# Transient Recovery Voltage at Series Compensated Transmission Lines in Piauí, Brazil

S. Henschel L. Kirschner M.C. Lima

**Abstract – As a part of ongoing 500 kV power transmission enhancements in Brazil, several new fixed series compensators are planned to be installed in two stages in 2006 and 2008 in the state Piauí. As series compensation affects the levels of transient recovery voltage and rate of rise of recovery voltage for circuit breakers and switchgear, a thorough study was carried out. This paper summarizes the procedure of the study and some of its most important findings.**

**Keywords: circuit breakers, fixed series capacitors, series compensation, phase opposition, TRV, RRRV, switching transients, simulation.**

## I. Introduction

In today's high-voltage AC transmission networks series capacitors are often used to reduce the effective line reactance in order to permit increased power transfer over long distances. One of the concerns however is their influence on the line breakers as very high levels of transient recovery voltage (TRV) and of rate of rise of recovery voltage (RRRV) may result when opening the line breakers in the case of abnormal conditions e.g. a short-circuit fault, tie-line between grids of opposing phase, etc. [1].

As fixed series compensation (FSC) will be added to the Brazilian 500kV transmission network, a TRV analysis study was carried out in close cooperation between CHESF, Brazil, and Siemens, Germany, in order to re-evaluate the breaking capability of existing circuit breakers and switchgear under the new system configuration. The main purpose of the analysis was to obtain a comparison between the TRV and RRRV levels of the present system configuration without series compensation and with the configurations in the years 2006 and 2008 with various stages of the compensation in service.

In this study, the TRV and RRRV at the 40kA breakers of only the series compensated lines Boa Esperança – S. J. do Piauí and S. J. do Piauí – Sobradinho were investigated. For this purpose numerous simulations of out-of-phase tripping of short-circuit clearing have been evaluated, whereby the fault location was varied along the series compensated lines, to obtain results for line faults and short-line faults.

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In addition, the fault type (3-phase short circuit with and without earth, 2-phase short circuit with and without earth, single-phase short circuit) and the point-on-wave fault begin were varied. Overall, the study comprised approx. 5000 different cases of which the TRV and RRRV levels were evaluated, including the first phase to clear but also the other phases. The evaluation was performed with Siemens NETOMAC™ software according to IEC 62271-100 standard [2] and compared with the accepted TRV and RRRV levels found in the test protocols of the existing circuit breakers.

## II. Transient Recovery Voltage

When the circuit breaker contacts open they draw an arc between the poles. In the current zero crossings of AC current, the arc extinguishes. Whether or not the arc reoccurs is determined by the breakers' capability to quickly de-ionize the gap between the poles. This, in part is influenced by breaker properties such as the speed of the departing contacts, SF6 gas pressure, the way the arc is mended within the chamber, but it also depends on the way voltage builds up as this has an effect on the dielectric strength of the gap. The objective of TRV analysis therefore is to determine the fastest initial build-up of the voltage after current interruption. Fig. 1 illustrates useful terms to describe TRV.

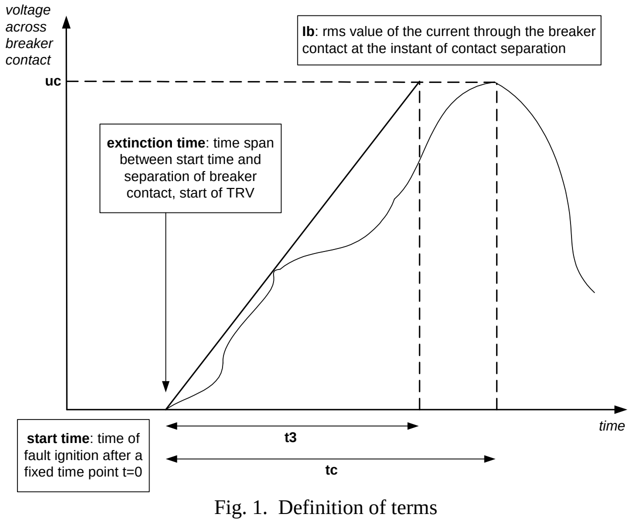


Fig. 1. Definition of terms

While a four-point representation of TRV would be applicable according to IEC 62271-100 [2], only the two-point representation, as shown in the figure, was used. The reason was that the circuit breaker test protocols were of older date and showed only the values of guaranteed peak TRV and of the RRRV slope at 100%, 60% and 30% of rated breaking current.

