USING ELECTRICAL TRANSIENT PROGRAMS TO DEFINE THE EQUIPMENT ASSOCIATED TO A SERIES REACTOR – A CONCEPT DEVELOPED TO THE NEW TUCURUÍ SWITCHING SUBSTATION

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Abstract - **The concepts developed through this report are based on the results of TRV studies carried out to define the main data of the new circuit breakers of the second switchyard of the Tucuruí power plant. Tucuruí is the largest Brazilian generating station. This power plant, located in the North of Brazil, with two power houses and two air-insulated switching substations, will generate, transform and transmit about 9 GVA. In order to reduce the short circuit level to a suitable value, it was decided to make use of a set of air-insulated series reactors connecting both switchyards at the level of 550 kV. The objective of this paper is to show some flashes of the studies developed during the phase of specifications of the circuit breakers of these reactors.**

Keywords: Circuit Breakers Modeling, Transient Recovery Voltages

I. INTRODUCTION

Tucuruí is the largest totally Brazilian generating station. At this power plant, which has two powerhouses and two air-insulated switching substations, it will be generated, transformed and transmitted around *9 GVA*.

In order to increase the system flexibility, it was decided to operate both air-insulated switchyards in parallel. In this way, the short circuit level reaches a value higher than the withstanding limit of the old equipment installed in the first switching station – *40 kA*. Therefore, it was necessary to provide means to reduce the global short circuit level to a suitable limit, usually *90%* of the maximum equipment withstanding current. The most attractive possibility is the use of an air-insulated series reactor, connecting both switchyards in the level of *550 kV*.

The reactance of the short-circuit current limiting device was established based on the results of *Load Flow* – under normal and emergency conditions – *Standard Short Circuit* studies, and *ATP Short Circuit* studies.

According to the results of these studies, the reactance value is *20 Ohms per phase*.

This set of reactors, as shown in *Fig.2*, is connected to two standard one-and-a-half circuit breaker bay, one in the old existing substation which should preferably be maintained without modifications, as for instance the attachment of opening resistors. In order to reduce to the maximum the number of the spare parts of the circuit breakers of the new switchyard, it is interesting to avoid any modification in the standard design. Therefore, to reach these objectives it was developed and studied a solution that deals with cross terminals surge arresters and surge capacitance devices. The objective of this paper is to show the studies carried out to reach these goals. The results of these studies were responsible for the complete basic specifications of the series reactors and of the associated equipment that was necessary to reduce the *TRV* level of the circuit breakers during bus bar faults.

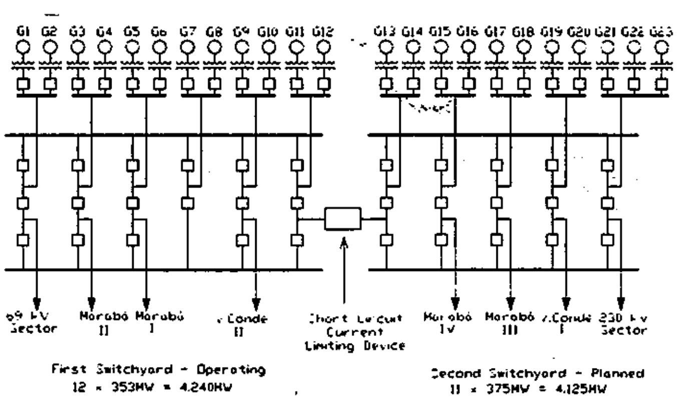

Fig. 1. – Short Circuit Limiting Device Connection

II. TUCURUI TRANSMISSION SYSTEM

Figure 2 shows a one-line diagram of the *Tucuruí Transmission System*. The diagram shows the possible connections that will be operating in the year *2010*. Three basic configurations were studied. The first one is related to the initial stage of construction of the *Second Powerhouse* of the *Tucuruí Power Plant – 2004*. The second one is an intermediate stage – *2007* and the final a

