Transient Testing of Protection Relays: Results, Methodology and Tools

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***Abstract* – The paper presents a new approach to application testing of protective relays. The approach utilizes a test methodology based on the use of transients. The paper outlines examples of test results that can be obtained using the new test methodology for assessing important application features of protective relays such as the response time and trip selectivity. Assessing these features may be extremely important for troubleshooting relay misoperations, adjusting relay settings, or when purchasing new relays. The paper also discusses the requirements for the testing tools to be used. For this particular methodology, a new testing tool called Batch Generator has been developed for the purpose of automating not only the process of testing, but the process of creating test cases as well. The need for selecting suitable commercial testing tools and using the newly developed tool - batch generator are given at the end.**

Keywords – electromagnetic transients, application testing, automated testing, protective relays, digital simulators

I. INTRODUCTION

Traditional testing of protection relay includes the use of phasors to calibrate the relay settings and evaluate the operating characteristics [1]. This practice is widely spread and is performed in the field using portable test sets. A variation of this technique is the dynamic testing approach were the inputs are still the phasors but they are artificially changed from pre-fault to postfault values. This enables evaluation of some relay designs whose operating characteristic is dynamically expanding as a result of the input phasor change [2]. Most of mentioned tests are performed in order to evaluate basic design characteristics of the relay, which are assessed using phasors and not transients.

A different type of test is needed when the application properties such as the response time and selectivity are to be evaluated. In order to assess relay performance under actual fault conditions, the test equipment has to generate fault transients that closely resemble actual transients occurring in the field. This type of test is typically needed when troubleshooting relay miss-operation or when evaluating a new relay for a purchase [3]. This type of test is not well defined and there is no wide understanding of the methodology that may be used to perform such tests.

This paper addresses two important issues: what is the methodology that should be used when performing transient tests and what kind of results may be obtained [4]. Even though some of the theoretical background for the relay algorithm behavior under transients was discussed in the literature before [5], detailed assessment of the actual relays when subjected to transients was not widely reported. The background and examples of testing relays with transients are presented first, which enables identifying methodology and requirements. Next, a simulator system that conforms to the outlined requirements and has been implemented in the CenterPoint Energy's test lab is described. Special attention is placed on the selection of the software tools that enable modeling and simulating the power system faults as well as techniques for replaying and injecting the test waveforms.

II. BACKGROUND

The relay behavior can be analyzed in the context of various influential factors: power network applications, fault characteristics, relay algorithms, etc. The analysis reveals that the relay behavior can be considered as either predictive or random [4].

To evaluate predictive behavior, steady-state phasor-based methods are used. By applying the input signals that are ideal sine functions, the relay algorithms have a predictive behavior. The operating characteristic of the relay can be obtained by recording the operating points and used for comparing the measured and theoretical operating characteristic to assess relay's behavior. This type of testing is called design testing [1].

Random behavior of the relay is related to transients that occur in real power systems. When applying input signals with transients, the relay behavior may not match the one observed for phasor-based test waveforms. In particular, the relay response and the operating time are variable depending on the content of fault transients. Measuring the direct-trip time and determining if the relay should have tripped constitutes the assessment approach in this case. This type of testing is called application or transient testing [3].

Most vendors of the relay test equipment offer computer-based test sets capable of performing steady-state phasor-based tests. Many of the test sets also provide capability for dynamic phasor testing and some include rudimentary transient testing capabilities. Test equipment fully capable of transient testing is rather rare and expensive especially in the case of the real-time simulators [6,7].

III. APPLICATION TESTING: EXAMPLES

Various requirements for application testing of protective relays using transients can be presented trough illustrative examples discussed in the following subsections.

A. Example I - Statistical Approach, Operating Time

An example of results that can be obtained by executing application testing on one transmission line relay using transients is given in Table I [3]. In this example, different test cases were simulated for different type of faults, and for different fault locations on the line. The relay in question is a distance relay set at 85% for Zone I direct trip operation. Each test waveform was repeated 30 times, and statistical formulae were used for determining operating times for the tested relay. One can notice very interesting results showing differences in operating times for various types of fault as well as differences between maximal and minimal operating time for the same fault case repeated many times.

