

Parametric Study, an Enhanced Methodology for analyzing Power System Contingencies

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Abstract--This paper presents the application of a parametric study to simulate and analyze transient phenomena that occur on the power network. These phenomena have a random nature in their location and duration. In addition, the model parameters of the network are not known with certainty. A parametric analysis allows the user to simulate multiple network configurations from the same base case, apply contingencies, change the location and time of fault applications to cover different disturbances that can occur in all possible operations of existing and future power networks in order to determine statistically the constraints to which the equipment is subjected. Thus, parametric analysis allows for greater accuracy in the analysis of equipment constraints and better risk management in the specification of the requirements, resulting in a significant cost optimization. A methodology and a parametric tool developed in the EMTP-RV environment is also presented.

Keywords: EMTP, Parametric studies, Optimization, Parallel simulations, Statistics, Impedance locus, Contingencies, Democratization of "Batch simulation", Efficient tool

I. INTRODUCTION

Parametric studies play an important role in the development and design of an equipment deployment project on the electric grid. They can simulate a large number of cases for studying contingency scenarios and their effect on the grid. Changes in a base case can affect both the parameters of EMTP elements and the network topology by including and excluding certain items or changing connections. Statistical-analysis modules included in the electromagnetic transient software are part of parametric studies. They are designed traditionally to generate random switching timings for estimating the worst overvoltage conditions, for example. A set of defined parameters may be disturbed using specific rules of random numbers to perform parametric studies where simulations are executed for each set of parameters to present an ensemble of results subjected to various analysis options and optimizations [1, 2, 3].

This paper describes the application of a parametric study to simulate and analyze transient phenomena that occur on the power network. These phenomena have a random nature in their location and duration. Furthermore, the model parameters of the network are not known with certainty. A parametric analysis allows the user to simulate multiple network configurations from the same base case, apply contingencies, change the position and time of fault

applications to cover different disturbances that can occur in all possible operations of existing and future power systems in order to determine statistically the constraints to which the equipment is subject. Thus, parametric analysis produces greater accuracy in the analysis of constraints that the equipment undergoes and a possible reduction in the equipment requirements and specifications. Since it is simple to re-run all the modification sets using a new base case, it is also a powerful time-saving tool, especially in planning when future networks are subject to change.

This paper presents a methodology and a parametric tool developed in the EMTP-RV environment that allows the user to automatically change the parameters or values of network elements or apply contingency scenarios by changing the network topology (connection change between elements) and by applying changes to the network status (insertion/deletion of elements). In order to respond to the network planner developing the strategic studies, the tool has to be able to launch thousands of simulations of a very large network in order to capture the transient phenomena in the most realistic situation. To meet this requirement efficiently, the tool was designed to exploit the parallel architecture of the modern computer and developed in a 64-bit mode to handle the large number of results generated. Analysis tools are also developed to facilitate data mining of the results that can bring to light some of the network behaviors not easy to detect. In this paper, the tool is applied to the study of harmonic distortion in the power network. The harmonic impedance loci describe the frequency behavior of the network under different operating conditions. This data is provided by utilities to their industrial customers and manufacturers enabling them to perform harmonic studies in order to demonstrate that the installations meet the harmonic emission limits imposed by the utilities and to design filters if required.

To enable an adequate design of third-party facilities, a large number of simulations need to be performed. The proposed tool therefore provides the user with the option to sweep a range of frequencies around those of interest in order to consider the uncertainty about the value of elements such as temperature variation, tap changer position, or aging of components. For example, optimization of the design of harmonic filters in an HVDC installation has to consider up to a few thousand configurations in order to represent all the topologies (possibility of switching capacitors in the surrounding area, different load scenarios, contingencies, etc.).

This new tool is a major improvement to the existing EMT simulation environment in terms of democratization of batch simulations. It is easy to use, very intuitive and does not require any special software skills from the end users, i.e. no code-writing is required. Sensitivity and contingency studies,

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or even a combination of both, are done through a graphic user interface. Results of batch simulations can be plotted on a desired graph by the user and the tool has a good response up to millions of points. Users can then easily identify the limit scenarios by inspecting the displayed results; a simple mouse-click on the worst curve will identify all the details of the corresponding scenario. The main goal is to take care of the software issues and leave the end-user to concentrate on the design engineering.