The shape of TRV and hence the two characteristic values peak TRV and RRRV slope depend on extremely many influences. The following is a (probably incomplete) list of influences that affect TRV levels in a high-voltage series-compensated transmission system:

- Transmission lines: a high-voltage transmission system typically involves long transmission lines that extend over hundreds of kilometres. Due to finite wave traveling times, distinct voltage shapes such as TRV may travel forth and back a line, producing a harmonic oscillation on its own (e.g. trapped line charge).
- Series compensation: a representation of series compensation as just a capacitor is over-simplified. There are different types of series compensation, FSC, TCSC, TPSC, etc., where each capacitor is equipped with protective devices such as a spark gap, metal-oxide varistors, and a bypass breaker. Since TRV is a process of fault clearing, these protective devices have already responded to the fault situation. Their response has a tremendous impact on the TRV levels: e.g. a bypassed series capacitor does not interact with the harmonics in the circuit.
- Fault sequence: When did the fault occur, what are the instantaneous voltages and currents in the system prior to the fault? The location of fault influences the fault currents and the contributing currents across the line breakers, and therefore has an effect on TRV. By the same argument, it is important to consider the fault type, i.e. single-phase-to-ground, three-phase, phase-to-phase with or without ground. Obviously, there are multiple possibilities of fault development, e.g. a single-phase fault that develops into a three-phase fault. Another influence is how long a fault lasts before the circuit breaker start opening their contacts.
- Fault clearing: Note that it matters if the faulted line is interrupted in only one phase or in all three phases. The opening of the line breakers at one substation may not start at exactly the same time as at the other terminal. There may be a few milliseconds of a difference due to different protection equipment, communication signals or different types of breakers.
- Arc: Most faults on a high voltage transmission system are not solid metal connections between phases but result in arcs. An arc dissipates electric energy and, therefore, adds resistive damping to high-frequency oscillations. Correct representation of the arc bears an effect on the TRV levels that can be experienced by the circuit breakers. By the same argument, the arc produced within the breaker chambers also contribute to the damping.
- Power system: During the fault, the entire power system in the vicinity is affected and in a state of transient oscillation so that, when the faulted line is isolated, the oscillations continue until a steady post-fault state is gained. Since TRV are voltages across the line breakers, the system oscillations also affect the level of TRV. As a consequence: not only is it important to analyze the affected transmission line with regards to TRV but also to consider the entire power system in the vicinity in all its detail.

From this list it can be concluded that it is a tedious, if not impossible, task to determine worst-case TRV levels for a circuit breaker. Particularly since the task involves minute representations of stochastic phenomena such as the arcs at the fault location or in the breaker chambers. In practice therefore a number of these parameters are varied in an iterative approach to include as many scenarios as possible [1], [3], [4].

While the objective of this work was to evaluate whether or not existing breakers can be further used in the series-compensated environment, a side aspect was also to analyze the simulated TRV with regards to its influencing parameters in order to perhaps establish rules of thumb, e.g. that a fault close to the circuit breaker causes higher TRV as a distant fault. This way the area of investigation could be confined to a reduced set of parameters allowing for faster simulation in the future.

## III. Modeling

The aforementioned sensitivity of TRV and RRRV to various influences requires minute models of the system. Therefore, the area around the series compensationed transmission lines was represented with detailed dynamic models. All three positive, negative and zero sequence of models needed to be considered. The load flow prior to the fault contingencies was adjusted to resemble peak loading conditions of the grid in the years 2006 and 2008. Fig. 3 and Fig. 4 show the configuration for both years.

### *A. Fixed Series Compensation*

The FSC's at S. J. do Piauí on the lines to Boa Esperança and Sobradinho are modeled as shown in Fig. 2. The FSC's are equipped with a bypass breaker to protect the device in the event of short-circuits on the series compensated transmission line. In addition, there is a metal-oxide varistor (MOV) to protect the series capacitor against over-voltages. A spark gap limits the absorbed MOV energy and protects against over-currents. The spark gap and bypass circuit breaker are represented through the switches in the model shown. The values for the capacitors as well as the trigger levels of the spark gap are listed below.

