PQ-SMART™ – a simulation tool for power quality modelling and analysis

PQ-SMART™ is a power systems engineering tool which combines off-the-shelf software products in a way that makes it suitable for users with different technical backgrounds. The design philosophy behind PQ-SMART, which stands for Power Quality Simulation, Monitoring And Relay Testing, was to re-use software products already in existence and widely used within the ABB Group. This resulted in the choice of MATLAB, EMTP and the Windows-based PC platform. The tool is designed for use in the analysis and modelling of power quality problems in electricity grids.

While many user-friendly software tools are available today for scientific computing and power system simulation, there is still no tool that caters to the specific needs of power quality modelling and analysis. Such a tool must be easy to use and must generate time-domain waveforms similar to those recorded in the real world.

Power quality simulation at the present time

A variety of user-friendly software tools are available today for studying the steady-state behaviour of power networks in terms of their power quality. While they allow, for example, the magnitude of voltage sags to be studied, steady-state models are inadequate when it comes to determining the duration of the sags. The same is true when users want to include the behaviour of complex devices, such as arc furnaces, electric drives, surge arresters, etc, in the system model. Another deficiency of steady-state tools is that they do not allow the operation of protective and monitoring algorithms embedded in microprocessor-based devices to be verified or tested.

The ElectroMagnetic Transients Program (EMTP) is used extensively by power engineers to study the transient behaviour of electrical systems. A major problem with EMTP (and its variations), however, is that it is difficult and time consuming to set up a case. Even the task of modifying an existing file to generate new simulation cases requires some level of expertise. As a result, the EMTP development group (Development Coordination Group, or DCG), a consortium of utility and industrial organizations, is planning to make the EMTP more user-friendly by adding a graphic interface; however, this new feature has not yet been made available.

An alternative to EMTP is EMTDC, which uses similar computing methods but is accompanied by a graphic interface (PSCAD). The two software packages are not compatible as the input and output files from one tool cannot be processed by the other. Even though EMTDC is more recent and has some catching up to do in some areas of modelling and computing, its graphic interface has made it the natural choice for first-time users. Each tool comes with its own library of models representing basic power circuit components. The user chooses components, specifies their parameters and assembles them (via text lines for EMTP, and graphics for EMTDC) to build a system. The standard library is somewhat limited, yet sufficient for normal use. In cases of simulation involving more complex devices and/or devices which are still at the development stage, expertise is needed to build detailed circuits. In such situations, building a model is not simply a matter of piecing together existing blocks or routine coding of a set of mathematical equations; rather, the process requires an understanding of the physical device, ad-hoc methods of avoiding numerical instability, and particularly the time-consuming task of validating the model.

More generic simulation software packages, such as SPICE, SABER, and MATLAB (with its companion SIMULINK) can also be used for power system simulation. However, these tools are not tailor-made for power system models, and therefore the time needed to set up a realistic system makes them impractical.

The organizational perspective

At ABB, as in other large organizations, computer simulation and studies as well as product development are carried out on a

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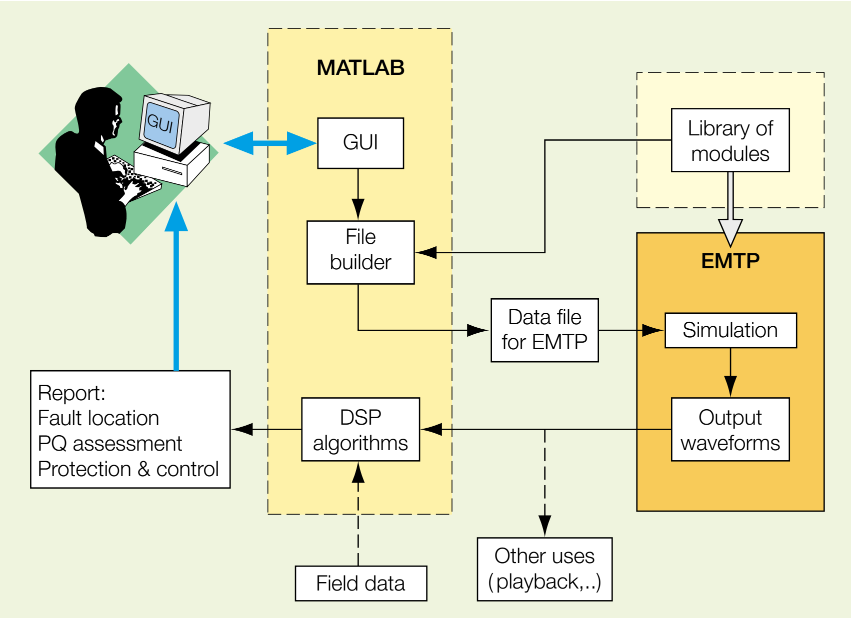