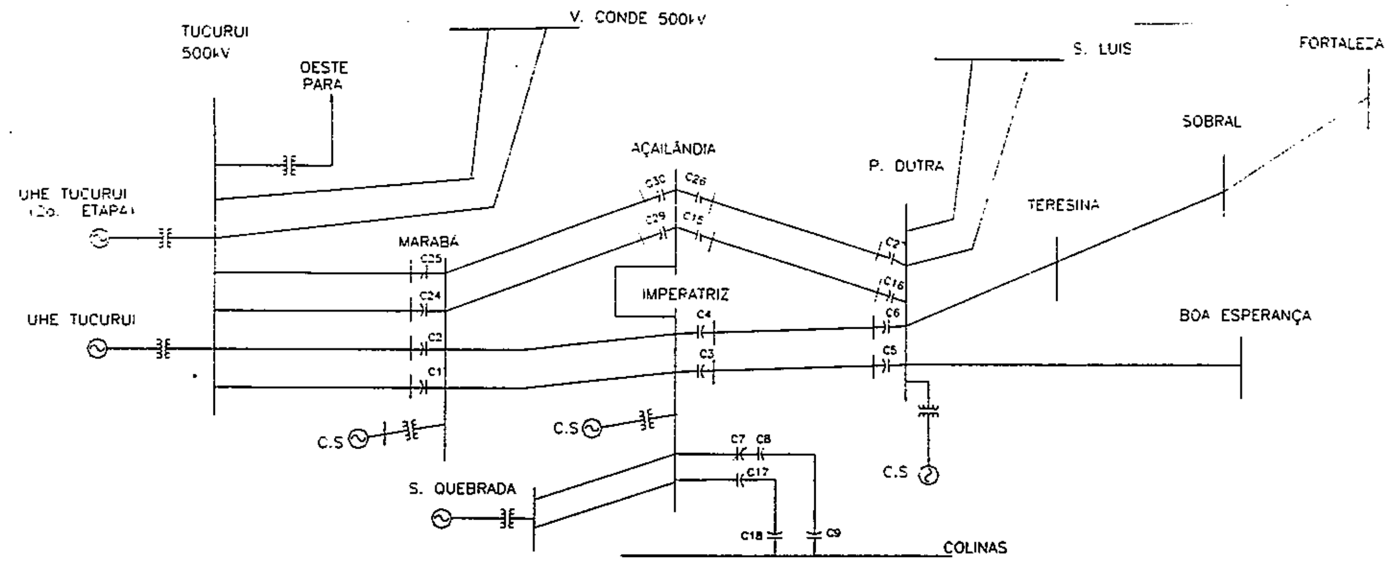

Fig. 2 - Year 2010 – Tucuruí Transmission System

heavy load condition related to the year *2010*.

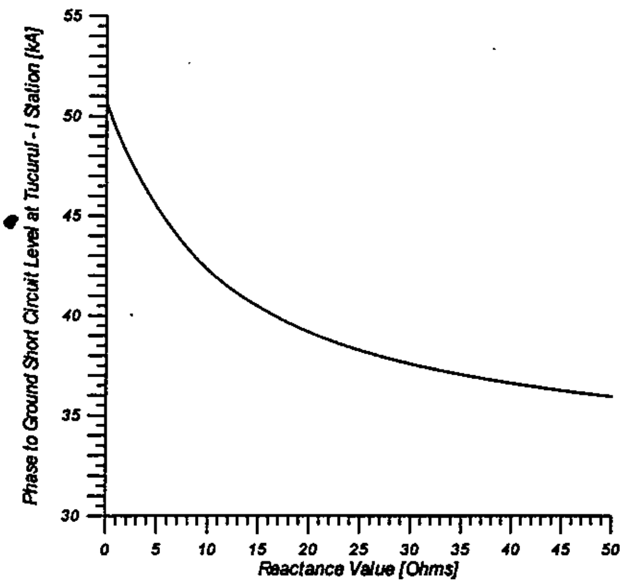

Fig. 3 – Efficiency of the Short Circuit Current Limiting Reactor

The load flow results used to set up the initial conditions to the transient studies were carried out in the complete system, i.e., considering the North – Northeast and the North – South connecting transmission lines.

The efficiency of the short circuit limiting device, considering the *2010* operating condition, is shown in *Fig.3*. In this case, it is possible to observe that there is an efficiency limit for the reactance value. Reactance values higher than *30 Ω* will not reduce the short circuit level significantly.

This is an important fact to the definition of the optimum reactance value. For sure, there is a construction range for these reactors. This range can be related, basically, to the construction, the installation and the electrical system limits. Considering the limits defined only by the electrical system, the lowest one is associated to the rated short circuit current of *Tucuruí – I* circuit breakers and the highest one to a switchyard or a transmission line overload.