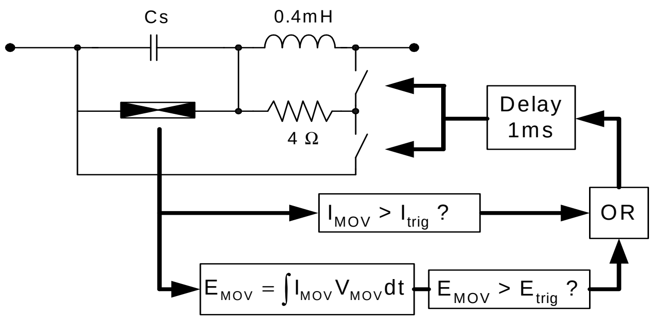


Fig. 2. Model of the FSC and protective circuits

TABLE 1
FSC Basic Design Parameters

| FSC | Cs [µF] | $E_{trig}$ [MJ] | $I_{trig}$ [kA] |
|---|---|---|---|
| Boa Esperança – S. J. do Piauí | 50.21 | 58.0 | 7.0 |
| S. J. do Piauí – Sobradinho | 55.62 | 62.4 | 10.8 |

The spark gap is triggered in the moment when the current or energy in the metal-oxide varistor exceeds either one of the trigger levels listed above (per phase). These trigger levels are tuned such that the spark gap only fires if the fault is on the transmission line with the respective series capacitor. There is a 1.0ms time delay until the gap fires, i.e. the switches in the model (see Fig. 2) close.

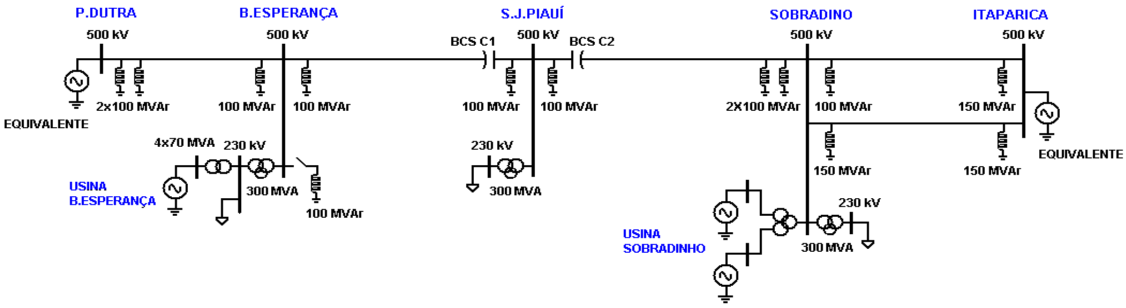


Fig. 3. System Configuration of Year 2006

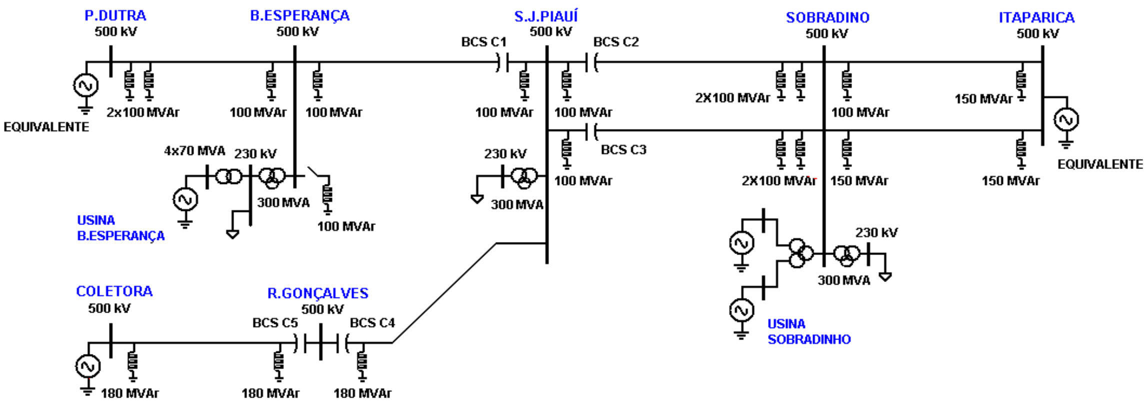


Fig. 4. System Configuration of Year 2008

This spark gap mechanism was individually implemented for each phase so that, in the case of a simulated two-phase fault without ground in the vicinity of a capacitor, the gaps would trigger in the affected phases but not in the healthy phase. The contacts of the bypass breaker close approximately 50 ms after fault ignition. With the exception of single-phase faults, all three phases of the bypass breaker close. In the case of a single-phase fault the bypass is closed in only the affected individual phase.