Applying the steady-state phasor-based methods cannot enable recognizing and assessing this interesting feature. It requires a statistical approach, using multiple-run testing with transients and ability to generate and replay a large number of different test cases, to meet this very important requirement.

Table I Example of Statistical testing

Type	Loc %	No. T	AvrgT [ms]	MaxT [ms]	MinT [ms]	Devtn [ms]
A-G	50	30	20.68	23.12	17.94	1.49
A-G	75	30	22.75	25.04	20.34	1.48
A-G	80	30	25.67	41.72	23.62	3.17
A-G	90	0	*****	*****	*****	****
A-G	95	0	*****	*****	*****	****
B-C	50	30	20.57	22.90	18.46	1.36
B-C	75	30	26.04	28.50	23.66	1.44
B-C	80	30	35.23	66.26	25.02	12.36
B-C	90	0	*****	*****	*****	*****
B-C	95	0	*****	*****	*****	*****
ABC	50	30	19.21	20.44	18.34	0.61
ABC	75	30	24.68	25.40	23.68	0.54
ABC	80	30	25.63	27.24	24.26	0.81
ABC	90	0	*****	*****	*****	****
ABC	95	0	*****	*****	*****	****
BCG	50	30	20.27	23.06	17.98	1.45
BCG	75	30	26.10	28.58	23.66	1.47
BCG	80	30	34.53	66.18	24.86	12.28
BCG	90	0	*****	*****	*****	*****
BCG	95	0	*****	*****	*****	*****

B. Example II – Comparative Analysis, Operating Time

Another example of results obtained by application testing is given in Fig. 1 [3]. The figure depicts a comparative analysis of operating times vs. fault location for four different distance relays. Operating times shown in the Fig. 1. are obtained statistically, after large number of test cases were repeated. Relays were expected to operate in Zone I (all faults located in first 85% of the line). An interesting outcome was that the operating time, for some relays, became much longer than it was expected for the first zone. Such testing also requires multiple-run testing and ability to generate large number of different test cases.

C. Example III – Trip/No Trip Evaluation

In the third example, an evaluation of relay trip/no trip operation has been done for five distance relays (Table II). Relays were tested with transients corresponding to different types of faults and different fault locations. Relays were expected to operate only in cases when the fault location was inside first 85% of the line (Zone I operation).

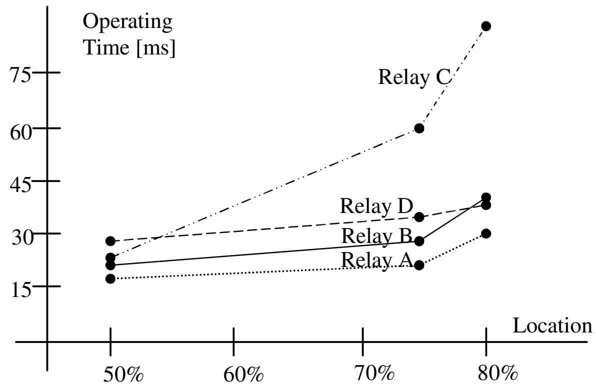

Fig. 1. Example of Comparative Analysis

As it can be seen in Table II, the relay B did trip for transients corresponding to faults located out of the Zone I of protection even though no operation was expected for the faults outside Zone I. In one case, this relay even misoperated for every single test run (ABC 90%).

As in previous two examples, to evaluate features such a trip/no trip response, one needs to use multiple-run tests with transients. An important requirement is to be able generate a large number of different test cases by taking into account several parameters that describe faulted conditions.

