An Alternative to Reduce Medium-Voltage Transient Recovery Voltage Peaks

D. M. Nobre W. L. A. Neves B. A. de Souza

Departamento de Engenharia Elétrica - UFPB
Av. Aprígio Veloso, 882 – Bodocongó
58.109-970, Campina Grande – PB – Brazil
diana@dee.ufpb.br, waneves@dee.ufpb.br, benemar@dee.ufpb.br

Abstract - **Circuit breakers can fail to interrupt three-phase fault currents when power systems have Transient Recovery Voltage (TRV) characteristics, which exceed their ratings. This paper is the outcome of a study for the reevaluation of three 15 kV breakers at the CHESF (Companhia Hidroelétrica do São Francisco) Angelim substation, located in the northeast of Brazil. Digital simulations are carried out with ATP® (*Alternative Transients Program*) to compute the TRV waveforms. Alternative actions are taken to bring circuits within the 15 kV circuit breaker ratings when the parameters of the simulated TRV exceed the breaker ratings. A simple and cheap alternative to reduce TRV peaks is the placement of ZnO devices across the breaker terminals.**

Keywords: Circuit Breakers, TRV, ZnO Devices, Electromagnetic Transients.

I. INTRODUCTION

Recently, a study to examine TRV characteristics for medium-voltage circuit breakers was conducted by Swindler et al [1]. It was considered 13.8 kV breakers in an oil refinery in which circuit parameters as originally designed would have exceeded the TRV (*Transient Recovery Voltage*) ratings. Digital simulations were carried out with the EMTP (*Electromagnetic Transients Program*) to analyze TRV parameters. Alternatives to bring circuits to within the 13.8 kV circuit breaker ratings were presented.

The circuit transient recovery voltage can be modified by the circuit breaker's design or by the use of additional components like opening resistors, surge capacitors, grading resistors or capacitors. The most common adopted solutions are:

- when the TRV peak value is above the breaker rating, the existing breaker is replaced by one of higher voltage class;
- when the rate of rise of the recovery voltage exceeds the specified value, surge capacitors are used to reduce it.

This paper is the outcome of a study for the reevaluation of three 15 kV breakers at the CHESF Angelim substation, located in Pernambuco State, Brazil. TRV parameters are analyzed for bus and line breakers, considering present and 2003 substation configurations.

II. METHODOLOGY

The TRV to which a circuit breaker is subjected depends on the type of fault, its location and the type of switching circuit. These studies must consider:

- three-phase ungrounded terminal fault interruption since it is usually the most severe TRV condition, with the highest peak voltage magnitudes across the first opening-pole of the breaker. This type of fault is used as the basis for the breaker rating;
- the short-line fault since it usually has the highest rate of rise of the recovery voltage.

The ATP® is used to compute the TRV waveforms and to calculate its parameters [2]. These parameters are compared with the TRV circuit breaker ratings.

III. CIRCUIT BREAKER RATINGS

In this TRV study, the NBR-7118 Brazilian Standard, which is based in IEC-56 International Standard, 1987, is used [3]. Its purpose is to provide an application guide on the TRV ratings for ac circuit breakers rated above 1000V. For circuit breakers rated 72.5 kV and below, the TRV is defined by the Two Parameter Method in which two TRV envelopes are used to define the TRV maximum value (U_c) and the rate of rise of the recovery voltage (*RRRV*). Fig. 1 shows TRV envelope for 15 kV circuit breakers.

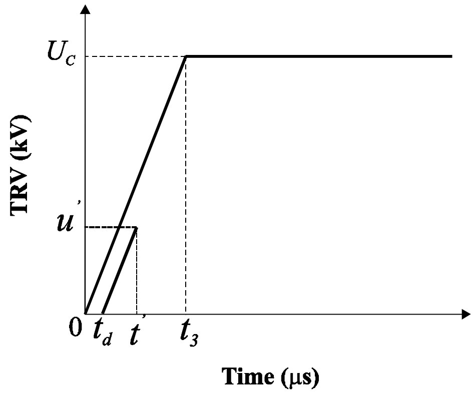

Fig. 1. Two parameter envelope for circuit breakers rated ≤ 72.5 kV.

