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Power Quality Studies Using the ATP Package

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***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:

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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

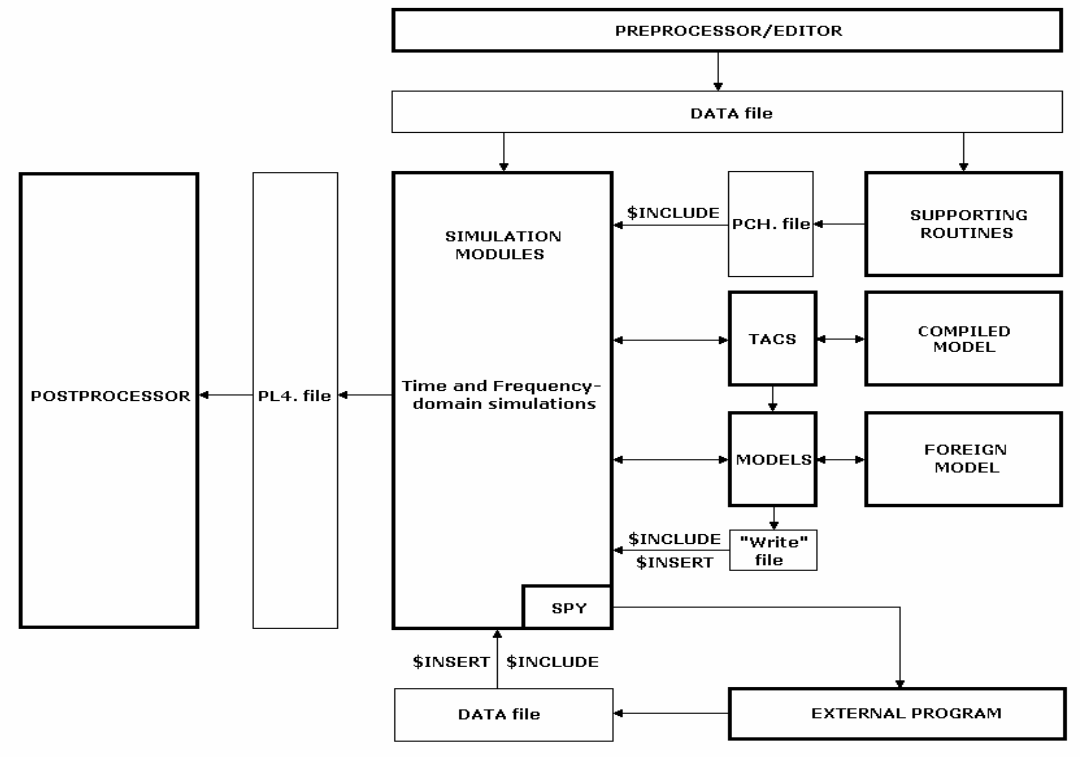


Fig. 1. Simulation modules and supporting routines.

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.

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

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

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

$$[G][v(t)] = [i(t)] - [I] \tag{2}$$

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.

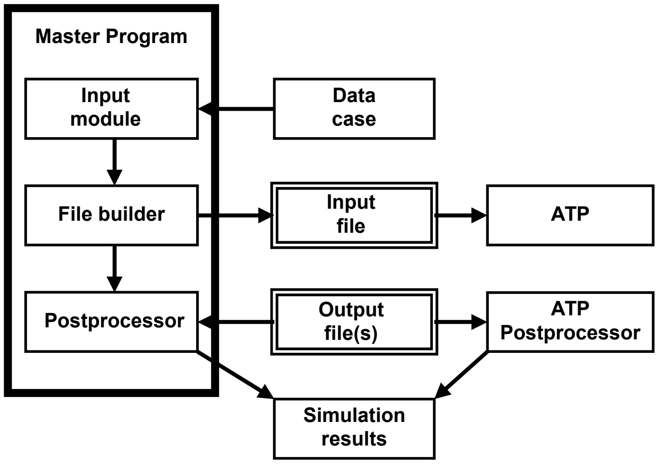


Fig. 2. Scheme of a custom-made tool.

V. ILLUSTRATIVE EXAMPLES

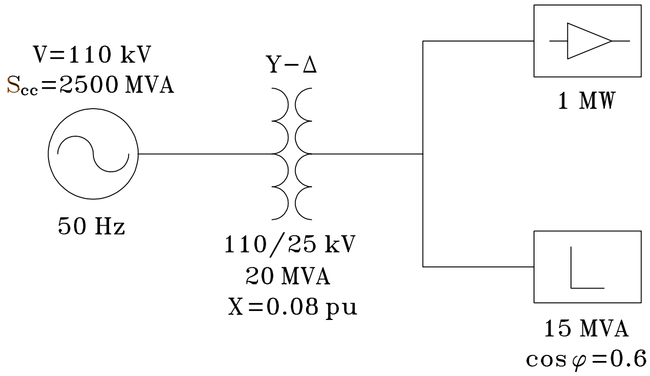
To illustrate the type of power quality studies that can be performed with this package, three case studies are described in the subsequent sections. They are based on most of the capabilities presented above.