Architecture of PQ-SMART. The software tool combines the simulation and modelling capabilities of the ElectroMagnetic Transients Program (EMTP) and the data processing and analytical tools in MATLAB. **1**

DSP *Digital signal processing*

GUI *Graphic user interface*

large scale. A range of software tools is purchased, and essentially a different tool is used for each different activity. Engineers sometimes write new software codes if there is no suitable tool commercially available. The co-existence of many different tools is obviously a cost factor; this applies particularly to the maintenance of the different programs and the training of new users. Efforts are being made to reduce the number of software tools to a minimum. Although it is impractical to think in terms of a 'unified' tool capable of satisfying every engineer's needs, a tool that can cater to a large group of engineers is feasible.

Recognizing that EMTP has been the industry standard for over 20 years, and that significant and valuable work has already been carried out in the area of power system component modelling, a team at ABB decided to build a new simulation tool based on EMTP. The tool is designed to run on personal computers. Basically, it relies on an extensive library of EMTP modules, each module being a parameter-based description of a particular power system component (eg, transformer, load, motor and rectifier). This library represents the heart of the simulation tool, as it directly influences how realistic the simulation results will be.

Description and applications of the software tool

The software tool was originally intended to be used to simulate and analyze power quality in distribution systems. It has been named PQ-SMART, for Power Quality Simulation, Monitoring And Relay Testing. Unlike competing tools for power quality study that rely on steady-state methods, PQ-SMART allows simulation in the time domain.

The tool combines the simulation and modelling capabilities of EMTP with the data processing and analytical tools in MATLAB. Communication between EMTP and MATLAB is via the data input and output files **1**.

The three main elements of the tool are:

- EMTP model library
- MATLAB-based graphic user interface (GUI)
- MATLAB-based output post-processing/analysis facilities

Each element of the model library is represented graphically by a custom-designed icon. Using the computer's mouse, the user can assemble icons to build the single-line diagram of a power network. The program compiles the user's input and starts the simulation automatically. Retrieval of simulated waveforms (voltages and currents) is achieved by clicking on icons designated as 'sensors'.

A number of menus allow the user to apply power quality analysis functions to the observed waveforms. The list includes not only functions being used in the power quality field, but also new functions that have potential applications. Most importantly, the analysis package allows the user to 'plug and play' his own algorithms. This flexibility is of great value to the product development process because the engineer can quickly evaluate and fine-tune a particular algorithm.

PQ-SMART can also be used to support equipment testing – a procedure in which the simulated voltages and currents are sent to a test apparatus via power amplifiers. The user can run a large number of cases and evaluate the performance of the apparatus under simulated conditions. For example, a harmonic analyzer can be tested and its results compared with the output of the MATLAB-based routines.

In another application for PQ-SMART, its DSP package can be used to post-process recorded field data. In this case, the user bypasses the EMTP simulation and imports the data directly into MATLAB. The DSP package contains MATLAB's factory-built as well as user-written functions.