### B. *Transmission Lines*

The transmission lines of the study area have been modeled as distributed parameter line model with lumped resistive losses at the terminals and in the middle. This representation is also known as constant parameter model or Bergeron model [5], [6] and it is often used in electromagnetic transients studies. The reason for this representation is to obtain a time response reflecting the traveling waves on long transmission lines during and after the fault. In order to apply a fault at a location on a transmission line, the model was tapped at the respective fault location. Incorporating positive, negative and zero sequence data has accounted for mutual couplings among the three phases.

### C. *Fault*

The short circuit fault was modeled as a solid connection to ground. The connection to ground remains in place even after the fault is cleared by opening the line circuit breakers. This somewhat unrealistic represenation was chosen in favour of a model with arc representation, in order to be able to compare the results with similar internal studies of the CHESF system. The fault was applied at various places along the series compensated transmission lines between Boa Esperança and S. J. do Piauí, and between S. J. do Piauí and Sobradinho.

### D. *Surge Arresters*

In order to include the effect of surge arresters on transient recovery voltage, models of a surge arrester have been placed at both sides of the investigated 500kVcircuit breakers. The line-side models represent the arresters for protecting the respective station against surges from the transmission line. The station-side models represent the surge arresters at other feeders of the station, which are not tripped during the simulated fault scenarios. The models account for the nonlinear V-I characteristic of the arresters.

### E. *Circuit Breakers*

While the utilized simulation software would permit a very detailed representation of SF6 circuit breakers and arcing chambers in transients studies, the characteristics (e.g. KEMA measurements) of the breakers in the Brazilian network were not available at the time of study. Therefore and in order to better compare the study results with previous TRV simulations of uncompensated lines, it was decided to model the line circuit breakers as ideal switches. Their contacts open in the current zero crossing of the respective phase following 100 ms after fault ignition.

## IV. Simulation

In order to determine worst-case stresses by transient recovery voltage on the four line circuit breakers (at Boa Esperança and at S. J. do Piauí of the Boa Esperança – S. J. do Piauí line, and at S. J. do Piauí and Sobradinho of the S. J. do Piauí – Sobradinho line), several simulations have been performed. The scenarios considered in this analysis are opening operations of the respective circuit breaker during short-circuit contingencies and during severe operating conditions. In this report, the short-circuit contingencies have been categorized as "line faults" and "short-line faults".

Short-line faults are short circuits that occur on the transmission line in the immediate vicinity of the circuit breakers (<5 km, e.g. Fig. 5), while line faults are faults located either directly at a line terminal or at greater distances (>10 km, e.g. Fig. 6) from the substations. The reason for the distinction is the experience from the analysis of uncompensated transmission lines, indicating that short-line faults typically result in more severe stresses of the circuit breakers than faults at greater distances. The simulation of both categories has been performed to compare whether this observation can also be made with compensated transmission lines.

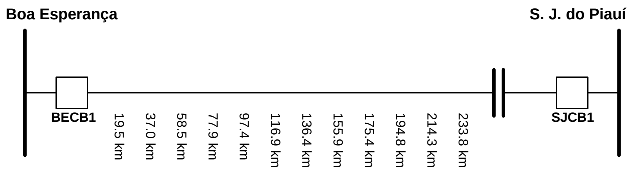


Fig. 5. Location of Line Faults

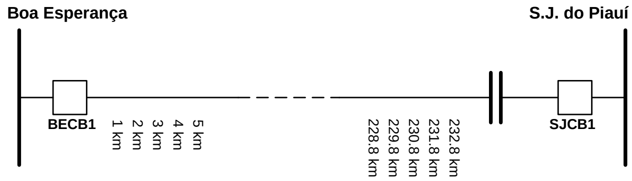


Fig.6. Location of Short-Line Faults

Simulations of breaker operation during out-of-phase conditions have also been performed. Specifically, the most severe cases of phase opposition have been studied. Phase opposition occurs during severe dynamic swings of the power system shortly before parts of the system are out of synchronism. Isolation of these asynchronous parts may lead to breaker opening situations in which the phase-to-ground voltages at both breaker contacts are 180° out of phase, causing voltages of 2 pu or more across the breaker contacts.

