Digital Testing of High-Voltage Circuit Breakers

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A circuit breaker is a switching device that the American National Standards Institute (ANSI) defines as: "A mechanical switching device, capable of making, carrying, and breaking currents under normal circuit conditions and also making, carrying for a specified time, and breaking currents under specified abnormal circuit conditions such as those of short circuit." ANSI adds, as a note: "A circuit breaker is usually intended to operate infrequently, although some types are suitable for frequent operation."

Manufacturers, standardizing bodies, test laboratories, and users gain new possibilities for fine tuning circuit breaker abilities in relation with standards and real power systems

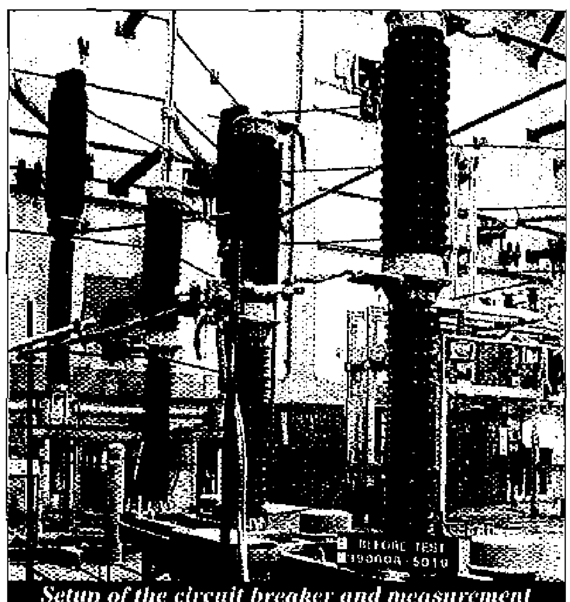
High-voltage circuit breakers play an important role in transmission and distribution systems. They must clear faults and isolate faulted sections rapidly and reliably. In short, they must possess the following qualities:

- In closed position, they are good conductors
- In open position, they are excellent insulators
- They can close a shorted circuit quickly and safely without unacceptable contact erosion
- They can interrupt a rated short-circuit current, or lower current, quickly without generating an abnormal voltage.

The only physical mechanism that can change in a short period of time from a conducting to an insulating state at a certain voltage is the arc. It is this principle on which all circuit breakers are based.

The first circuit breaker was developed by J.N. Kelman in 1901. It was the predecessor of the oil circuit breaker and capable of interrupting a short-circuit current of 200 to 300 A in a 40 kV system. The circuit breaker was made up of two wooden barrels containing a mixture of oil and water, in which the contacts were immersed. Since then, circuit breaker design has undergone a remarkable development. Nowadays, one pole of a circuit breaker is capable of interrupting 63 kA in a 550 kV network, with SF_6 gas as the arc quenching medium.

Still, the design of a circuit breaker is not only a science but also an art. Because of the complex phenomena involved, circuit breaker prototypes have to be verified by practical tests in the laboratory. In high-power laboratories, the ability of circuit breakers to interrupt short-circuit currents is verified in test circuits, which are in fact lumped element representations of the power system. These test circuits must produce the correct waveforms for the (short-circuit) current as well as for the voltage that strikes the circuit breaker immediately after the breaker has interrupted the test current. The waveforms of current and voltage to which the test object is subjected are laid down in ANSI and International Electrotechnical Commission (IEC) standards. These standardized waveforms represent 90% of the possible fault conditions in the real system.



Setup of the circuit breaker and measurement equipment in the KEMA High-Power Laboratory

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ISSN 0895-0156/00/$10.00©2000IEEE

Circuit Breaker Switching and Arc Modeling

The switching action, the basic function of the circuit breaker, refers to the change from conductor to insulator at a certain voltage. Before interruption, the (short-circuit) current flows through the arc channel of the circuit breaker. Because of the nonzero resistance of the arc channel, this short-circuit current causes a voltage across the contacts of the circuit breaker: the arc voltage. The arc behaves as a nonlinear resistance. Thus, both arc voltage and arc current cross the zero-value at the same time instant. If the arc is cooled sufficiently at the time the current goes through zero, the circuit breaker interrupts the current, because the electrical power input is zero. During current interruption, the arc resistance increases from practically zero to almost infinite in microseconds. Immediately after current interruption, the transient recovery voltage builds up across the circuit breaker. As the gas mixture in the interelectrode space does not change to a completely insulating state instantaneously, the arc resistance is finite at that time, and a small current can flow: the post-arc current.