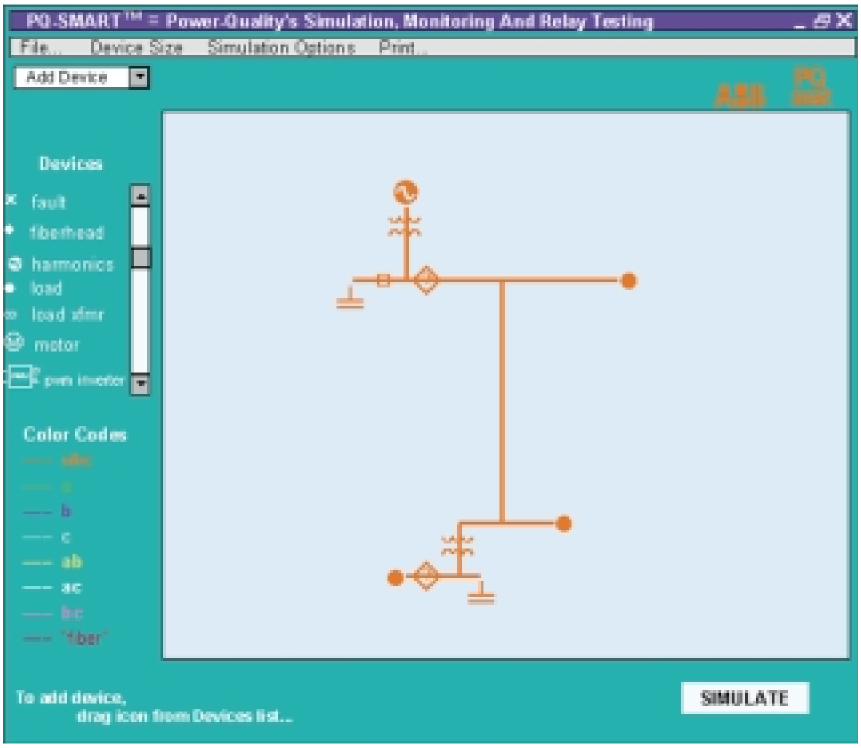
EMTP-based component library

The EMTP data module feature has been used extensively to simplify the use of the basic equipment models and to extend the modelling capabilities to more complex equipment models. The model library developed for this purpose relies heavily on the enhanced features of version 3.0 of EMTP (EMTP96).

The modules that have been developed to date include:

- Line models
- Transformer models
- Breaker/switch models
- Source/equivalent models
- Harmonic source and filter models
- Load models
- Protection models
- Power electronics models (rectifiers, inverters, etc)
- Sensor models
- Shunt and series capacitor bank models
- Fault models (impedance-based faults and arcing faults)

The component library is still growing. Every time a new module is needed, it is built, tested and validated by an EMTP expert. A written description of the module is prepared and stored in a database for future reference. By using a set of MATLAB-based programs, the design team can link this module to PQ-SMART.



Single-line system diagram via which the user interacts with PQ-SMART **2**

MATLAB-based graphic user interface

Interaction between the user and PQ-SMART is strictly via the graphic user interface, or GUI. The GUI consists of many windows, the main one being the single-line diagram. A simple example of a single-line diagram is shown in **2**. Colours are used to denote multi- and single-phase feeders (lines). The user can zoom in/out, draw and reshape lines, add or remove devices, etc.

To inspect, assign or change parameters of a particular component, the user double-clicks on the device icon. This action opens a parameter window belonging to the second level in the GUI hierarchy. The complexity of a parameter window varies from one component to another. For example, a capacitor bank is fairly simple (the parameters being the voltage and var ratings), and its window contains only 'edit' boxes which the user has to fill in. In contrast, a meaningful window for a rectifier requires the display of a detailed circuit with diodes, thyristors, resistors, etc. A complex window, for example, has several lower-level windows hidden beneath it, and can be opened one by one for parameter input.

The general appearance of each parameter window is fixed (ie, its appearance cannot be changed by the end-user) and is composed of a variety of graphic objects allowed by MATLAB. These graphic objects include `text`, `axes`, `line`, `menu`, and `uicontrol`. Sometimes 'special effects' are embedded to help the user visualize his actions. For example, the window for 'harmonic source' automatically computes and displays the injected current based on the harmonic amplitude and phase angles that the user specifies. In this way, the user can 'see' the injected waveform, and can make necessary adjustments before invoking the time-domain simulation.

MATLAB-based post-processor of signals

In addition to the EMTP library and the set of GUI windows, the tool contains utilities that allow post-processing of signals generated during an EMTP simulation. However, the post-processing feature is not restricted to EMTP-generated signals; field-recorded signals can also be processed after a data conversion.

With a double-click of the mouse button on a sensor icon, the voltages and currents recorded at the sensor's location are fetched and plotted on the screen. The user can zoom in on any portion of the waveform and apply a number of analysis functions to the displayed time window.