### *A. Line Faults*

In order to find the most severe impact on transient recovery voltage, the fault location was varied in steps of approx. 20 km along each line. Also the type of fault was varied, the possibilities being (i) single-phase short circuit to earth, (ii) two-phase short circuit without earth, (iii) two-phase short circuit with earth, three-phase short circuit, (v) three-phase short circuit with earth. Multiple faults have not been considered.

The instant of fault ignition was varied with 1 ms increments between 20 and 29 ms. From the moment of short circuit ignition, there is a time delay for measurement, fault detection and signal communication to the circuit breakers until they open to isolate the fault. Here it was assumed that the breakers open at once in the first current zero crossing that follows 100 ms after fault ignition. This way the influence of the arc is neglected. In order to compare the effect of series compensation on TRV levels with transient recovery voltages on an uncompensated transmission line, the aforementioned scenarios were also simulated without the FSC in the investigated transmission line. Overall, 5000 different fault variants have been simulated, yielding approx. 25000 TRV curves that were monitored across the contact gaps of the circuit breakers.

### *B. Short-line Faults*

In addition to the faults at greater distance from the substations, short-line faults have been evaluated at distances at and below 5 km from a substation. As three-phase short circuits with and without earth produce highest TRV values, only these two have been simulated. The fault location was varied at 1, 2, 3, 4 and 5 km distance from Boa Esperança, S. J. do Piauí, and Sobradinho substations. As before, the instant of fault ignition was varied with 1 ms increments between 20 and 29 ms. The opening of the breaker contacts was assumed to occur at the zero crossing of the line current in the respective phase following 100 ms after fault ignition. In total, 1600 different short-line fault scenarios and 9600 TRV curves have been evaluated.

### *C. Out-of-Phase Breaking*

In practice the conditions for breaker operation in phase opposition can only be achieved as a result of severe system upsets. Analysing the event by simulation of a simplified power system model, similar conditions can be artificially obtained by decelerating the machines on one side of the observed breaker until their terminal voltages lag by 180°.

However, due to the presence of strong power system equivalents on either side of the four studied circuit breakers (namely at Presidente Dutra and Itaparica substations), the desired conditions for phase opposition cannot be obtained without switching off one of these equivalents. Thus, the network equivalent at Itaparica was tripped prior to the investigation. In its place, a load of 850MVA and PF 0.94 (lag) was connected to destabilize this side of the system and slow down the hydro units in the power plant at Sobradinho. For the purpose of the analysis, it was necessary to maintain a marginally stable operating point. Therefore, a fictitious governor model was added to the hydro units at Sobradinho, which kept them stable and in synchronism at 180° lagging behind their initial voltage phase angle. The generators at Boa Esperança had been ignored in the simulations. The breakers open 20 ms after the out-of-phase situation has been obtained in the simulation, when the current has a zero crossing in the respective phase. The voltage phase angle at the Sobradinho side of the breaker jumps by approx. 180°, which causes high TRV above 2 pu across the open breaker contacts.

Both configurations of 2006 and 2008 have been analysed with and without series compensation. Due to the parallel line between S. J. do Piauí and Sobradinho in the year 2008 configuration, phase opposition cannot be achieved by opening a circuit breaker of only one line. This case therefore was omitted.

## V. RESULTS

The following tables summarize the worst-case TRV and RRRV levels obtained by simulation of the aforementioned numerous case scenarios. Note that the voltage base is the peak value of the line-to-ground voltage at 550 kV.