The TRV envelope comprises a two-parameter reference line (two straight line segments) and a delay line of specified value, where:

U_C is the TRV maximum value, in kV;

t_3, time to reach U_C, in μs;

t_d, specified delay time, in μs; $u' = 1/3U_c$, in kV;

t', time to reach u', in μs.

The required 15 kV circuit breaker TRV capabilities at three interrupting current levels for terminal faults are indicated in Table 1.

Table 1. 15 kV breaker's capability.

Percent of interrupting rating	U_C (kV)	*RRRV* (kV/μs)
0 - 30%	27.6	1.97
30% - 60%	27.6	0.95
60% - 100%	25.7	0.38

Fig. 2 shows how to obtain these TRV parameters in practical situations. The *RRRV* is defined as the slope of the OP line segment. For the interruption process to be successful, the computed curve must be under the two-segment curve leading to calculated TRV parameters within 15 kV breaker ratings.

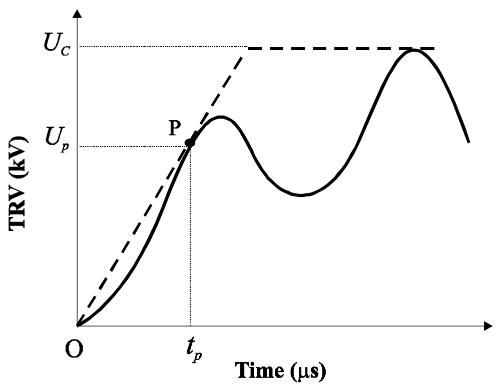

Fig. 2. TRV parameters.

IV. CASE STUDY: 13.8 kV CIRCUIT BREAKERS

Digital simulations using ATP® were made for the Angelim substation. Two configurations were considered: the configuration for the year 1998 up to the year 2002 and the one for the year 2003 up to the year 2007. The Angelim substation diagram is shown in Fig. 3 and its data are summarized in tables 2 to 6.

The power system is represented by its 230 kV bus Thévenin equivalent (when performing transient simulations it is recommended that one should represent at least two buses, besides the one in which the breaker to be evaluated is connected) [4]. The 230 kV and 13.8 kV transformer windings are wye connected with grounded neutral. The 69 kV windings are delta connected.

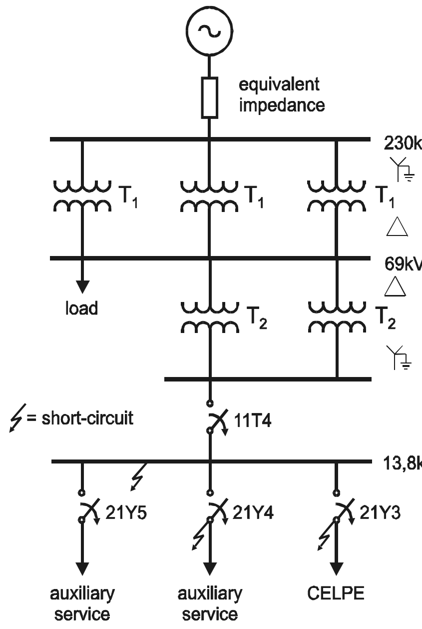

Fig. 3. Angelim configuration

Table 2. 230 kV bus equivalent.

Sequence	1998-2002		2003-2007	
	R (Ω)	X (Ω)	R (Ω)	X (Ω)
Positive	0.0025	0.0205	0.0023	0.0187
Zero	0.0049	0.0224	0.0029	0.0165

Table 3. Transformer ratings.

	T_1 (1998)	T_2	T_1 (2003)
MVA rating	33.3	5	100
positive-sequence impedance (S_{base} = 100 MVA) (%)	73.15	125.2	13.2

Table 4. 69 kV and 13.8 kV load.