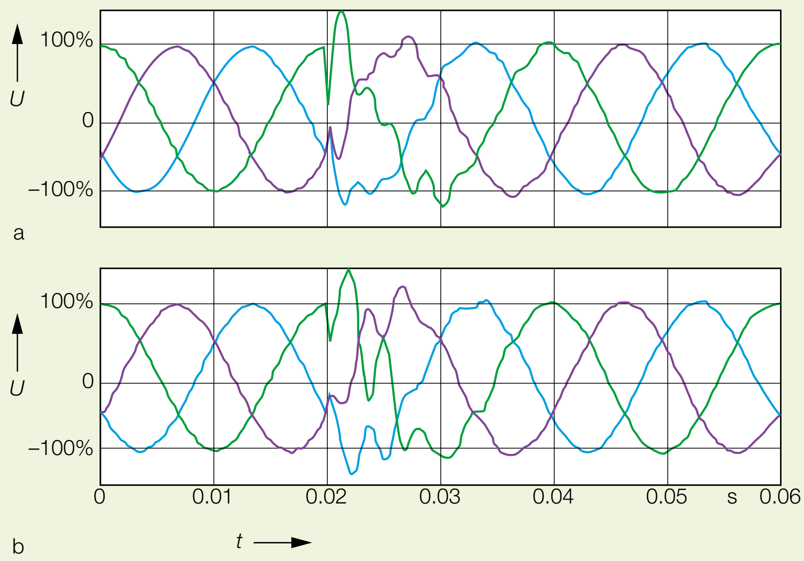
Power spectral density

This function employs the FFT (Fast Fourier Transform, a built-in MATLAB funtion) in the calculation of the power spectrum of the signal. The spectrum can be computed using all the data points, or just a selected window of data points; the choice is up to the user, who can zoom in or out of a section of the waveform.

The total harmonic distortion (THD) is also computed for each phase and displayed on the graph automatically:

$$\mathrm{THD} = \frac{\sqrt{A_2^2 + A_3^2 + \ldots + A_n^2}}{A_1} \qquad (1)$$

$A_{1\text{-}n}$ Harmonic amplitudes found by the FFT method



Magnification of capacitor-switching transients in the distribution network in **2** **3**

Voltage (U) on capacitor bus (a) and remote bus (b) when 3-MVA substation capacitor is switched on at time t = 0.02s

Voltage imbalance

The voltage imbalance (VI) is defined as the ratio between the negative- and positive-sequence voltages:

$$\mathrm{VI} = \left|\frac{\overline{V}_2}{\overline{V}_1}\right| = \left|\frac{\overline{V}_a + (\overline{V}_b \cdot 1\angle 240°) + (\overline{V}_c \cdot 1\angle 120°)}{\overline{V}_a + (\overline{V}_b \cdot 1\angle 120°) + (\overline{V}_c \cdot 1\angle 240°)}\right| \quad (2)$$

V_a, V_b, V_c Voltage phasors of the three phases a, b and c (the phase sequence is abc). The method for calculating the phasor based on data samples of the waveform is a standard one.

Voltage imbalance can be represented statistically in terms of cumulative probability and probability density. The cumulative $F(x)$ = Pr(VI ≤ x) refers to the percentage of observation time that the imbalance VI is below a given level x. The probability density function is $f(x) = dF/dx$.

Voltage sag/swell

Voltage sags and swells refer to rapid deviation of the voltage amplitude from its nominal value. A voltage is considered acceptable if its amplitude falls within a prescribed range.

The analysis function performs the following tasks in connection with voltage sag/swell:

- Tracking and displaying of the signal amplitude as a function of time.
- Sag level versus duration characteristic. Each point on the characteristic represents the magnitude of the sag and the time duration over which the magnitude stays below that level. Such a characteristic is superimposed on an industry standard such as CBEMA. If the sag level versus duration characteristic crosses the acceptable boundaries specified by the standard, then the underlying voltage disturbance can be declared as violating the standard; otherwise, the disturbance is tolerable.

'Test your own algorithm'

The analysis functions listed in the three preceding subsections are typical in a power quality assessment. However, there are situations in which the user wants to test his own functions or algorithms with the simulated waveform. The menu 'test your own algorithm' is designed to meet this need. Some familiarity with the MATLAB syntax is required. An example is given in the next section.

