, distributed generation and electromagnetic compatibility. He is a member of Italian Electric and Electronic Association (AEI).

Paolo Pinato. He received the M. SC. Degree in Electrical Engineering from the Politecnico di Milano (Italy) in 1999 and he is now a Ph.D. student in the Department of Electrical Engineering of the Politecnico di Milano, Milano, Italy. His area of research includes Electric Power Systems and Electric Traction. Dr Pinato is a member of the Italian Electric and Electronic Association (AEI) and of the Italian Group of Engineering about Railways (CIFI).

Dario Zaninelli (M' 87 – SM' 96). He received the Ph.D Degree in Electrical Engineering from the Politecnico di Milano (Italy) in 1989 and he is now a Full Professor in the Department of Electrical Engineering of the Politecnico di Milano, Milano, Italy. His area of research include Power System Harmonics and Power System analysis. Dr Zaninelli is a senior member of IEEE, a member of AEI and a member of Italian National Research (C.N.R.) group of Electrical Power Systems.

Time-Frequency Signal Processing Methods for Automated Power Line Signal Analysis

Domingo Rodriguez, Marlene Vargas, Efraín O'Neill, Francisco Hernández

***Abstract*—This work presents a methodology for developing computational methods in Signal Processing for automated power line signal analysis. A set of tools is presented for time-frequency analysis of power line signals. An operator approach is taken where finite discrete signals are viewed as approximate representations of continuous time epochs on the power line. These finite discrete signals are then treated as elements in finite dimensional linear signal spaces. Special attention is given to the use of the discrete-time, discrete-frequency short-time Fourier transform and the ambiguity function. The methodology is evaluated on simulated data used in modeling identified power line conditions appearing in harsh scenarios in certain residential and industrial complexes in developing countries such as the Dominican Republic. All computational methods are developed using the scientific computation and visualization software language-tool MATLAB.**

Index Terms—Signal Processing, Power Line Monitoring, Power Quality, Time-frequency Analysis