II. SOFTWARE ARCHITECTURE

The simulation environment formed by the graphical user interfaces (GUIs) EMTPWorks and EMTP-RV establishes a higher level of capabilities in the simulation of large-scale electrical networks. It is possible to design, simulate and rapidly visualize large complex systems reducing the engineering and development time and allowing more detailed studies of the complex phenomena of power system transients.

EMTPWorks is designed to efficiently create and maintain small circuits as well as very large-scale networks. It has an open architecture for maximized user configurability from basic user-defined model assemblies to more advanced script-based programming. EMTPWorks offers script methods for simple data management tasks to more advanced object attribute settings, library functions and network device symbol redrawing and updating. The data for each device is specified using the HTML web interface. Device data web pages can reside on the user's computer or anywhere on the web. The script source code of all device data management functions is available to the user. EMTPWorks has automatic subcircuit creation methods with unlimited levels of hierarchy. Subcircuit masking options can accommodate user programming from simple data statements to more complex scripts and data capture panels. Scripts can be also used to launch calls to ActiveX objects or to programs created in other environments.

Parametric Studio is grafted onto the EMTPWorks/EMTP-RV simulation environment. It interacts with the EMTPWorks script engine through COM (Component Object Model) calls in order to apply the modification for each scenario. The scenarios are later simulated in parallel using the EMTP-RV engine.

Figure 1 presents the general architecture of the parametric studio. The main module "Parametric Studio" **1** allows the user to define and launch parametric studies using EMTPWorks while the main graphical window makes it possible to:

- Select a base case
- Define contingency scenarios to be applied to the base case (parametric variations: data, connections and status changes)
- Generate the scenario files using EMTPWorks services
- Submit the generated scenarios to the simulation launcher

Parametric Studio interacts with EMTPWorks **2** using

COM services to provide access to all the network devices, signals and connections defined in EMTPWorks. The user starts by selecting the devices to which the parametric variations have to apply. Once all the scenarios are defined, Parametric Studio uses the COM services to generate the netlist files. Those files are submitted to the Parametric Study Launcher **3** to be sequenced in the queue of the parallel process. Each netlist file is then launched using parallel threads for the EMTP-RV engine **4**. The parallel threads extract the simulation results and perform statistical analyses for different variables (max., min., abs., etc.).

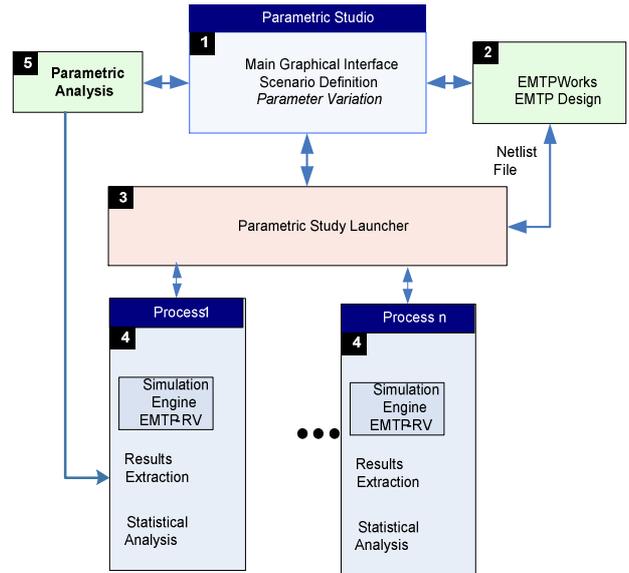


Fig. 1 Parametric Studio Architecture

The Parametric Studio software can perform any type of parametric-study variation: data, connection and status, and the user may define multiple nesting levels of those variations.

The four types of EMTP study, namely steady-state, load-flow, transient and frequency scan, that do not require elaborate post-processing can be defined using the basic elements provided by the GUI.