Voltage Bus (kV)	1998-2002 MW	1998-2002 MVAr	2003-2007 MW	2003-2007 MVAr
69	104	27.4	123	32.3
13.8	3	0	4.2	0

Table 5. Connecting lead parameters.

R Ω/km/phase	X_L Ω/km/phase	C nF/km/phase
0.147	0.349	12.35

Table 6. Lead lengths.

230 kV Bus – 33.3 MVA Transformer	45m
69 kV Bus - 5 MVA Transformer	30m
5 MVA Transformer - 11T4 Breaker	15m
11T4 Breaker –13.8 kV Bus	3m
13.8 kV Bus - 21Y5 Breaker	5m
13.8 kV Bus - 21Y3 Breaker	10m
13.8 kV Bus - 21Y4 Breaker	2m

The bushing and winding capacitances of the transformers were considered to be nearly 3000 pF [5]. The effective capacitances of the circuit breakers were considered to be 600 pF.

A. Digital Simulations

The circuit breakers to be evaluated are located at the 11T4, 21Y4 and 21Y3 substation positions, according to Fig. 3. For each breaker, using a time step of 1μs, the simulated TRV waveforms are obtained for three-phase ungrounded terminal faults. For the 21Y3 breaker, digital simulations are also performed for short-line fault clearing for 1, 3 and 5 km from the breaker terminals.

The effect of the 13.8 kV load on the short-circuit current and on the TRV is taken into account for the following situations: no load, 0.5 MW and full load. The effects of bushing add winding capacitance to ground values of transformers T_1 and T_2 are considered in TRV simulations. AC short-circuit current peak values, I_{sc} , and the maximum allowed circuit breaker currents, I_{max} , are shown in Table 7.

Table 7. Short-circuit breaking current levels.

Breaker	Year	I_{sc} (kA)	I_{max} (kA)	I_{sc} (%)
11T4	1998	7.39	40	13.07
	2003	9.30		16.44
21Y4	1998	7.39	16	32.66
	2003	9.29		41.07
21Y3	1998	7.38	16	32.60
	2003	9.27		40.98

Three-Phase Faults

Fig. 4 shows the TRV waveform for the 11T4 breaker when clearing a three-phase ungrounded terminal fault in present configuration. The TRV peaks and rate of rise calculated for each breaker opening operation are shown in figs. 5 and 6.

It is necessary to identify the short-circuit breaking capacity for all breakers to be evaluated. From Table 7 and Table 1, one can see that the interrupting current levels for the 11T4, 21Y4 and 21Y3 breakers are in the range from 0 to 30%, from 30% to 60% and from 30% to 60% of their rated short-circuit current, respectively.

For the 11T4 breaker the *RRRV* values are above the standard ratings for all situations and the TRV peak exceeds the standard ratings in the following situations:

- no load at 13.8 kV bus, years 1998 - 2002;
- up to a 0.5 MW load, year 2003 - 2007.

For the 21Y4 and 21Y3 breakers, The *RRRV* values exceed the standard ratings up to a 3 MW load for the years 1998-2002 and up to a 4.2 MW load for the years 2003-2007. The TRV peaks exceeds the standard ratings for:

- no load at 13.8 kV bus, year 1998 to 2002;
- up to a 4.2 MW load, year 2003 to 2007.