Black-box arc models are mathematical descriptions of the electrical properties of the arc. This type of model does not simulate the complicated physical processes inside the circuit breaker but describes the electrical properties of the circuit breaker. Measured voltage and current traces are used to extract the parameters for the differential equations describing the nonlinear resistance of the electrical arc for that specific measurement.

Digital Testing

The functionality of high-voltage circuit breakers is tested in high-power laboratories. Due to the necessary power and the physical size of the equipment, testing is rather expensive and time consuming. In order to obtain as much information as possible about the degradation and operating limits of the circuit breaker from the cost-intensive tests, a project started with the following partners: KEMA High-Power Laboratory, The Netherlands; Delft University of Technology, The Netherlands; Siemens AG, Germany; RWE Energie, Germany; and Laborelec cv, Belgium. This project is sponsored by the Directorate General XII of the European Commission in Standards, Measurements, and Testing Program under contract number SMT4-CT96-2121. The project is aimed at developing digital testing of high-voltage circuit breakers, i.e., a software product for testing of a model of such a device, once its characteristic fingerprints are obtained from refined measurements during standard tests. Digital testing offers a wide range of new possibilities for users, manufacturers, standardizing bodies, and test laboratories for fine tuning circuit breaker abilities in relation with standards and real power systems. Some developments are:

- Evaluation of the relevance of future standards with respect to real power systems
- Evaluation of the relevance of future standards for different circuit breaker technologies and extinguishing media
- Estimation of the circuit breaker's interrupting limit
- Reduction of full-scale testing in high-power laboratories
- Identification of network topologies that can pose special difficulties to a circuit breaker
- Acceleration of development of new circuit breaker designs
- Monitoring the aging processes of circuit breakers in service
- Expansion of services for high-power laboratories.

The steps followed so far to enable digital testing are described in the following sections. At the end of the article, examples of digital testing are presented.

Measurements and Data Analysis

High-resolution measurements of current and voltage in the critical period around short-circuit current zero must supply the necessary parameters, characterizing the breakers' behavior. A tailor-made high-frequency measuring system was realized for this purpose. This system consists of a number of battery-powered, single-channel, 40 MHz, 12 bit AD converters, each storing the data temporarily in on-board local RAM (256k samples each). The concept of on-site data storage is necessary for reaching a maximum overall system bandwidth. Cables to the current and voltage sensors can thus be kept very short, and the system can operate on floating potential. The arc voltage is measured with standard broad-band RCR-type voltage dividers; current is measured with a special Rogowski coil. After the remote RAM is filled, data is transmitted serially through optical fibers to the processing unit in the command center. The greatest challenge with respect to developing the equipment in this application design lies in the electromagnetic compatibility, since the microelectronics has to function in an extremely hostile environment of intense EM fields of various origin.

The system relies heavily on digital signal processing methods for reconstructing the actual voltage and current signals from the raw sensor output. On the one hand, this has to do with the specific frequency response of the sensors and on the other hand, with corrections needed for the (reproducible) induced voltages and capacitive current that distort the measured signals. Tests in various laboratories have proven that the system can measure post-arc current as small as 50 mA, microseconds after the interruption of many tens of kA.

Data analysis software has been produced to carry out the signal reconstruction practically on line during the tests (Figure 1), and to evaluate the performance of the test object. Even the newest professional multipurpose mathematical or laboratory software is not competitive to this custom-made software considering