Under these conditions, the theoretical range for the reactance is from *17* to *27 Ohms*. After defining the reactance range it is necessary to define the rated current under normal and overload conditions. These values are obtained from load flow studies. These two currents are responsible for the reactor physical dimensions and, therefore, for its costs. In order to take a right technical and economical solution, it is also necessary to submit the reactor pre-specifications to the manufactures or technical experts to have a price – dimension evaluation.

Table 1 shows the short circuit limiting reactor dimensions, according to *ELETRONORTE* previous evaluation.

Short Circuit Current Limiting Reactor – Basic Dimensions				
Reactance [Ω]	*Height [mm]*	*Diameter [mm]*	*Weight [kg]*	I_N *[A]*
17	*3600*	*3100*	*18000*	*1200*
27	*6000*	*2850*	*28000*	*1000*

Table 1 – Short Circuit Current Limiting Reactor Basic Dimensions

III. ATP SIMULATION HINTS

The first simulations results show that in some specific system points, for a single line to ground fault and after a simulation time of *100 – 150 ms*, the voltage in the sound phases starts increasing. This problem is addressed to the *System Equivalent* at the level of *242 kV* that presents a high impedance value. Similar conditions were reported for all the faults involving the ground.

Therefore, in order to extend the simulation time it is necessary to solve this abnormal voltage increase by using a modified *242 kV* sub-system equivalent, as shown in *Fig. 4*. This was carried out considering the load flow data, physical configuration of the system and load profile.

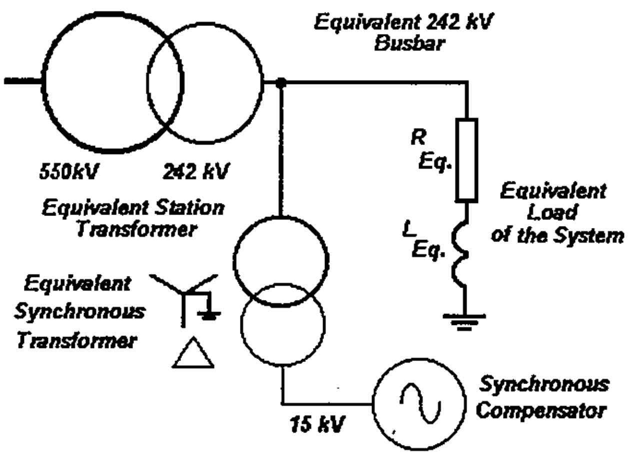

Fig 4 - Sub-System Phase Equivalents applied to the 242kV Sub-systems

To model *Tucurui* generators it was used the simplest generator representation, i.e., constant voltage and impedance – the sub-transient one. The voltage behind the generator impedance, as usually done and recommend by old practices *[1]*, was computed using the X_q reactance. However, for the short circuit calculations it was used the X_d one. For sure, it is possible to use a better generator modeling. However, as most of the simulations are dealing with electrical time constants for the impedance of the generators in the order of *100 ms*, a period of time that probably claims for the back-up protection tripping, this can only result in an extra computational effort. Besides this, it is necessary to consider that the subtransient impedance is the lowest one. This procedure results, indirectly, in a higher safety margin for the circuit breakers, a fact of extreme importance for *Tucuruí – I* switchyard.

Maximum Short Circuit Level With Short Current Limiting Devices: X_R=0; X_{DLCC}=20 [Ω] – [kA]				
Year	$I_{3\phi}$	$I_{1\phi}$	$I_{2\phi}$	$I_{2\phi T}$
2010	*31.11*	*35.75*	*34.91*	*34.83*

Table 2 – Results of the Short Circuit Studies Using the ATP Program

The results obtained with the *ATP Program* indicate the possibility and the necessity of reevaluating the reactance of the short circuit current limiting device. This is shown in *Table 2*. As observed, the reactance value of *20 Ohms* is a quite suitable one, offering a reasonable safety margin to the *40 - kA* circuit breakers. This reactor has characteristics close to the presented by the *17 Ohms*, therefore, probably they will have physical dimensions quite similar to that one. This means a strong economy in equipment and installation facilities.