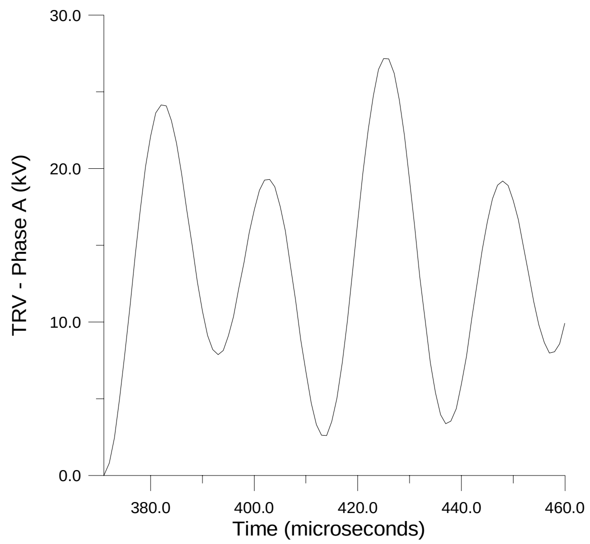

Fig. 4. TRV waveform for the 11T4 breaker. (13.8 kV bus with no load)

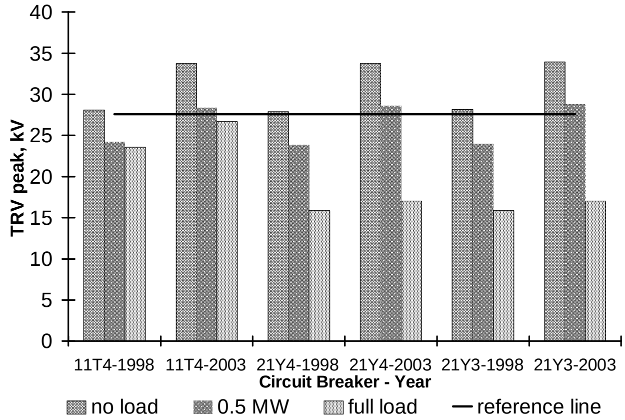

Fig. 5. Three-phase fault TRV peaks.

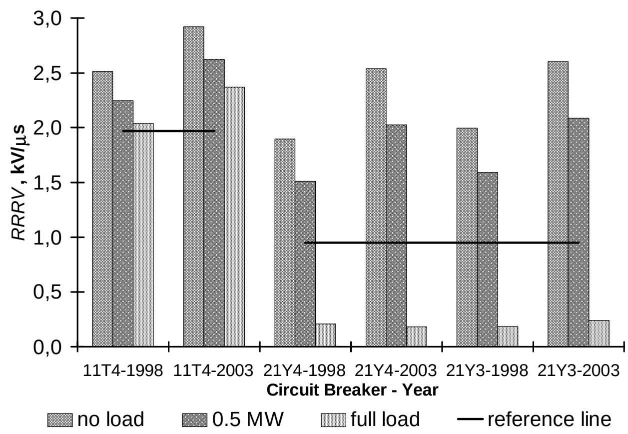

Fig. 6. Three-phase fault TRV rate of rise.

Short-Line Fault

Fig. 7 shows the TRV waveform for the 21Y3 breaker when clearing a fault at 1 km from the breaker terminals for 2003 configuration. The calculated TRV parameters are shown in figs. 8 and 9. The parameters for short-line faults are within standard values. The three-phase ungrounded terminal fault at the 13.8 kV bus with no load presented the most severe TRV condition in all simulated cases.

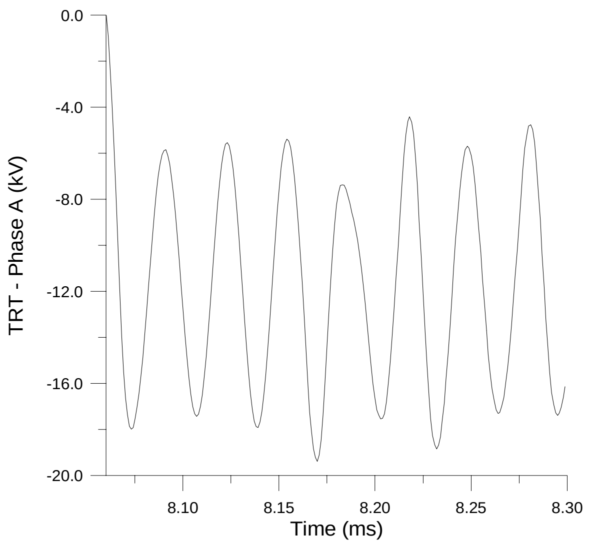

Fig. 7. TRV waveform for short-line fault at 1km from 21Y3 breaker terminals (13.8 kV bus with no load).