Specialized studies such as harmonic analysis, TTR studies, etc. will also be performed. These particular studies use the results generated from the different simulations and are performed using the Parametric Analysis tool **5**. Local and global processing, as well as the generation of graphs and reports, are predefined for these specialized studies.

III. PARALLEL SIMULATION ENVIRONMENT

The traditional parametric and statistical studies performed using off-line simulation tools [4, 5] are mainly sequential and do not benefit from the number of cores available nowadays. Performing parametric studies with real-time simulators [6, 7] use a different paradigm based on the fact that real-time simulation can run continuously for a long period. Thus the different variation scenarios are applied successively using the same setup. The user has to ensure that the simulation reaches the steady-state regime before launching a new scenario.

Parametric Studio was developed using the .Net framework and thus uses the latest parallel technologies available to launch the simulation and treat the results in Parallel using the concept of Task provided in the parallel Task Parallel Library (TPL). The TPL scales the degree of concurrency dynamically to make the most efficient use of all the processors that are available. In addition, the TPL handles the partitioning of the work, the scheduling of threads on the ThreadPool, cancellation support, state management, and other low-level details [8, 9]. This makes it possible to write a robust code giving the users the ability to control the number of threads to be used, start jobs in parallel and safely interrupt and cancel their jobs.

As much as launching all the scenarios in parallel is quite challenging, treating the results and presenting useful information to the user is equally challenging. In order to treat the large amount of data provided from the multiple simulation, the Parametric Analysis tool provides a powerful means of visualization based on the Arction LightningChart visualization package [10]. This package provides a full 64-bit support that smoothly renders the huge amount (several millions) of data obtained from the multiple scenarios, and remains very responsive to user interaction, zooming, panning and resizing.

IV. PRACTICAL SIMULATION CASES

The Parametric Studio software can perform any type of parametric study. Generic studies such as steady-state, load-flow, transient and frequency scans can be performed. The post-processing tools provided with the software allow extraction of the output signals and provide some post- and global processing to establish some performance criteria.

Specialized studies such as Harmonic Analysis, TTR, etc. can also be performed. These studies require special analysis, available in the Parametric Analysis tool, which allows definition of the root loci for harmonic analysis studies, for example, calculation of the energy consumed by the arresters, etc. Local and global processing, as well as the generation of graphs and automatized reports, are predefined for these specialized studies.

A. Steady-state

This case uses Parametric Studio to simulate and study the influence of the inter-circuit mutual coupling of a double-circuit line and the errors for single-phase and three-phase short circuits introduced in distance protection measurements when the two circuits are connected in parallel. Distance relay impedance measurements are based on the following equations [11]:

$$Z_{phase} = \frac{V_{phase}}{(I_{phase} + 3K_0I_0)} \quad (1)$$

where

$$I_0 = 3 * (I_a + I_b + I_c) \quad (2)$$

is the zero-sequence current and

$$K_0 = \frac{1}{3} * (Z_0/Z_1 - 1) \quad (3)$$

is the residual compensation signal for ground fault measuring elements which take into account the difference between the zero- and positive-sequence impedances.

Figure 2 shows a ground fault on a double-circuit transmission line interconnected at both ends. The total current in the fault is subdivided between the two lines, giving an induced voltage in one circuit due to the mutual sequence current flow in the adjacent circuit. This will affect the behavior of the distance relay and introduce a distance measurement error and since the two lines act as current divider.

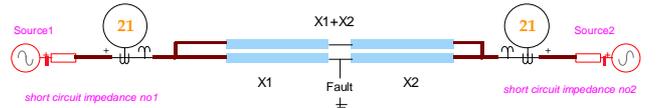


Fig. 2 Ground fault on a double-circuit line.

For a double line and if the fault is in the middle of the line, the relay on the left side is supposed to measure the fault at $0.5 * X_1$ but the actual impedance excluding the source impedance will be

$$Z_{fault} = X_1 * \frac{(X_1 + 2X_2)}{2 * (X_1 + X_2)} \quad (4)$$

and at the mid line, $X_1 = X_2$,

$$Z_{fault} = \frac{3}{4} * X_1 \quad (5)$$

To study the impact of this error, a parametric study is performed in steady-state and the fault location is varied from one extremity of the line to the other with a 2% increment, creating 50 scenarios in total. Parametric Studio extracts the magnitude and phase result of the voltage, the current and the transmitted power for all the scenarios and provides a csv export for further treatment and calculation of the line impedance.