IV. THE SWITCHING OPERATION OF TUCURUÍ SHORT CIRCUIT LIMITING DEVICE

During a fault at one of the buses of the *Tucuruí* switchyards it is necessary to disconnect the substation tie, i.e., to disconnect the reactor by means of its four circuit breakers.

The circuit breakers on the fault side will open without any difficulty. However, the circuit breakers on the sound switchyard will be submitted to a very strong stress mainly regarding the *RRRV*. This is a particular stress that can result in an SF_6 circuit breaker failure. The high *RRRV* stress is associated to the high inductance of the short circuit current limiting device – the series reactors – and its low stray capacitance. In these cases, the *RRRV* can reach *10 kV/μs* or even higher values. This is a very severe stress to any design of circuit breaker.

The control of the *RRRV* can be achieved by the use of surge capacitors and metal oxide surge arresters. The surge arresters must be connected across the terminals of the reactor. However, regarding the surge capacitances there are three different possibilities of connection:

- Phase – to – ground;
- Across the terminal of the reactors; and
- Phase – to – phase.

The main physical characteristics and differences among these connections are the number, the voltage and the maximum capacitance per voltage level of the surge capacitors.

Surge Arrester Rated Voltage	*120 [kV]*	*132 [kV]*	*144 [kV]*
RRRV [kV/μs]	*3.21*	*4.48*	*6.29*
TRV [kV]	*435*	*440*	*440*
Surge Arrester 100 ms TOV Capacity [kV]	*150*	*165*	*180*

Table 3 – TRV – RRRV on the Circuit Breaker of the Sound Switchyard for a Phase – to – Ground Fault and for a Surge Capacitance of 4,000 pF

To correctly solve the problem it is first necessary to know the value of the stray capacitance of the reactors. After this, it is necessary to define the surge arrester rated voltage. The rated voltage of these arresters is determined by the reactance value and by the short circuit through the reactors. During the fault the voltage across the terminals of the reactor is applied to the surge arrester. Therefore, the surge arrester *TOV* capacity must be checked against the developed voltage. This can easily result in a straight forward rule: The higher is the surge arrester rated voltage, the higher is the *TOV* capacity and the lower is the stress applied to the surge arrester during a fault. This is a very important condition once the surge arrester failure results in the reactor by - pass and therefore in an increase of the short circuit level, which severely stress the circuit breakers.

The key problem against this procedure is that any increase in the surge arrester rated voltage means, for a fixed surge capacitance, in an increase in the *Rate of Rise of the Transient Recovery Voltage - RRRV*, as shown in *Table 3* and in *Fig. 5* and *6*.

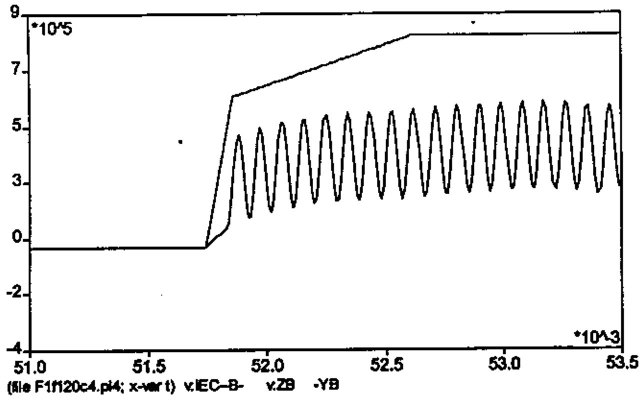

Fig 5 – TRV on the Circuit Breaker of the Sound Switchyard, for a Phase – to – Ground Fault, a 120 kV Surge Arrester and a Surge Capacitance of 4,000 pF

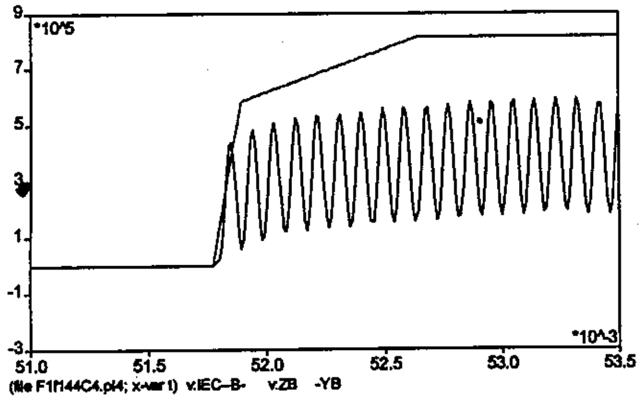

Fig 6 – TRV on the Circuit Breaker of the Sound Switchyard, for a Phase – to – Ground Fault, a 144 kV Surge Arrester and a Surge Capacitance of 4,000 pF