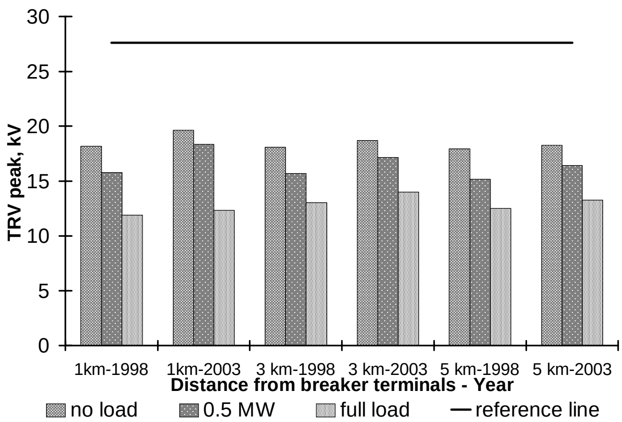

Fig. 8. TRV peaks (short-line fault).

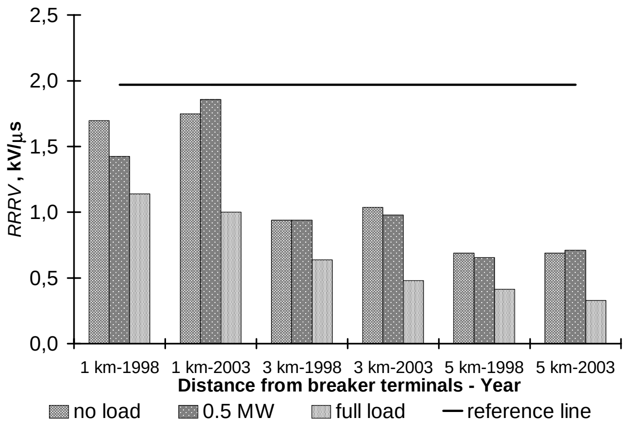

Fig. 9. TRV rate of rise (short-line fault).

Note in figs. 6 and 9 the reference line values for 21Y3 breaker are different since the AC short-circuit current peak values calculated for interrupting short-line faults are smaller than for three-phase ungrounded terminal faults. Thus, as shown in Fig. 9 and according to Table 1, the 21Y3 breaker TRV capability is at 0-30% level of interrupting rating (1.97 kV/μs).

V. ALTERNATIVE ACTIONS TO REDUCE TRV

The placement of ZnO devices (three or four ZnO disks - commercial layout - 62 mm diameter and 23 mm height) across the breaker terminals (Fig. 10) is an alternative to reduce TRV peaks. Figs. 11 and 12 show simulation results for the 11T4 and 21Y4 circuit breakers when clearing a three-phase ungrounded terminal fault (the TRV waveform for the 21Y3 breaker is similar to the one for the 21Y4 breaker).

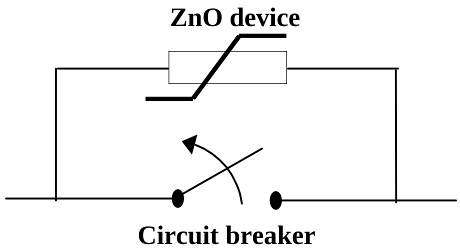

Fig. 10. ZnO device to reduce TRV peaks.