Table II Number of Trips out of 30 Tests

Fault Type & Locations	Relay A	Relay B	Relay C	Relay D*	Relay E*
A-G 50%	30	30	30	0	0
A-G 75%	30	30	30	0	0
A-G 80%	30	30	30	0	0
A-G 90%	0	**20**	0	0	0
A-G 95%	0	**19**	0	0	0
BC 50%	30	30	30	30	30
BC 75%	30	30	30	30	30
BC 80%	30	30	30	30	30
BC 90%	0	**12**	0	0	0
BC 95%	0	0	0	0	0
ABC 50%	30	30	30	30	30
ABC 75%	30	30	30	30	30
ABC 80%	30	30	30	30	30
ABC 90%	0	**30**	0	0	0
ABC 95%	0	0	0	0	0
BC-G 50%	30	30	30	30	30
BC-G 75%	30	30	30	30	30
BC-G 80%	30	30	30	30	30
BC-G 90%	0	**14**	0	0	0
BC-G 95%	0	0	0	0	0

* Relays D and E did not have a ground-protection element

D. Example IV – Filter Evaluation

An evaluation of analog input signal filtering implemented in a tested relay is shown in Fig. 2. This particular application assumed a presence of higher harmonics. The figure depicts a percentage of the levels for each harmonics that went through the analog input filters and affected the measurement. For this particular application, the voltage differential relay was unusable since the presence of harmonics affected the measurement so much that the relay was tripping even when there was no difference in the amplitudes of fundamental components. The desired filtering characteristics shows that for the particular application the relay needs around four times higher harmonic suppression to be able to operate correctly. The desired filtering characteristics was obtained from harmonic levels calculated during the short-circuit analysis.

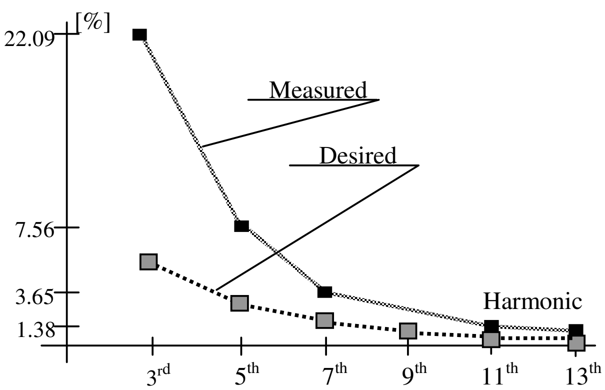

Fig. 2. Example of Assessing Input Filters

It is not hard to imagine that several other interesting performance features could be identified, measured, and compared if more different cases, with variation of additional parameters (for example, varying fault incidence angle and fault resistance) were generated.

III. Methodology and Requirements

A. Methodology

Application testing is based on the use of transients for testing protective relays in order to simulate the behavior of the power network during the faulted conditions. Generally, there are two ways of creating tests for transient testing of protective relays: using transients obtained from recorded waveforms or generating transients by simulation.

In the case of a purchase of new relays, one can use test cases to assess several parameters to compare the results, and to narrow the choices for the final decision. One example would be studying trip/no trip operations under various conditions. Typically, for these cases, application testing is done using transients obtained trough simulation.

In the case of troubleshooting miss-operation, testing starts with transients recorded by digital fault recorders (DFRs) at the time when relay miss-operated. More comprehensive troubleshooting requires additional test cases generated by simulation where transients are obtained by varying parameters of the original fault.

In both cases, to develop and implement methodology for application testing using transients, it is required that the chosen methodology utilizes automated means of performing multiple-run testing as well as generating a large number of different test cases.

To meet the requirements, a system for testing should provide means to automatically perform tests, obtain the results, and generate and archive test reports.

B. Software and Hardware Requirements

The requirements for the simulator system for application testing with transients are summarized below:

- Possibility to import waveforms with native file formats for different types of recording devices.
- Availability of several signal-editing features to enable customizing replaying of prerecorded transients.
- Flexibility of utilizing customized interface for simulation tools such as ATP [8,9].
- Possibility to generate the tests automatically by utilizing simulation tools.
- Capability to perform automated transient testing.
- Ability to create test reports automatically.
- Capability for high-performance waveform reconstruction with respect to D/A resolution and sampling rate.
- Possibility to use high power voltage and current amplifiers.