Case studies

Algorithm design and testing

In the case of digital relays, it is common practice for algorithms to first be coded in MATLAB, tested thoroughly and fine-tuned before being implemented on a hardware platform. When PQ-SMART was first conceived in 1996, a major goal was to support algorithm testing (therefore the name 'Relay Testing' in the acronym). To do this, the engineer first builds a power system, specifies disturbances and runs the simulation. Waveforms (voltages and currents) are then retrieved and monitored within so-called 'sensor' windows. A sensor window has a number of menus that allow the user to apply pre-coded analysis functions, such as those described in the previous section. One menu allows the user to 'plug and play' his own MATLAB codes. *Table 1* gives an example of a typical plug-and-play code. Generally, the first few lines (1 through 7) call the function `getWave` to retrieve the time, voltages and currents that are plotted in the sensor window. These data are then applied to a user-defined function, `calcPhasor`, which converts selected waveforms (v_a–v_b and i_a–i_b) into complex-valued phasor representation. Phasor calculations are based on sliding windows, and when there is a disturbance in the waveforms the output experiences a fluctuation. In the case of a short circuit, the DC component in the transients can produce erroneous phasor values and affect the operation of the impedance relays. In this example, the engineer has to design `calcPhasor` so that the output phasors reach their steady-state values as fast as possible. He can fine-tune the algorithm until a certain performance is reached. In the simple example shown (*Table 2*), the performance is evaluated visually by computing and plotting the apparent impedance z_{App}.

Magnification of capacitor-switching transients

Capacitor switching can produce transients and adversely affect the power quality in a network. It is not uncommon to find that transients generated at the switching site are less severe than those at a remote location. This phenomenon was publicized in the late 1980s and has become known as capacitor-switching transients magnification. The distribution network shown in **2** is used for demonstration. The 3-MVAr capacitor in the substation is switched in at time t = 0.02 s, and sensors record the voltages in the substation and at the remote bus. The simulated waveforms are shown in **3**, where the transients in the remote voltages are more severe than those in the voltages at the switching site. (The voltage levels are 13.8 kV and 400 V, respectively.) These waveforms can be further analyzed by applying selected MATLAB built-in functions, and its companion Signal Processing Toolbox.

Table 1
Example of algorithm design and testing.
`calcPhasor` **is the user-defined function under test.**

```
t     = getWave ('time');                  %  1
v_a   = getWave ('volt', 'a');             %  2
v_b   = getWave ('volt', 'b');             %  3
v_c   = getWave ('volt', 'c');             %  4
i_a   = getWave ('amp', 'a');              %  5
i_b   = getWave ('amp', 'b');              %  6
i_c   = getWave ('amp', 'c');              %  7
%                                          %  8
dt    = t(2)-t(1);                         %  9
V_ab  = calcPhasor(v_a-v_b,dt,60,1);       % 10
I_ab  = calcPhasor(i_a-i_b,dt,60,1);       % 11
z_App = V_ab/I_ab;                         % 12
figure;                                    % 13
plot(z_App)                                % 14
xlabel('R')                                % 15
ylabel('X')                                % 16
  % etc.
  % et cetera
```

Sag analysis

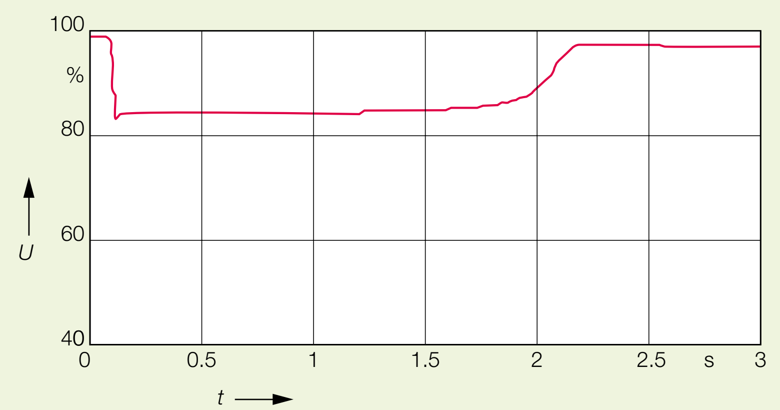
Voltage sags in a distribution network are typically caused by a short circuit (on a distribution feeder or in the transmission system), or by starting of a large motor. Steady-state analyses are commonly performed for voltage sags. While fast and capable of providing some insights, the steady-state approach inherently lacks the time dimension. Time-domain simulation using an EMTP-like computing engine can take into account the dynamics of network components, and therefore can produce the duration of voltage sags realistically. An example of voltage sag due to the starting of a motor is given in which the load at the remote bus **2** is replaced by an induction motor with a rating of 280 kW (375 HP), 480 V. The motor is turned on at time t = 0.1 s. The voltage waveform recorded at the nearby sensor is processed by a function in the PQ menu, which produces the rms profile shown in **4**. It is seen that the motor starting results in a sag to 85 % for about 2 seconds, before settling at a steady state of 98 % voltage. In the real world, such a long-duration voltage depression can cause electronic and computer-based equipment to fail.