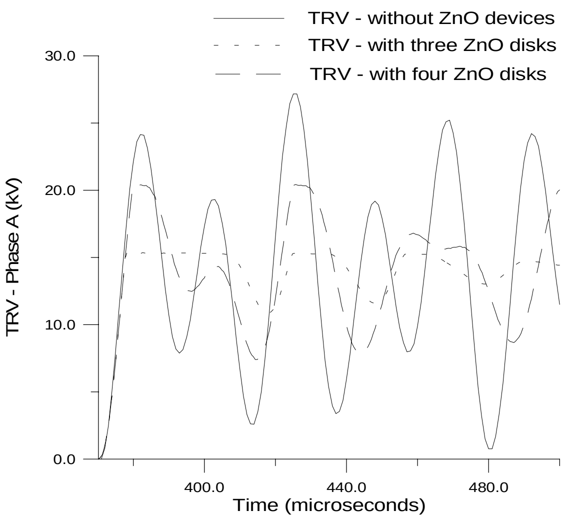

Fig. 11. TRV – 11T4 breaker.

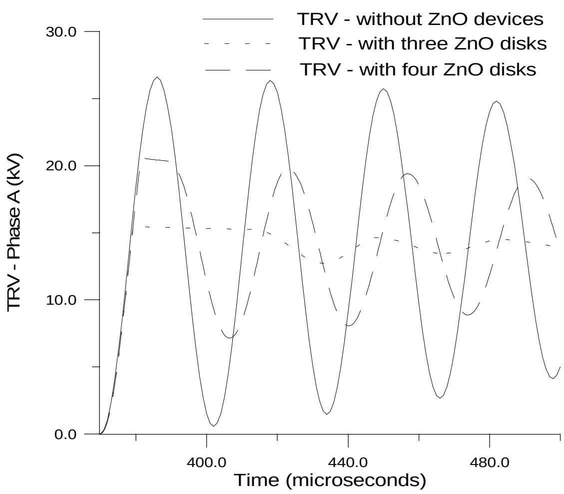

Fig. 12. TRV – 21Y4 breaker.

The calculated TRV parameters are shown in tables 8 and 9. If ZnO devices are used the TRV peaks will be within standard values (Table 1).

The simulated absorbed energy curve for a three ZnO disk device is shown in Fig. 13. After 2ms the energy increase is very small.

Table 8. TRV calculated parameters - three ZnO disks

Year	Breaker	U_c (kV) without ZnO device	U_c (kV) with ZnO device	$RRRV$ (kV/μs) without ZnO device	$RRRV$ (kV/μs) with ZnO device
1998	11T4	28.07	15.44	2.51	2.14
	21Y4	27.92	15.50	1.90	1.72
	21Y3	28.17	15.56	1.99	1.72
2003	11T4	33.73	16.86	2.92	2.43
	21Y4	33.72	15.60	2.54	1.93
	21Y3	33.94	15.67	2.60	1.98

Table 9. TRV calculated parameters - four ZnO disks

Year	Breaker	U_c (kV) without ZnO device	U_c (kV) with ZnO device	$RRRV$ (kV/μs) without ZnO device	$RRRV$ (kV/μs) with ZnO device
1998	11T4	28.07	20.49	2.51	2.24
	21Y4	27.92	20.60	1.90	1.83
	21Y3	28.17	20.62	1.99	1.84
2003	11T4	33.73	20.64	2.92	2.66
	21Y4	33.72	20.72	2.54	2.18
	21Y3	33.94	20.81	2.60	2.14

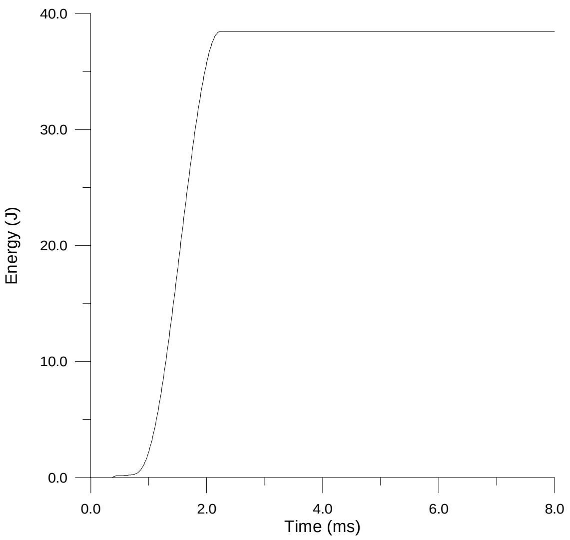

Fig. 13. Three ZnO disk devices absorbed energy.