IV Simulator System for Application Testing

The architecture of a simulator system, which meets above-mentioned requirements for application testing with transients, implemented at CenterPoint Energy's testing lab, is shown in Fig. 3.

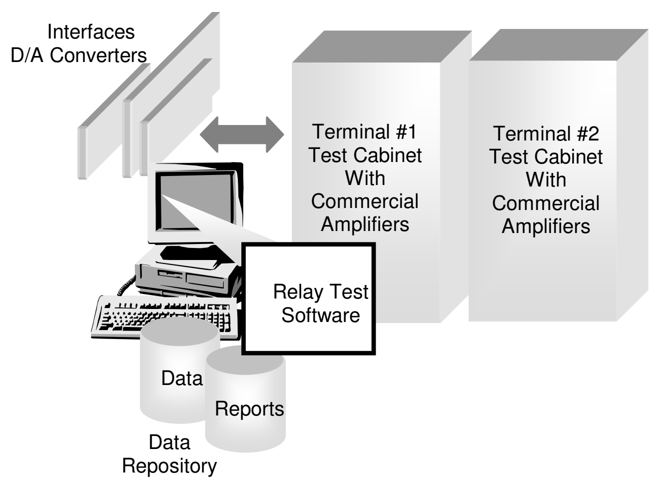

Fig. 3. The architecture of a PC-based open-loop simulator

This test system is a personal computer (PC) based open-loop simulator [10]. The PC platform was selected due to cost-benefit considerations. This simulator hardware can be upgraded to three terminals.

This simulator used for application testing is able to utilize both recorded (obtained from DFRs) and simulated (obtained from EMTP/ATP) waveforms. A user-friendly GUI with signal editing features for waveform processing, and test results visualization is provided. The integration with transient simulation programs was supported by presence of several importing/exporting file filters.

The selected and implemented hardware configuration, based on a custom communication interface and 16-bit D/A conversion is flexible in meeting the application testing requirements. Higher D/A resolution, with a possibility of selecting different sampling frequencies up to 40kHz, enables reproducing transients more accurately. The high-fidelity power amplifiers utilized enable accurate replaying of a wider spectrum of simulated waveforms. This configuration is ideal for test laboratory use, and, all the generated waveforms can be replayed in the field using standard test sets.

V. Selection of Software Testing Tools

Efficient testing requires software tools designed or customized for automated testing. The most important automation aspects are: test preparation, test execution, result collection, result processing and result reporting. These requirements are aimed at reducing the time and cost of testing, while increasing the accuracy and reliability of test results.

Automating the test result reporting is very important aspect of testing. Both collection of relay responses and test report generation must be automated. After collecting the relay responses, the following information must be recorded: relay response (trip/no trip), relay trip time and relay zone of operation. The test report should also include scenario data, test data and relay data. Finally, performance indices such as the number of failures, the number of missoperations and the operating time should be calculated and included.

The relay test software implemented at CenterPoint Energy's testing lab conforms to above mentioned requirements and consists of four modules : 1) import filters for reading several waveform file formats (COMTRADE [11], ATP, native DFR) and creating arbitrary test waveforms; 2) waveform processing and editing (cut/paste, copy, crop, insert, rescale, resample, invert, pre- and post-fault extension etc.); 3) user-friendly access to simulator functions (displaying waveforms, reviewing test results, editing test reports, signal massaging etc.); 4) automated waveform replaying that includes drivers for variety of supported I/O hardware.

In order to test relays with transients recorded by DFRs, it is necessary to select good tools for handling and retrieving DFR files. Master station software provided by DFR vendors can be used for this purpose. There are more advanced software solutions that provide automated analysis, sorting, archiving, and reporting [12]. The records, together with the reports are stored into the centralized database and available for easy search and retrieval.