TABLE 1
MAXIMUM TRV FOR LINE-FAULTS & SHORT-LINE FAULTS

| Circuit breaker | 2006 without compensation | 2006 with compensation | 2008 with compensation |
|---|---|---|---|
| Boa Esperança | 1116.3 kV<br>2.49 pu | 1458.7 kV<br>3.25 pu | 1384.1 kV<br>3.08 pu |
| S. J. do Piauí<br>(to Boa Esperança) | 913.9 kV<br>2.04 pu | 1480.2 kV<br>3.30 pu | 1326.4 kV<br>2.95 pu |
| S. J. do Piauí<br>(to Sobradinho) | 911.7 kV<br>2.03 pu | 1480.9 kV<br>3.30 pu | 1428.4 kV<br>3.18 pu |
| Sobradinho | 943.6 kV<br>2.10 pu | 1196.3 kV<br>2.66 pu | 1354.5 kV<br>3.02 pu |

TABLE 2
MAXIMUM TRV FOR OUT-OF-PHASE BREAKING

| Circuit breaker | 2006 without compensation | 2006 with compensation | 2008 with compensation |
|---|---|---|---|
| Boa Esperança | 684.5 kV<br>1.52 pu | 901.6 kV<br>2.01 pu | 791.3 kV<br>1.76 pu |
| S. J. do Piauí<br>(to Boa Esperança) | 791.9 kV<br>1.76 pu | 1036.0 kV<br>2.31 pu | 761.0 kV<br>1.69 pu |
| S. J. do Piauí<br>(to Sobradinho) | 768.6 kV<br>1.71 pu | 1019.2 kV<br>2.27 pu | n/a |
| Sobradinho | 766.9 kV<br>1.71 pu | 949.6 kV<br>2.11 pu | n/a |

TABLE 3
MAXIMUM RRRV FOR LINE-FAULTS & SHORT-LINE FAULTS

| Circuit breaker | 2006 without compensation | 2006 with compensation | 2008 with compensation |
|---|---|---|---|
| Boa Esperança | 2.30 kV/µs | 1.88 kV/µs | 1.84 kV/µs |
| S. J. do Piauí<br>(to Boa Esperança) | 1.84 kV/µs | 2.44 kV/µs | 2.01 kV/µs |
| S. J. do Piauí<br>(to Sobradinho) | 1.43 kV/µs | 1.61 kV/µs | 2.04 kV/µs |
| Sobradinho | 2.42 kV/µs | 1.66 kV/µs | 2.37 kV/µs |

TABLE 4
MAXIMUM RRRV FOR OUT-OF-PHASE BREAKING

| Circuit breaker | 2006 without compensation | 2006 with compensation | 2008 with compensation |
|---|---|---|---|
| Boa Esperança | 0.46 kV/µs | 0.58 kV/µs | 0.67 kV/µs |
| S. J. do Piauí<br>(to Boa Esperança) | 0.47 kV/µs | 0.57 kV/µs | 0.39 kV/µs |
| S. J. do Piauí<br>(to Sobradinho) | 0.52 kV/µs | 0.61 kV/µs | n/a |
| Sobradinho | 0.47 kV/µs | 0.55 kV/µs | n/a |

The breakers' capability to withstand TRV and RRRV and to successfully interrupt the fault current is summarized in Table 5 and Table 6. The values for 40kA, 24kA and 12kA in Table 6 are specified in the circuit breakers' test protocols whereas the other entries are the results from additional tests obtained through consultations with the breakers' manufacturer [7].

Evaluating the simulation results and comparing them with the breakers' performance characteristics shown in Tables 5 and 6, the following observations have been made, which represent the most important findings of this study:

- A few simulated TRV values from line and short-line faults exceed the breakers' capability. The RRRV values from the simulation of out-of-phase breaking exceed the breakers' capability.
- In most cases high TRV levels result from three-phase faults without earth. Single phase faults produce less severe TRV levels than the other fault types.
- The expectation that faults close to the breakers would produce high TRV levels was not confirmed. On the contrary, in many cases it was found that faults at the remote line end would produce the highest TRV at the investigated breaker. With series compensation in place, TRV was typically highest when the capacitors were between the investigated breaker and the fault location.
- Overall the highest TRV occur in the 2006 configuration whereby the results with series compensation are 30-45% higher than without series compensation. The TRV levels in the 2008 configuration are slightly lower. The highest simulated TRV on the 500kV system was 3.3pu ($1408kV_p$) across the circuit breaker contacts.
- Of all the simulated cases, RRRV levels as high as 2.44 kV/µs were found. In general these values vary widely among the cases and thus did not permit an association with certain simulation parameters such as fault location or fault duration.