Considering *Table 3*, *Fig. 5* and *6*, it is possible to define a general trend, i.e., the increase of the rated voltage of the surge arrester is necessary to protect this equipment from the *TOV* associated with the system. However, this also results in an increase in the *RRRV*, which is a strong limitation for the circuit breaker. The computed *100 ms System TOV* is *170 kV* and the standard circuit breaker *RRRV*, as required by *IEC – 60056*, for a first breaking pole factor of *1.5* and *30%* of the rated short circuit current, is *5 kV/μs*.

As it is necessary to keep some *TOV* safety margin for the surge arrester, it is necessary to have a suitable way to reduce the *RRRV*. This can be done by increasing the surge capacitance. The effect of increasing the surge capacitance, considering a *144 kV* surge arrester, is shown in *Table 4* and in *Fig. 7*.

Capacitance of the Surge Capacitor[pF]	*4000 [pF]*	*6000 [pF]*	*8000 [pF]*
RRRV [kV/μs]	*6.29*	*5.62*	*5.30*
TRV [kV]	*440*	*450*	*455*

Table 4 – TRV – RRRV on the Circuit Breaker of the Sound Switchyard for a Phase – to – Ground Fault and a 144 kV Surge Arrester

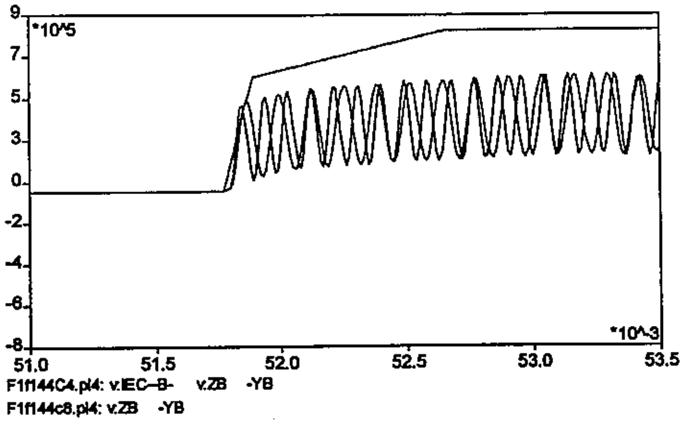

Fig 7 – TRV on the Circuit Breaker of the Sound Switchyard, for a Phase – to – Ground Fault, a 144 kV Surge Arrester and a Surge Capacitance of 4,000 pF and of 8,000 pF

The results of *Table 3* and *4*, *Fig. 5*, *6* and *7* are related to the results of simulations considering *6* surge capacitors connected between phase to ground – *3* in each side of the short circuit current limiting reactor. These capacitors are insulated to *550 kV* to ground and installed in grounded supporting structures. The key problem in this case is the high value of the capacitance for this voltage level.

There are another two possibilities to connect the surge capacitors: the first one is across the reactor terminals and the second between the system phases.

The connection across the reactor terminals results in virtually the same *TRV* and *RRRV* values except for the three phase faults. In these cases the *RRRV* is *5%* higher than in the connection phase – to – ground. In fact, for practical reasons this difference can be neglected. The surge capacitor rated voltage must be compatible with the voltage across the reactor during faults, i.e., not less than *170 kV*. It is probable that surge capacitors with this rated voltage will present a failure rate practically null, because during most of the time the applied voltage to the set formed by the reactor and the surge capacitor will be less than *30 kV*.

The only strong problem in this case is the need of improving the reliability of the complete set up – reactor, surge arrester and surge capacitor – because a failure in one of the protective elements will result in the reactor short circuit and in an overstress to the circuit breakers. However, it is possible to get higher capacitances at this voltage level. This is very important because the increase of the capacitance, associated to the reduction of the rated voltage of the surge capacitor, can make feasible the use of higher total capacitance values and this is necessary to have surge arresters with higher rated voltages.

According to some initial considerations, the surge capacitors, at least *3*, and also the surge arresters must not be installed in the existing space inside the short circuit current limiting reactor. As presently defined, they must have proper insulating supports structures.