In addition, a useful integration with ATP and ATPDraw is utilized by developing a new software tool called Batch Generator (BGEN). BGEN is an add-on module that facilitates an automatic way of generating several test cases and reduces time needed for both training on how to use the simulation tools and producing actual test waveforms.

VI. Application Testing: Two Approaches

There are two main approaches when using transients for application testing: 1) using recorded waveforms, and 2) using simulated waveforms. The methodology assumes combining both approaches.

A. Application Testing Using Recorded Waveforms

Fig 4. depicts the software and hardware setup needed for application testing using recorded waveforms. Typically, recorded waveforms are coming from monitoring devices such as DFRs.

As mentioned, the test software has several import filters and can effectively read recorded waveforms in native file formats for the most widely used DFR types as well as COMTRADE file format [11].

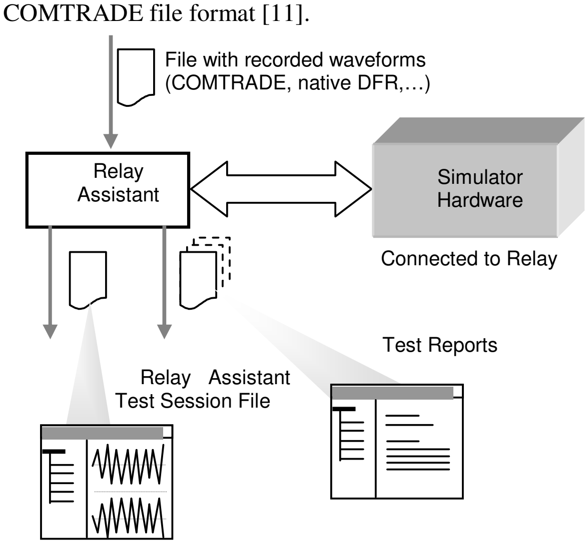

Fig. 4. Test setup for testing using recorded waveforms

In practice, a situation when an imported DFR file can directly be used for testing is very rare. Typical problems are signals in different ranges, inverted signals because of the wiring methods, short pre-fault and/or post-fault duration, noise, etc. The software is equipped with several features for editing the waveforms. Once the waveforms are imported into the software, they can be rescaled, filtered, inverted. There are also more advanced features such as extending the pre- and/or post-fault for a given number of cycles, resampling, reconstructing waveform of a missing phase. More details on test waveforms can be obtained using the tools for displaying the signal frequency spectrum, calculating the steady state parameters, and calculating and displaying the sequence (symmetrical component) values.

All the mentioned software features help preparing the waveforms for transient test replaying. The test data are organized and saved in a test session file. One session file can contain several tests, and each test can contain different waveforms. Session and waveform files are stored to the database and reused when needed.

During the tests, the waveforms from each test file are automatically sent to the simulator hardware, which is connected to the protective relay. The outcome of the relay's behavior under the tested condition (trip, no trip), relay trip time, and relay zone of operation, are automatically obtained and saved in the report file repository for further use. Each test can be repeated any given number of times.

Using transients recorded by DFRs has its benefits for initiating the troubleshooting of misoperations, or evaluating relays under certain conditions in the system. Unfortunately, for more elaborate testing, it is unrealistic to expect that a sufficient number of test cases obtained using DFR file will be available.

Currently, CenterPoint Energy is deploying an installation of a modern DFR data file management software that provides means for locating DFR files by variety of parameters specified in the search criteria: substation, line, type of fault, etc [12]. Even a reason for a relay miss-operation can be identified automatically using such a tool. It is expected that this software tool with its database will be a powerful tool for retrieving and locating good transient test cases. However, it has to be installed in the system for some time, for a database containing a large number of DFR files to be created.

B. Application Testing Using Simulated Waveforms

Test setup for application testing by simulating faults is shown in Fig.5.