Figure 3 shows the impedance seen by the distance relays at both ends, 1 and 2. The two straight lines represent the ideal linear impedance when source 1 has an impedance of 1000 MVA and source 2 has an impedance of 5000 MVA. The double-circuit line is 50 km long with the following sequence impedances: $X_1 = 0.374 \Omega/km$, $X_0 = 1.32 \Omega/km$ and $X_{0m} = 0.83 \Omega/km$.

It is clear from Figure 3 that the error introduced in the measurement of the impedance and, thus, the distance has a definite impact on the relay operation. For example, if the relay is set to cover 80% of the line, the impedance at that distance is 8Ω but, when the fault occurs, the distance covered by the 8Ω is only 40% of the line distance.

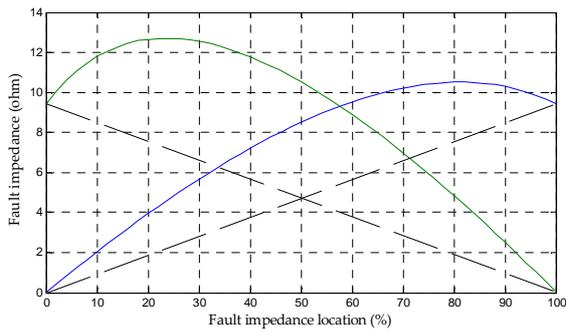


Fig. 3 Impedance viewed by the relays. No jumper.

To mitigate this problem, reference [11] proposes a parallel-line compensation scheme which will eliminate the error only on the faulted circuit (lower circuit in Fig. 2). The permanent solution consists in adding jumpers between the lines at the maximum-error locations. This is an iterative process which consists in repeating the parametric scenarios with the modified circuit. The best solution in this case requires three jumpers which minimize the error to acceptable levels, as shown in Figure 4.

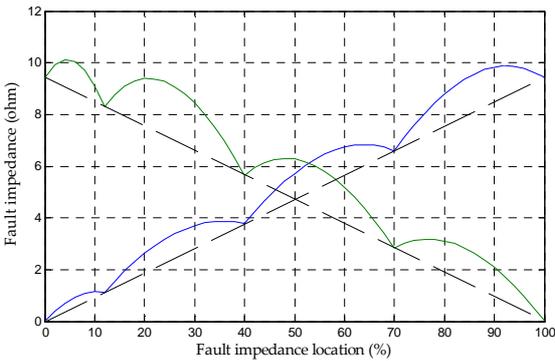


Fig. 4 Impedance view by the relays using three jumpers

For a single fault and with similar jumper locations, the zero-sequence current expressed with the $3K_0I_0$ term introduces another error, as shown in Figure 5.

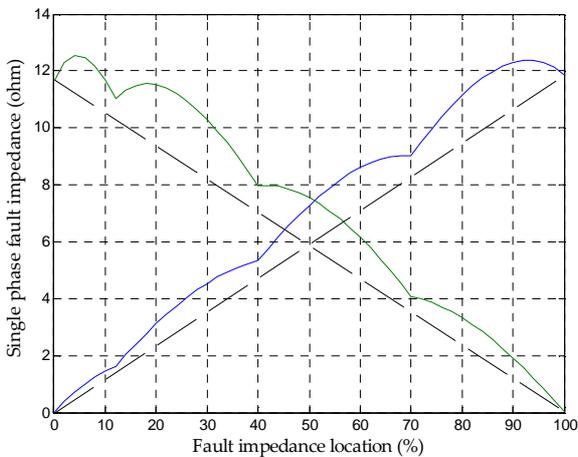


Fig. 5 Impedance of single-phase fault viewed by the relays using three jumpers

B. Time domain

The next example demonstrates the use of Parametric Studio to study an auto-excitation case on the test circuit of Figure 6.