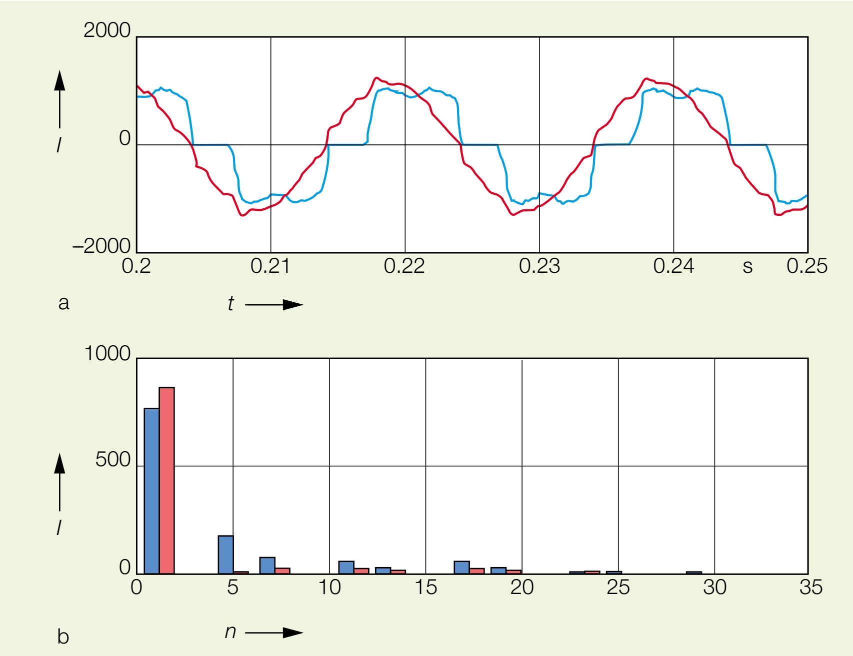
Harmonics and filters

Power electronics devices, such as rectifiers, are known for injecting harmonic currents into the power network. This is a power quality problem, and can be mitigated by the use of harmonic filters. The example illustrates the use of a passive filter installed at the problem site to compensate for the generated harmonics. When the load at the remote bus (480 V) **2** is replaced by a rectifier (three-phase, full-wave diode bridge), the phase current at its terminal would be a 6-pulse current waveform – the blue curve in **5a**. With a 300-kVAr filter tuned to the 4.8th harmonic (or 240 Hz), the harmonic contents of the net current are reduced. The spectral analysis shown in **5b** reveals that the THD in the current is reduced from 26 % to around 5.5 %.

Time-domain simulation of voltage sag due to a large motor starting **4**

U *Phase voltage (rms)*
t *Time*





Analyzing the effectiveness of a harmonic filter tuned to the 4.8th harmonic **5**

a *Current before filter (blue) and after filter (red)*
b *Spectral analysis, showing total harmonic distortion in current reduced from 26.4 % before filter (blue) to 5.5 % after filter (red). The large reduction in THD is due to the fact that the amplitude of the fundamental component increases, whereas all harmonic components decrease.*
I *Current in amperes*
n *Harmonic orders*

Concluding remarks

The design philosophy behind PQ-SMART was to re-use and combine off-the-shelf products already in existence and widely used within the company. This resulted in the choice of MATLAB, EMTP and the Windows-based PC platform.

As with any simulation software, simulated waveforms can only be realized through an elaborate library of components. Constructing a model for a new element is not a simple task, as it requires a thorough understanding of the actual physical device and the numerical methods, as well as many man-hours to validate the model. The choice of EMTP, as opposed to competing tools, was based on the fact that the EMTP engine is the most proven in the industry and, in particular, on the extensive library of components built in the past by the company's engineers. The shortcomings of EMTP are its input/output interface, but these are compensated for by MATLAB.

PQ-SMART became a fully functional package in 1996, after five man-months of development. The casual user does not have to learn MATLAB or EMTP in order to generate complex waveforms. PQ-SMART has a structure which allows the design team to add new equipment models as they become available.

In addition to power quality analysis and algorithm testing, the package has other important applications. System study engineers have access to a wide variety of system components, and are relieved of the laborious task of having to make and modify systems. Sales representatives can run the tool from a laptop computer to demonstrate to their customers the operation and benefit of an item of equipment.

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