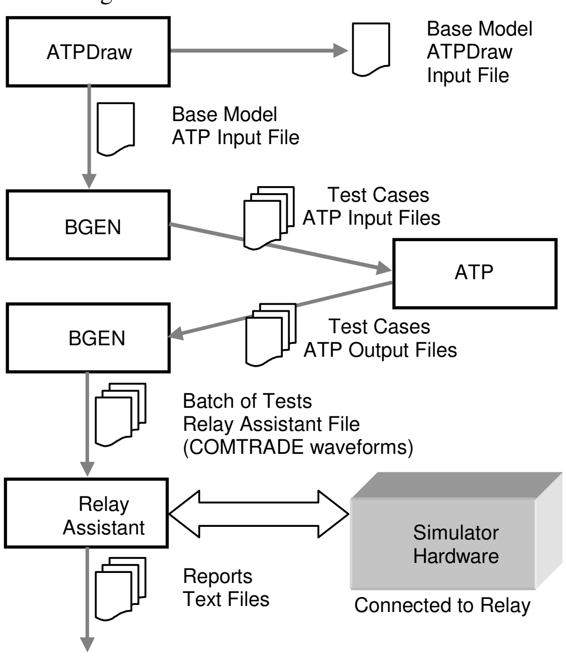

Fig. 5. Application testing setup

The base model of the power system is normally created by using ATPDraw graphical editor [9] or ATP directly. For example, a section of CenterPoint Energy's power system is shown in Fig. 6. Generally, a user can manually incorporate faults in the model, run the simulation, and import the waveforms into the software.

For this particular methodology, a new software tool called Batch Generator has been developed. The main purpose for developing this new tool was to automate process of creating test cases.

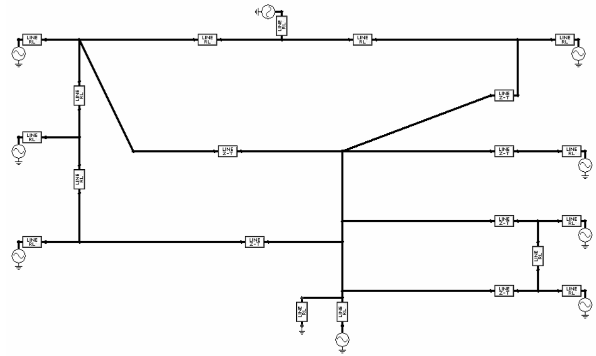

Fig. 6. An example of base model created in ATPDraw editor

VII. BATCH GENERATOR (BGEN)

BGEN reads the base model information from the ATP input file. Specifying measurements of interest is done by selecting relay position and entering the CT and CCVT ratios (Fig 7.)

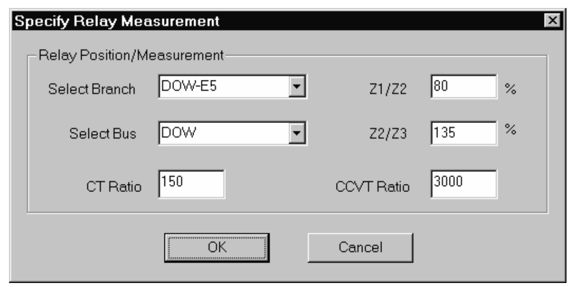

Figure 7. BGEN utility: specifying relay measurement

Up to four relay measurements can be specified. BGEN generates waveforms with synchronized samples that can be used for testing up to four relays simultaneously. The hardware setup at the CenterPoint Energy's lab has two terminals, which at present enables simultaneous testing of two relays.

Once, the locations of the relays are specified, user adds descriptions of test cases. Each fault is specified by a set of parameters: fault type, location, resistance, initiation and clearing times (Fig. 8.) .

Values of the parameters can be varied, so BGEN can automatically generate several test cases for the similar faults. For example, one can set the phase A-to-Ground fault, and than vary the location of the fault from 10% to 90% with a step of 5% (total of 17 cases). All the settings can be accessed and edited through the BGEN's main window (Fig. 9.). One batch can contain different types of faults on different lines, and with several fault parameters varied. This way, user can easily generate several test cases without even knowing the input data format of ATP.

After the user defines the batch of possible faults, for each test case, BGEN automatically generates ATP input files, performs ATP simulation, and converts the simulation results into COMTRADE format file that is stored in the file repository.