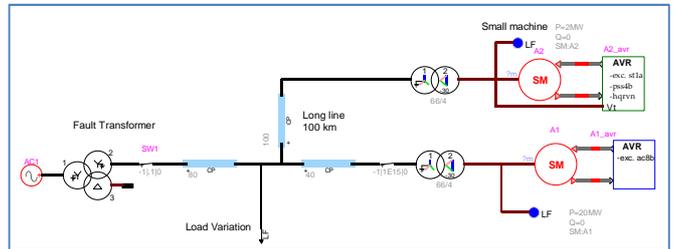


Fig. 6 Auto-excitation circuit test

Auto-excitation occurs when a fault appears at the transformer end. After clearing the fault, the energy trapped in the 100-km line will auto-excite the small machine (4 MVA) that is connected. If the field current reaches zero, the 60-Hz resonance between the capacitance of the line and the reactance of the machine could become uncontrollable and the voltage level could go beyond 2 p.u. Other parameters have to be assessed in this type of study: the variation of the excitation system response and the load variation connected to the line. Figure 7 represents the sensitivity of the field current when the load connected to the long line varies from 0 MW to 5 MW. In this case, the auto-excitation appears when the load is less than 2 MW. To eliminate this problem, it is necessary to order the dismantling of the network by opening first the breaker of the machine and then the breaker of the faulted transformer.

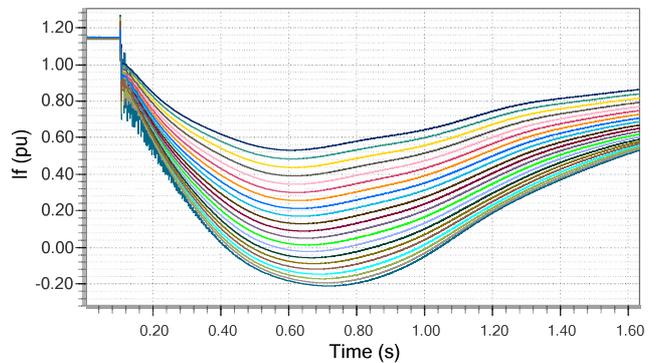


Fig. 7 Field current of the machine for 21 load values from 0 to 5 MW

C. Frequency Domain

The impedance locus can quickly become complex when located near a few capacitor banks, many filter configurations of an HVDC link and several line topologies (and length). The following example is based on an industrial customer with a point of common coupling (PCC) fed by two transformers close to all the independent switching possibilities of previously mentioned components (capacitor banks, filters, lines). The combination of all those elements, as well as load variations and uncertain future customers in the surrounding area, made the number of network configurations to consider

enormous for manual processing. (Manual processing also increases the risk of error).

The simplified schematic in Figure 8 represents the main network components and the numbers in parentheses represent the different possibilities: main power supply transformer(s) {2}, filter configurations based on the number of HVDC converters and transmitted power {8}, capacitor banks in substation 1 {4}, transformer contingency in substation 1 {2}, capacitor banks in substation 2 {3}, transformer contingency in substation 2 {2}, possible configurations of the two double-circuit lines {5}, different line lengths to connect this industrial customer {2}. The total number of scenarios is $2*8*4*2*3*2*5*2 = 7680$.