At steady-state the rms voltage across the ZnO device is nearly 8 kV. The maximum continuous operating voltage (MCOV) for the power system is 8.8 kV. The steady-state current peak values to three and four block ZnO devices are nearly 0.65mA and 0.18mA, respectively. The used arrester *v-i* curve was the one for a temperature of 40ºC [7]. The energy absorbed by the ZnO blocks in either case is very small.

Comparing tables 8 and 9 with Table 1, the TRV rate of rise values are still above the standard ratings. Thus, it is recommended the installation of surge capacitors at the source side breaker terminals.

For the 11T4 circuit breaker a 37 nF (four ZnO disks) surge capacitor would reduce the *RRRV* to values within the standard rating in the two configurations. With this surge capacitor, a *RRRV* reduction of nearly 50% is accomplished for the year 2003-2007 configuration.

Similarly, for the 21Y4 and 21Y3 circuit breakers, 159 nF (four ZnO disks) surge capacitors would bring the *RRRV* values to standard rating.

The use of four ZnO disks to reduce TRV peaks is more appropriate and secure comparing to the use of three ZnO disks. The maximum continuous operating voltage (MCOV) of the arrester and its residual voltage are nearly 11.2 and 20 kV, respectively.

VI. CONCLUSIONS

A study for the reevaluation of 15 kV breakers was performed for the CHESF Angelim substation. The calculated TRV responses were compared to the capabilities of the circuit breakers.

In some situations, the TRV exceeded the breaker ratings. From simulation results, it was shown that the placement of ZnO devices across breaker terminals reduces TRV peaks. Surge capacitors, at the source side, were used to reduce the TRV rate of rise.

Although simulations have shown that ZnO devices placed across the breaker terminals are effective in reducing TRV peaks, it would be interesting to carry out laboratory or field tests for validation purposes.

VII. ACKNOWLEDGMENTS

The authors are grateful to the reviewers for their valuable suggestions. The authors would like to thank the Electrical Engineering Department of UFPB for its support and CHESF for the substation data used in this work. The authors also would like to thank M. O. B. C. Melo, F. R. Alves, J. S. Monteiro (CHESF Engineers), and prof. E. G. Costa, D. Sc. (UFPB). Miss D. M. Nobre wishes to acknowledge to Brazilian National Research Council (CNPq) for financial support.

VIII. REFERENCES

[1] D.L. Swindler, P. Schwartz, P.S. Hamer, S.R. Lambert, "Transient recovery voltage considerations in the application of medium-voltage circuit breakers", *IEEE Transaction on Industry Applications*, vol. 33, nº. 2, March/April 1997, pp. 383-388.

[2] Leuven EMTP Center, *ATP - Alternative Transients Program Rule Book*, Belgium, July 1987.

[3] *NBR-7118 High Voltage Circuit Breaker Brazilian Standards* (In Portuguese), Rio de Janeiro, Brazil, 161 p., September 1994.

[4] CCON ((North-Northeast Operation Coordinating Committee), *Methodology and Criteria for the Analysis of Circuit Breakers Adequacy to Transient Recovery Voltages* (In Portuguese), Recife, Brazil,214 p., June 1991.

[5] *IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis - IEEE C37.011-1994 Standard*, New York, NY, June 1995.

[6] D.M. Nobre, *Transient Recovery Voltage Reevaluation Studies for 15 kV-class Circuit Breakers* (In Portuguese), M.Sc. Dissertation. UFPB. Campina Grande, Brazil, 85 p., November 1999.

[7] E. G., COSTA, *ZnO Surge Arrester Performance Analysis* (In Portuguese), D.Sc. Thesis. UFPB Campina Grande, Brazil, 177 p., April 1999.