In addition, it creates a test session file that contains links to each of the newly created test cases and allows automated replaying of waveforms to the relay(s) under test. Relay response can be monitored through digital inputs and automatically stored into the file repository and is available for later report generation. Each test can be automatically repeated several times, which allows a statistical approach to testing.

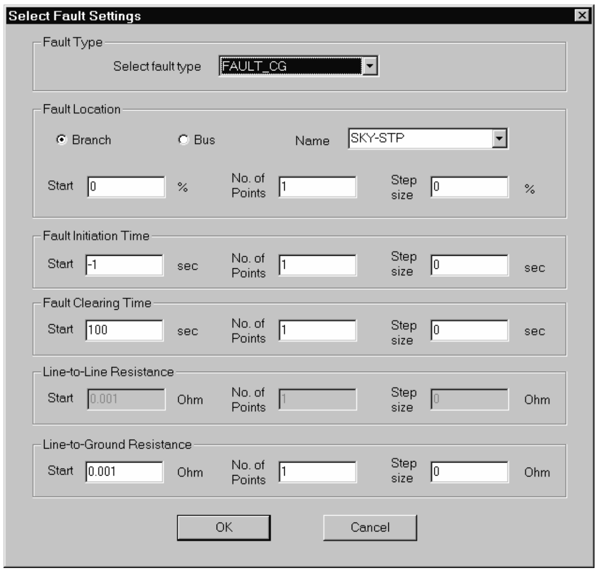

Fig 8. Fault description – adding a set of cases to the batch

BGEN is designed to work as an add-on for both ATPDraw/ATP and Relay Assistant. It can be invoked directly through ATPDraw graphical editor in which case the active ATP file generated by ATPDraw will be processed by BGEN. Optionally, BGEN can be used as a stand-alone application where user needs to specify a path to the starting ATP model, and the waveforms generated through simulations are stored into the COMTRADE file repository.

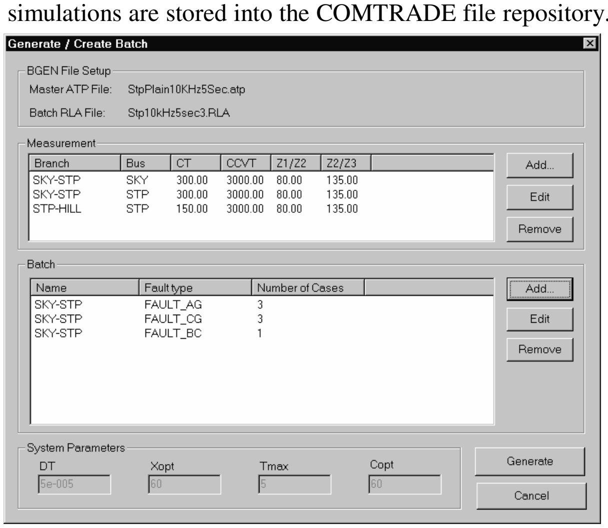

Fig. 9. BGEN Main window: specifying batch of test cases

VIII. CONCLUSIONS

Based on the discussion, the following conclusions can be outlined:

- Application testing using transients allows "discovery" of important relay performance characteristics for a given application.
- Hardware and software tools selected for use in CenterPoint Energy's test lab made the transient testing efficient and cost-effective.
- The selected relay test software for replaying recorded transients provides a number of waveform-editing functions to enable preparation of proper test waveforms.
- Automated replaying of waveforms is an essential requirement when performing transient testing.
- Newly developed software tool called BGEN provides automated means for generating simulated transients and enables dealing with large number of fault conditions. BGEN also enables user to efficiently generate several test cases starting from the base system model without knowing the ATP input data format.
- Presented methodology and test system, currently used at CenerPoint Energy's test lab for troubleshooting relay miss-operation and evaluating new microprocessor relays, enabled an assessment of relay performance that was not possible with earlier generation of testing tools.

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