A. Harmonic Resonance

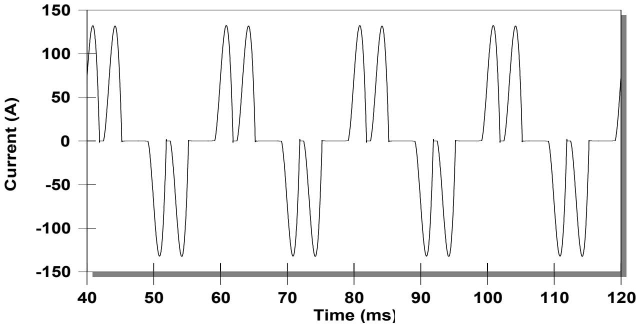
Fig. 3a shows a three-phase linear load, paralleled by a diode bridge, fed from the medium voltage side of a step-down transformer. A 12 MVAr capacitor bank is to be placed at the point of common coupling (PCC) to improve the power factor. After installing the capacitor bank, a resonance problem could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

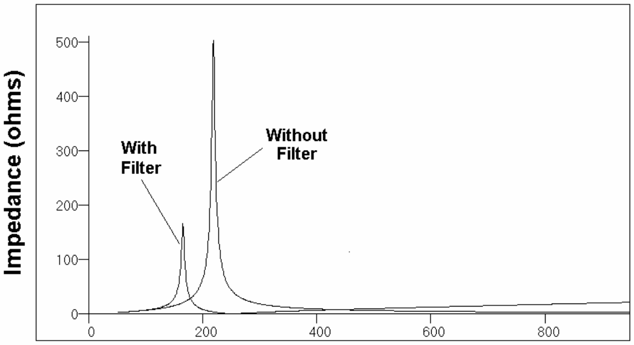
It is well known that this harmonic is present in the ac current of a diode rectifier. The problem can be solved by installing a passive filter instead of a capacitor bank. The frequency responses with and without the passive filter are also shown in Fig. 3c. The filter can be used for both improving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

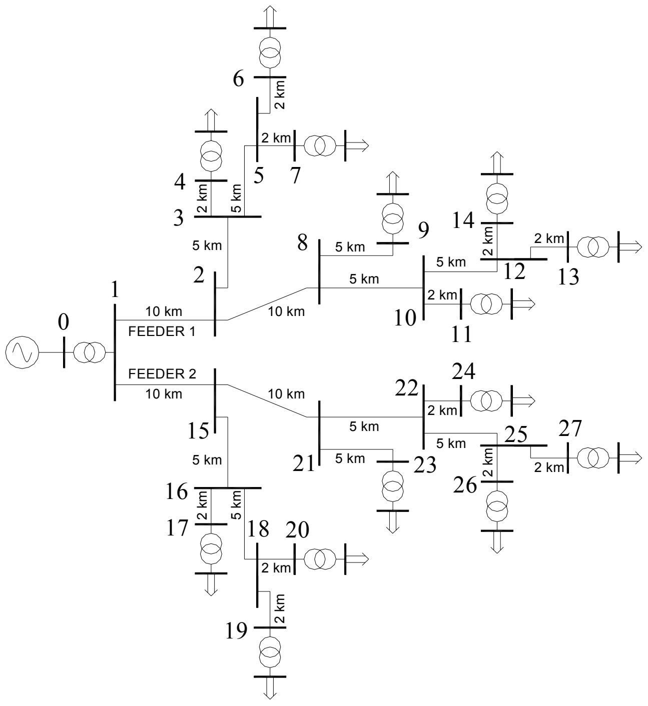
- The fault location is selected by generating a uniformly distributed random number, since the probability of fault is the same for any point of the distribution system.
- The fault resistance has a normal distribution, with a mean value of 10 Ω, and a standard deviation of 1 Ω.
- The initial time of 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
- 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.



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.

The following information was recorded at every run:

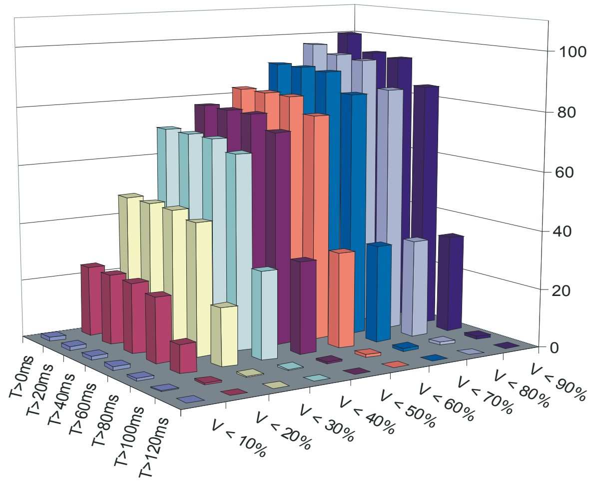
- the characteristics of the fault (location, initiation time, duration, resistance, faulted phases, type of fault)
- the characteristics of the sags (remaining voltage, duration) on every phase of the selected nodes.