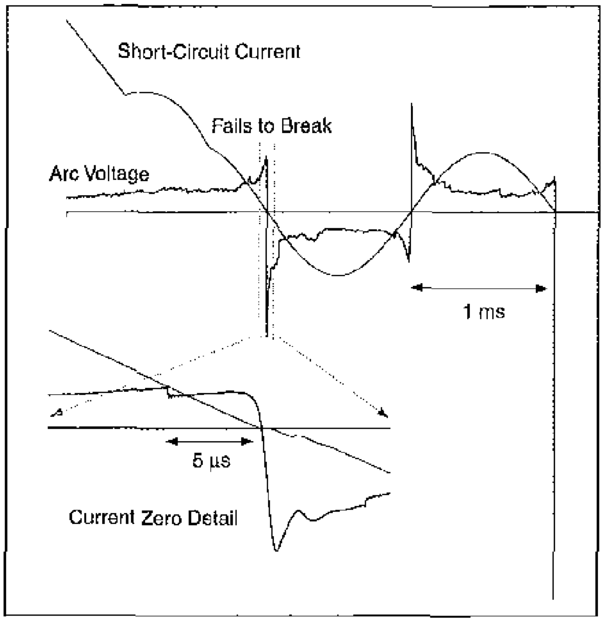

Figure 1. Voltage and current measurement data

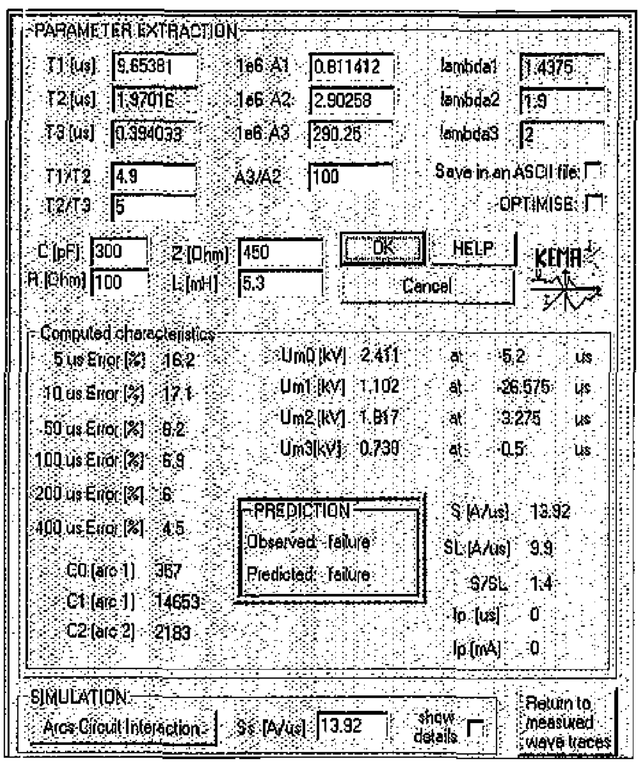

Figure 2. Parameter extraction software

flexibility and speed in visualizing and data processing of practically unlimited amount of measured data in a user-friendly way.

After an extensive series of the most critical fault interruption duty for circuit breakers (the so-called "short-line fault," see the section on "Applications of Digital Testing"), a test database from various types of com-

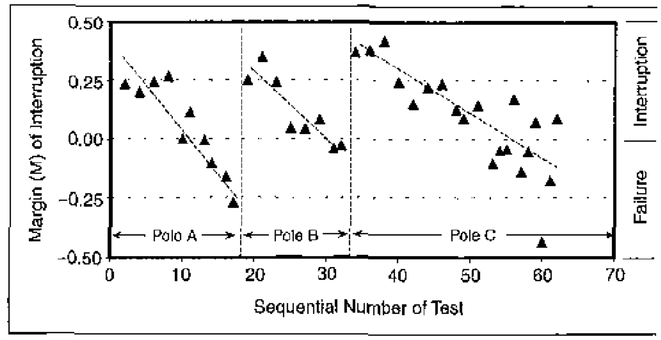

Figure 3. Degradation of the circuit breaker poles

mercially available circuit breakers was set up. With this experimental material, an empirical arc model based on classical arc models was validated that gave very good coverage of the observed processes. From the total number of (>250) interruption attempts, the result of the attempt (failure/success) was predicted correctly in more than 90% of the cases by evaluating the characteristics of the arc behavior with the model.

The model has a set of (three) parameters, which are extracted automatically during the evaluation of each test (Figure 2). Automated analysis of the collection of all the parameter sets (in other words, the breakers' "fingerprints") obtained from a whole series of tests makes it possible to evaluate various physical quantities as a function of test conditions.