The last connection possibility for the surge capacitors is between phases. In terms of installation difficulty and also surge capacitors construction, this is the worst alternative. The surge capacitors must be *550 kV* phase to phase insulated and installed in insulating supporting structures. In this case, at least *6* surge capacitors are necessary in this connection, *3* installed in each side of the reactor.

Figure 8 shows the comparison of the *TRV* for the phase to phase and phase to ground connections of the surge capacitors. As shown, the phase – to phase connection introduces a higher damping and also reduces the *TRV – RRRV* stresses.

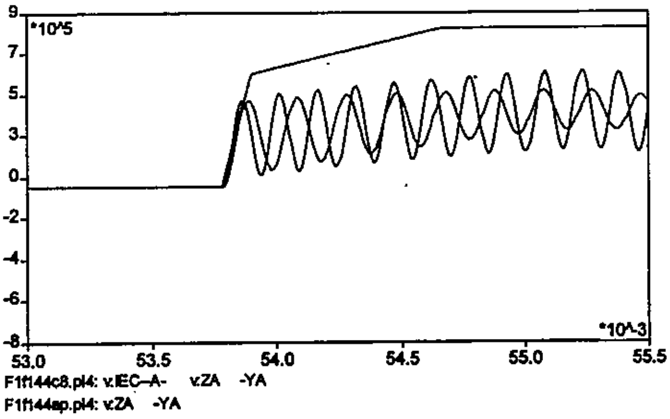

Fig 8 – TRV on the Circuit Breaker of the Sound Switchyard, for a 144 kV Surge Arrester, a Surge Capacitance of 8,000 pF, considering the Connections, Phase – to – Phase and Phase – to – Ground

It is reasonable to suppose that the capacitance of a surge capacitor increases with the reduction of the rated voltage. This can be observed in *Table 5*. In spite of the possibility of facing a system protection collapse during a fault due to a surge arrester or even a surge capacitor short circuit it appears reasonable to adopt the surge capacitor cross terminal connection. This will make feasible the use of surge arresters with high rated voltages, which intrinsically have a higher *TOV* withstanding capacity and, therefore, a higher safety margin. However, this will claim for a higher surge capacitor capacitance. This possibility appears to be suitable only for surge capacitors with low rated voltage because, this is the only way to keep a low number of surge capacitors in parallel, a necessary condition to have a high capacitance value.

This connection presents some risks. However, the potential risk of a surge arrester failure, a strong problem during short circuits with a simultaneous breaker failure, is reduced by the increase – keeping a low number of surge capacitors in parallel – of the capacitance across the terminals of the short circuit current limiting device.

Rated Voltage of the Surge Capacitor [kV]	*1 Minute Withstanding Voltage [kV]*	*Capacitance [pF]*	*BIL [kV]*
100	*180*	*20,000*	*450*
123	*180*	*17,000*	*550*
145	*275*	*14,000*	*550*

Table 5 – Main Characteristics of 145 kV Surge Capacitors

The use of a *162 kV* surge arrester to protect the short circuit current limiting reactor claims for at least the use of a capacitance of *24,000 pF*. *Fig 9* shows the result of *TRV* considering two *123 kV* surge capacitors in parallel per phase, a connection that has *34,000 pF*. This value excludes the necessity of the previous knowledge of the stray capacitance of the reactor. In this case, the *RRRV* for a three-phase fault is *4.0 kV/μs*.

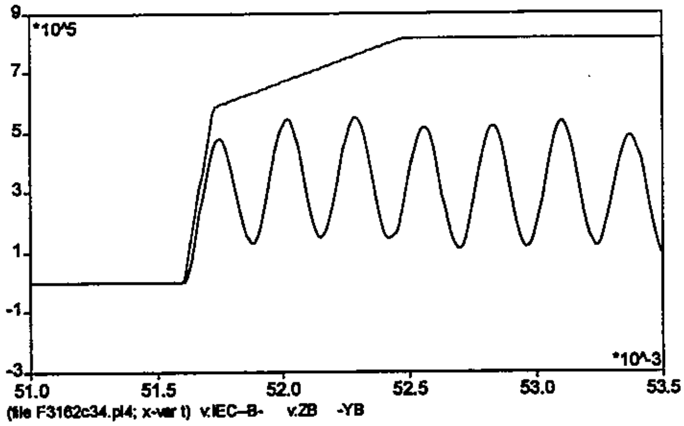

Fig 9 – TRV on the Phase – B of the Circuit Breaker of the Sound Switchyard – 162 kV Surge Arrester, Surge Capacitance 34,000 pF for a Three Phase Fault