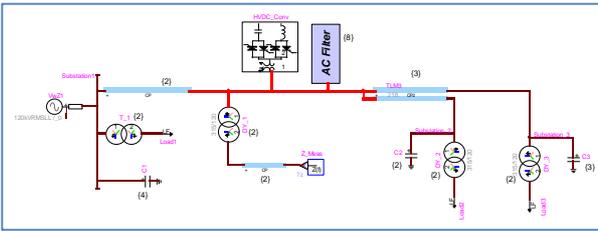


Fig. 8 Simplified circuit for the frequency scan example

The figures below (Figures 9-11) represent the frequency scan of all the cases simulated as well as the network harmonic impedance envelopes as defined by CIGRE standards [12][13]. Reference [13] recommends that, with the advent of advanced design software and study techniques, the customer should not feel constrained to specific envelopes of a relatively simple shape such as circles, arcs, sectors... as done traditionally but should specify any shape that avoids the inclusion of non-relevant points (e.g. discrete polygons). The Parametric Analysis tool implements an advanced version of the Chan Convex Hull algorithm [14, 15] able to process millions of points and compute such enclosing polygon in an acceptable time. The use of such envelope diagrams enables simplification of the a.c. filter design process and also provides a degree of conservatism in the design. Note that the example of the 5th harmonic's polygon includes a frequency sweep of $\pm 7\%$ in order to take into account any uncertainties in the models used. As seen in Figure 5, the user can add a polygon (convex hull) and/or sector on the graph to encircle all the plotted impedances and export the summarized results for further harmonic studies.

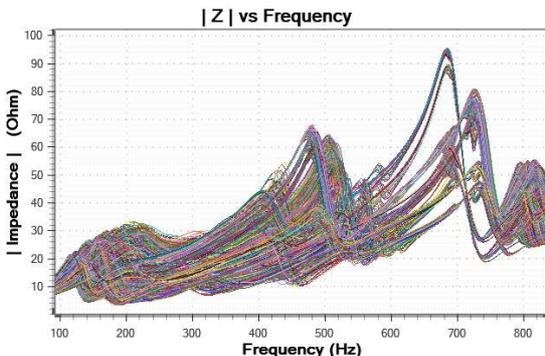


Fig. 9 Magnitude of the multiple scenarios

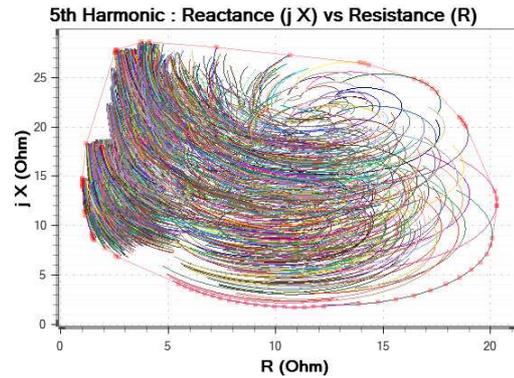


Fig. 10 Example of 5th harmonic polygon

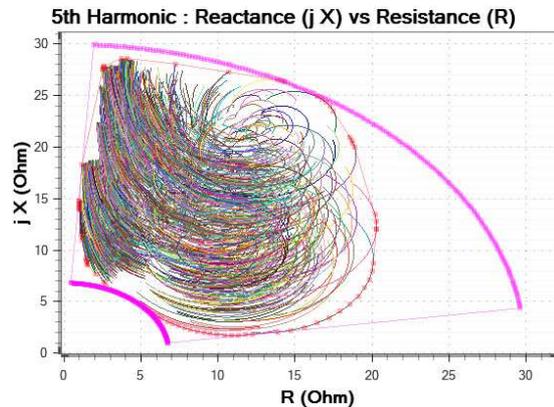


Fig. 11 Example of 5th harmonic polygon and sector

V. CONCLUSIONS

This paper introduces a new tool for performing parametric studies using a well-known transient simulator, EMTP-RV. The structure of the Parametric Studio tool is presented. It contains a module that allows the user to define the variations to apply to the circuit components. This includes data variations, connection variations and inclusion/exclusion status. Parametric Studio allows the user to simulate multiple scenarios in parallel and explore the results with the parametric analysis module.

The purpose of this program is to help the user to study, simulate and analyze transient phenomena that occur on the power network. These phenomena are random in their location and duration while the model parameters of the network are not known with certainty.

Three different study cases are presented which demonstrate different uses of the parametric studies in the main area of the transient simulation type of studies, namely steady-state and load flow, time domain and frequency scan. Treatment of the large amount of generated results allows useful results to be obtained from the analysis of the different contingencies, thereby helping the study engineer to identify all the uncertainties in the network and therefore make better decisions.

Parametric studies will open up a new era in the area of transient studies and ensure better understanding of the uncertainties when severe events occur on the network.

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