The aim of using this method is to quantify the breaker performance (the margin M of interruption), indicating how successful the breaker passed the test (M > 0) or how far off it is from passing it (M < 0).

An example is given in Figure 3, where the degradation of the three breaker poles (A, B, and C) is presented during a sequence of successive tests. It can be seen clearly that the margin of the breaker decreases with every test. The rate of margin decay (among others) is a measure of the endurance of the breaker with respect to this type of tests.

Arc-Circuit Interaction Software

At the final stage of the realization of digital testing, measured arc model parameters will be used as input for the arc model. Of course, this arc model behaves as a nonlinear element in the electrical circuit and must therefore be analyzed with a dedicated computer program. The analysis of arc-circuit interaction involving nonlinear elements in relation to stiff differential equations makes it necessary to perform the calculations with a variable step size and adjustable accuracy of the computed currents, voltages, and conductances. Because they have fixed step-size solvers, EMTP and comparable programs are less suitable for this purpose and therefore a new approach, the integration of differential algebraic equations (DAE) by means of the backward differentiation formulas (BDF) method, has been chosen in developing a new software package for electrical transients computation. This new transient program, XTrans, has been developed at the Delft University of Technology especially for arc-circuit interaction studies. The program runs on a PC with the MS-Windows operating system and works fully graphical, as shown in Figure 4. The program is in use at several high-power and high-voltage laboratories in the world.

The program makes use of libraries that contain information about the behavior of element models. The program structure is depicted in Figure 5. This structure has been realized with object-oriented programming. The compiled code of the element models is placed in dynamic link libraries (DLLs). The models are, therefore, separate from the main program, which makes it easy to create new models and use them in the main program.

A full working demonstration version of the XTrans program can be downloaded from the homepage of the electrical power systems group at the Delft University of Technology, http://eps.et.tudelft.nl.

Applications of Digital Testing

Influence of Parallel Capacitance

Powerful possibilities with digital testing are created when the arc model, validated as described in the section on Measurements and Data Analysis, is coupled with a circuit analysis package. Then, the performance of a circuit breaker, the fingerprints of which were obtained from real tests, can be estimated in circuits other than the test circuit.

For example, the influence of various standard substation components on the breakers' capabilities can be estimated through digital testing.

Here the influence of a parallel capacitance is calculated (for example, the parasitic capacitance of a current transformer, CT) in the substation. In Table 1, the performance of a short-line fault interruption is compared in the presence of two types of CTs: CT 1, having 200 pF of parasitic capacitance, and CT 2, having 400 pF. These CTs can be located near the circuit breaker and remote (the latter implying an additional 50 μH of busbar between CT and breaker). As a reference, the case without CT has a performance of 1.0.

Table 1 shows that the difference between the two types of CTs is rather small when compared to the gain obtained by the CT that was installed to the breaker as closely as possible.

Critical Line Length Determination

One of the most severe currents for a circuit breaker to interrupt is the short-line fault (SLF). In the case of a short-line fault, the short-circuit point is on a high-voltage transmission line a few kilometers away from the breaker terminals. After current interruption, a very steep, triangular-shaped waveform (with a rate of rise of 5-10 kV/microsecond) stresses the extinguishing medium between the contacts. The percentage SLF indicates to what extent the short-circuit current is reduced by the transmission line, e.g., a short-circuit current of 40 kA is reduced to 36 kA in case of a 90% SLF. In the IEC standard, 75% and 90% SLF tests are prescribed.