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

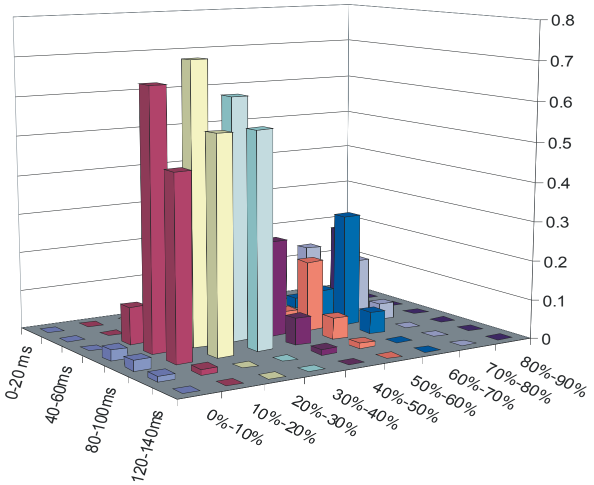
Several criteria can be used to decide when the convergence of the Monte Carlo simulation is achieved. For instance, the convergence can be determined by checking the error between a few points of the cumulative probability curve of all random variables against the theoretical values, or by checking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

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

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

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

- 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.

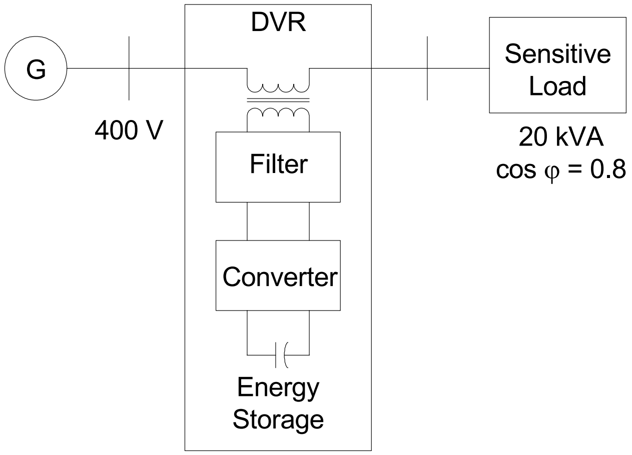
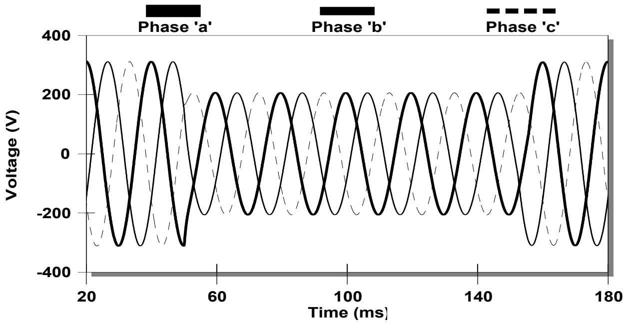
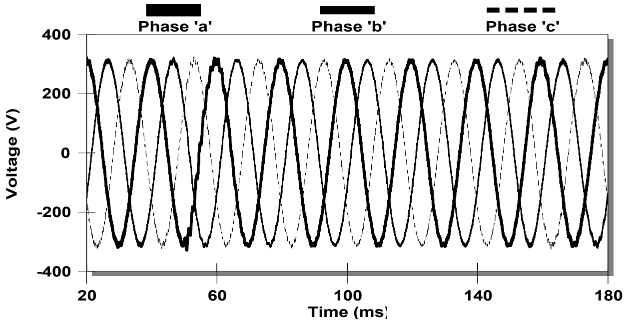


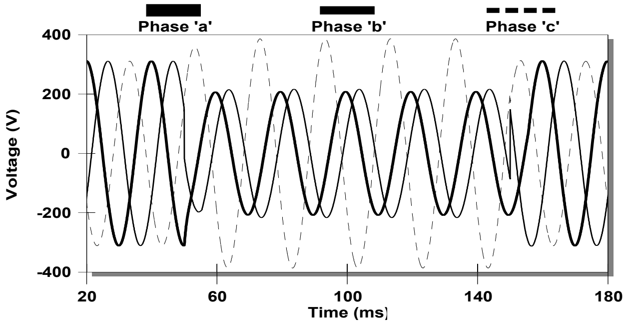
Fig. 6. Mitigation of voltage sags. Scheme of the test case



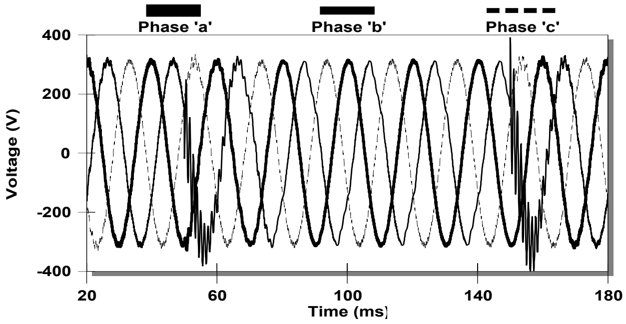
a) Case 1 : DVR input voltages



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.

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VIII. BIOGRAPHY

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