TABLE 5
BREAKER CAPABILITY FOR LINE-FAULTS & SHORT-LINE FAULTS

| Breaking current | TRV | RRRV |
|---|---|---|
| 40 kA | 900 kV<br>2.00 pu | 1.00 kV/µs |
| 24 kA | 960 kV<br>2.14 pu | 2.00 kV/µs |
| 12 kA | 960 kV<br>2.14 pu | 5.00 kV/µs |
| 12.7 kA | 1215 kV<br>2.71 pu | 1.47 kV/µs |
| 8.0 kA | 1470 kV<br>3.27 pu | 1.09 kV/µs |

TABLE 6
BREAKER CAPABILITY FOR OUT-OF-PHASE BREAKING

| Breaking current | TRV | RRRV |
|---|---|---|
| 10 kA | 519 kV<br>1.16 pu | 0.50 kV/µs |

## VI. CONCLUSIONS

The objective of the presented study was to determine whether or not existing line circuit breakers would have to be replaced in order to accommodate the series compensation. While it can be noticed that some of the values formally exceed the breaking capability of the circuit breakers, a decision was reached to maintain the breakers at this stage, which was based on the following discussion:

- The breaking current associated with the worst-case TRV often is below the standard 10% margin.
- The time, tc in Fig. 1, to reach the peak TRV is higher than the standardized times, allowing the breaker poles to be farther apart and decrease the likelihood of restrike.
- The RRRV values are within the breakers' capability.

- The likelihood of excessive TRV values is low, as they occurred with 2% in 5000 simulated cases at very specific locations on the transmission lines.
- Modeling stray resistance and capacitance of the circuit breakers has been ignored, which would smoothen the shape of TRV across the contact gap. Also the arc resistance has not been modeled due to lack of data, and modeled as ideal switch which would yield prospective and rather conservative TRV values.

In addition to evaluating the breakers' performance in a series compensated environment, an attempt was made to classify and associate the levels of TRV and RRRV with the fault location, fault type, fault duration and other simulation parameters. It is hoped that in the future this will allow to reduce the number of parameter variations and obtain reliable study results with only a few simulations. At the current stage it would be too soon to interpret the study findings in Section V as general rules. Continuous effort is being made throughout similar studies to gain further experience and refine these results.

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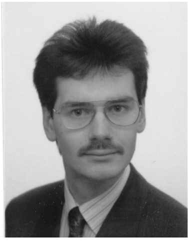
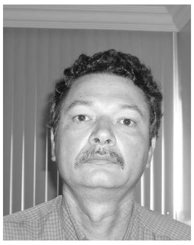
## VIII. Biographies

**Sebastian Henschel** was born in Berlin, Germany, in 1969. He obtained the Diploma in Electrical Engineering from the Technical University Berlin, Germany, and was recipient of the Erwin-Stephan Award 1993, donated by the university to encourage academic research abroad. In 1999, after he received the Ph.D. in Electrical Engineering from the University of British Columbia, Canada, he joined the Power Transmission and Distribution Department of Siemens AG in Germany. There he is senior consultant for the design, planning and analysis of industrial systems and FACTS.



**Lutz Kirschner**, Senior Project Engineer, MIEEE, received his Diploma in Electrical Engineering 1992 from the University of Aachen, Germany. He joined Siemens in the HVDC Department as a system design engineer. He was involved with technical and commercial design of HVDC converter stations. Since 1995 he is responsible for the design of FSC, TCSC, TPSC and other FACTS, and he has performed the basic design studies for several series capacitor projects. In the FSC S. J. do Piaui project he carried out the final basic design studies comprising the transient fault calculation and main component ratings. His special fields are time domain digital simulations and system studies. Since 1998 he is a member of IEEE.



**Manfredo Correia Lima** was born in Recife, Brazil, in 1957. He received his B.Sc. from Federal University of Pernambuco in 1979 and his M.Sc. degree in Electrical Engineering in 1997 from the same University. He joined CHESF in 1978, where he developed his experience in power electronics, static var systems, power quality, control systems, electromagnetic transients and series compensation. In 1992, Mr. Lima joined University of Pernambuco, where he works with power electronics classes and research. Currently he is developing his Ph.D. work, based on SVC adaptive control systems.