As an example of digital testing, the critical line length, the short-line fault percentage that stresses the circuit breaker most, will be determined for a 145 kV,

Table 1. Influence of a current transformer

Performance	Near	Remote
CT 1 (200 pF)	1.9	1.2
CT 2 (400 pF)	2.4	1.4

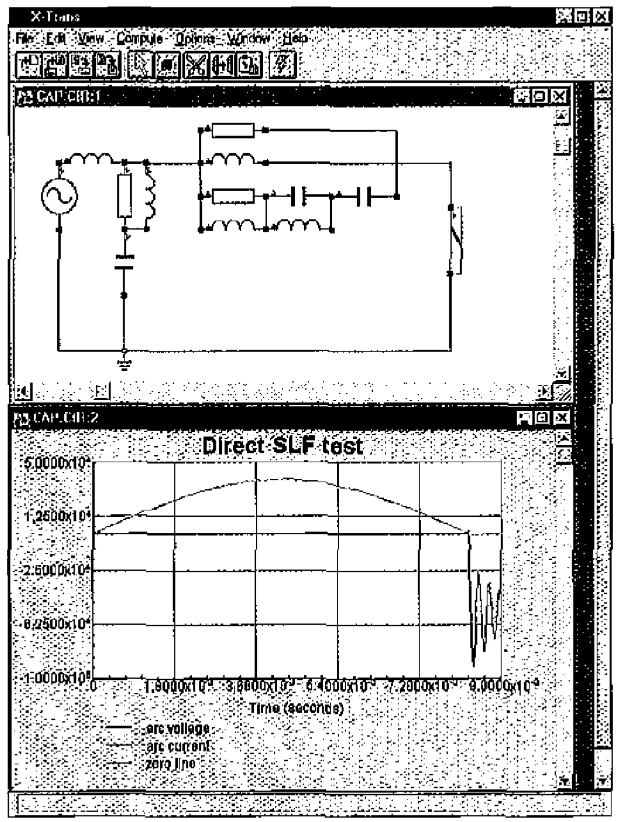

Figure 4. XTrans transient program

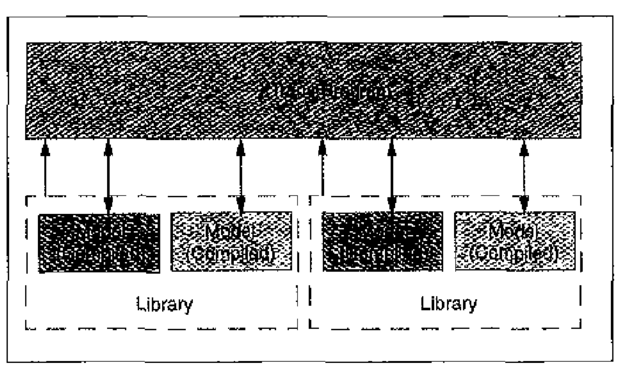

Figure 5. Structure of the XTrans transient program

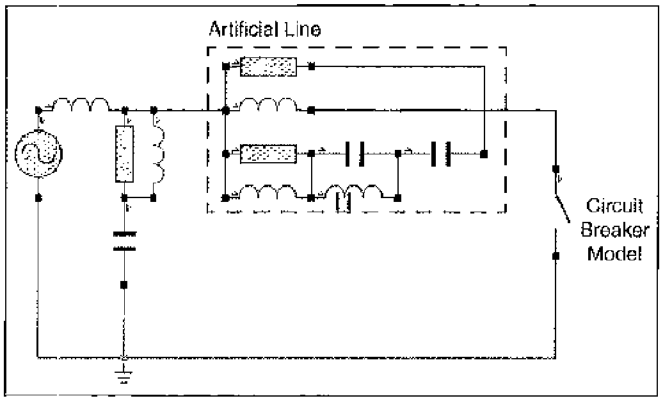

Figure 6. A direct SLF test circuit in the XTrans program

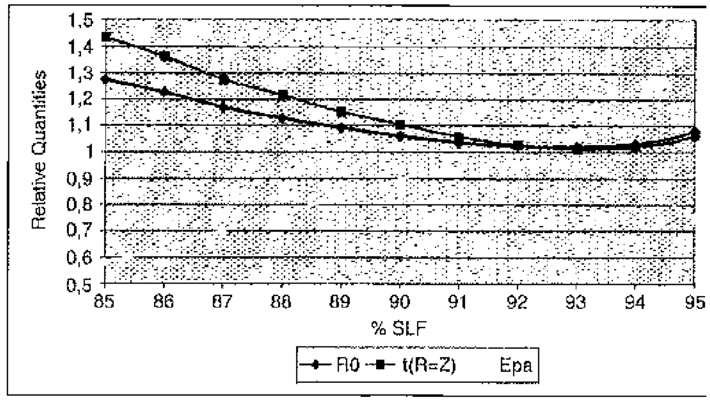

Figure 7. Critical line length determination by means of digital testin

31.5 kA, SF_6 circuit breaker. A direct SLF test circuit is shown in Figure 6. Three different indicators, active at different time intervals (before current zero, at current zero, and after current zero) are used to quantify the stress on the circuit breaker model.