As previously stated, the surge arrester and the surge capacitors must not be installed in the existing space inside the short circuit limiting reactor in order to avoid that any violent failure of one of these devices results in a further damage on the short circuit current limiting device. Due to their importance to the operation of both *Tucurui* switchyards in parallel, it is strongly recommended to install some kind of on–line monitoring device on these apparatus. It is also part of the common sense, that the reactor manufacturers must verify the *RRRV* limiting system, as they have all the data that can be used to optimize the whole specification process of the apparatus and system.

According to this paper, one of the surge protection system for the proposed short circuit current limiting device, suitable to keep a low circuit breaker *RRRV*, is composed by *6 – 123 kV* surge capacitors and *3 – 162 kV* gapless metal oxide surge arresters, connected across the reactor terminals.

The parallel connection can present some degree of danger to the whole *Tucurui Electrical System*. However, the right choice of the characteristics of the apparatus, associated to a reliable monitoring system, is the key factor to the successful operation of the electrical system. The knowledge of the cost figures is also necessary to the correct definition of the surge capacitor connection, but this is a problem closely attached to the manufactures and must be object of further discussions.

V. CONCLUSIONS

The switching of power reactors is a very hard task because, normally, this operation results in a circuit breaker overstress. In the case of *Tucuruí* switchyards it is very important to make use of standard circuit breakers, mainly due to the fact that it is interesting to keep operating the circuit breaker generation installed in the first substation switchyard. This requires the study of non-conventional means of reducing the *TRV* and *RRRV* stresses.

The possibilities of controlling these stresses are discussed in this paper. Two of them use extra-high voltage surge capacitors. However, both connections present a low potential risk for the system operation. The third one appears to be of easy implementation.

A better solution claims for a better knowledge of the stray capacitance of the short circuit current limiting device and also of the maximum capacitance, per voltage level, of the surge capacitors. These informations must be combined with cost figures in order to provide a good picture of the whole problem.

Adopting the cross terminal connection, at least, in a first approach, appears to be a reasonable practice, mainly because it is quite apparent that this configuration will present a higher number of possible solutions. It is necessary to check the surge arrester rate of failure under *TOV* stresses and also to have some idea about the aging under this type of stress. The increase of the surge arrester rated voltage is, basically, the only solution to minimize these problems. However, this claims for an increase in the capacitance of the surge capacitors and, depending on the maximum value of capacitance of each capacitor per voltage level, this means the installation of parallel units per phase. The failure rate of surge capacitors is usually low, and probably there will be a further reduction in this rate attached to the standard operational conditions of the electrical system. However, mainly for this connection the value of this rate must be object of a careful study.

The application of a complete monitoring system, i.e., the on-line verification of the most important equipment data – reactor, surge capacitors and surge arresters – is the key factor for a successful global system operation. Therefore, it is considered that the reactor manufacturer must supply an on-line monitoring system. Furthermore, he must verify the efficiency of the complete *TRV/RRRV* proposed solution.

The above study was responsible for the basic specification of the short circuit current limiting device and the associated devices to control the *RRRV* applied to the circuit breakers of the *Tucuruí Power Station*. However, as the analyses of the alternatives were not based on a complete marketing view, the manufacturers must check them because, depending on their source of technology, some of them can not be completely fulfilled.

Finally, it is necessary to state that in the beginning of this study the adopted solution for the connection of the surge capacitors was the phase – to – ground connection. However, after some verifications it was decided to stress the cross terminal connection that seems to present the highest degree of flexibility. The potential system operational danger associated with this connection can be reduced by a proper surge arrester and surge capacitor specification. Therefore, it is recommended that the manufacturer in agreement with *ELETRONORTE* verify these specifications and the complete system design.

VI. REFERENCES

[1] Westinghouse, *Electrical Transmission and Distribution Reference Book*, Copyright 1964, East Pittsburgh.

[2] *ATP Reference Rule Book* – 1990.

[3] *IEC 60056 - High-voltage Alternating-Current Circuit Breakers*