- Before current zero: the time before current zero where the arc resistance equals the surge impedance of the transmission line $t(R = Z)$. The closer the value is to current zero, the more severe the breaker is stressed by the test circuit.
- At current zero: the arc resistance $R0$. The lower the arc resistance value at the current zero crossing, the stronger the breaker is stressed by the test circuit.
- After current zero: the post-arc energy Epa. This value is the integral of the multiplication of the small post-arc current and the recovery voltage. It is clear that only for successful interruptions an Epa value can be calculated. The higher the Epa value is, the more severe the breaker is stressed by the test circuit.

The actual computation is based on 75 current zero recordings of the circuit breaker of which the circuit breaker model parameters have been determined. For each set of parameters, the stress at the various short-line fault percentages is computed. At last, the overall stress is visualized, which is shown in Figure 7.

All three indicators show that the circuit breaker model is stressed most severely at a 93% SLF, whereas a 90% SLF is prescribed in the IEC standard. This shows that digital testing can be applied to use the information obtained from laboratory tests for the development of future standards.

Acknowledgments

The authors are indebted to the Directorate General XII of the European Commission in Standards, Measurements, and Testing Program for sponsoring. The effort of the other partners involved in the project is greatly appreciated.

For Further Reading

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Biographies

Pieter H. Schavemaker obtained his MSc in electrical engineering from the Delft University of Technology in 1994. After graduation, he performed research on power system state estimation with the Power Systems Laboratory. In 1995, he started as an application engineer programming Substation Control Systems with ABB in the Netherlands. Since 1996, he has been with the Power Systems Laboratory, where he is currently assistant professor. He is working on PhD research on digital testing of high-voltage circuit breakers within the framework of a European project. His main research interests include power system transients and power system calculations. He is a member of IEEE. He can be reached by E-mail, P.H.Schavemaker@its.tudelft.nl.

Lou van der Sluis obtained his MSc in electrical engineering from the Delft University of Technology in 1974. He joined the KEMA High-Power Laboratory in 1977 as a test engineer and was involved in the development of a data acquisition system for the High-Power Laboratory, computer calculations of test circuits, and the analysis of test data by digital computer. In 1990, he became a part-time professor, and, since 1992, he has been employed as a full-time professor at the Delft University of Technology in the Power Systems Department. He is a senior member of IEEE and convener of WG CC-03 of Cigré and Cired to study the transient recovery voltages in medium and high voltage networks. He can be reached by E-mail, L.vanderSluis@its.tudelft.nl.

René P.P. Smeets obtained his MSc in physics from the Eindhoven University of Technology in 1981. He obtained the PhD degree in 1987 for research work on vacuum arcs at the same university. From 1983 to 1995, he was a staff member of the Energy Systems Division of the Faculty of Electrical Engineering, Eindhoven University. During the year 1991, he spent a sabbatical leave at Toshiba Corporation's Heavy Apparatus Engineering Laboratory in Japan. In 1995, he joined KEMA for R&D of the High-Power Laboratory. He is a member of Cigré WG 13.04, the Current Zero Club, Cigré, and the IEEE. He can be reached by E-mail, r.p.p.smeets@kema.nl.

Viktor Kertész obtained his MSc in electrical engineering from Budapest University of Technology in 1966, PhD in 1976, and DSc in 1989. He joined the High-Power Laboratory of the Electrical Power Research Institute, Budapest, as a researcher and test engineer in 1966. He became a professor of mathematics at the Budapest University of Technology in 1979 and has held the chair of full professor since 1989. He has had a scientific contact with KEMA in the field of circuit breaker measuring problems and the analysis of arc phenomena since 1978. He contributed as a member to Cigré WG 13.01 (arc modeling). He can be reached by E-mail, kerteszv@elender.hu.