Short Circuit Studies Using Electrical Transient Programs – The Impact on the Definition of Old Equipment Withstanding Limits and Related Subjects An Overview Based on Studies for Tucuruí Switching Substation

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Abstract - **In general there is a very large sort of specific *Short Circuit Program*. The main use of them is to define some basic data for system – equipment specifications, related to thermal – mechanical stress, or even to verify if old system – equipment can withstand new stresses attached to the system growth. The present reported experience was based on the results of a set of studies, including simulations of short circuit using the *ATP Program*, carried out to define the basic data for the second power house and switching substation of Tucuruí power plant. The main results of this procedure were the reduction of the size of the short circuit limiting reactor and a suitable definition of the short circuit current to ground, a very important parameter on the design of the system protection.**

Keywords: Transient Analysis, Modeling, Short Circuit and Transient Studies

I. INTRODUCTION

Tucuruí is the biggest Brazilian generating station, once that Itaipú is only partially owned by *Brazil*. At this power plant it will be generated, transformed and transmitted at about *9 GVA*.

The first aim of the present study was to get data in order to define a new set of equipment specifications. However, it was decided to operate both switchyards in parallel. In this way, the short circuit level reached 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 of reducing the global short circuit level to a reasonable limit, usually *90%* of the maximum equipment withstanding. The most attractive possibility was the use of a series reactor, connecting both switchyards in the level of *550 kV*.

To study the parameters of these reactors – it was decided, as a first step, to use air insulated reactors, one per phase – a set of steady state simulations were carried out. From the results of *Load Flow* – under normal and emergency conditions – and *Standard Short Circuit* studies, it was defined a range for these reactors – *17* to *27 Ohms per phase*. After this, some consults were directed to reactor manufactures and based on the obtained answers some important mechanical data and installation requirements were determined.

There are some limits for the reactors size, physical – due to installation restrictions, electrical – due to short circuit level and transmission lines overloads. Besides this, the efficiency of using reactors to control the short circuit level is limited to a small range. Beyond a reactance value, there is no net benefit and more, in this particular case, beyond *27 Ohms* there is a series of problems related to overloads in some of the transmission lines. This, for sure, can be addressed to the particular *Tucuruí System*. However, this can be also a general trend.

This paper deals with the impact of the short circuit studies on the definition of the system security level, the reactor main parameters and also the value of the injected current to ground that is used to define the protection and grounding system main parameters. As usual, the obtained short circuit level with the *ATP Program* was lower than the standard one. It is interesting to observe that the arithmetic sum of all the contributions to the fault is practically the standard value. Therefore, this reinforces the necessity of considering the voltage phases before fault application in computing the short circuit level. The use of the standard short circuit equivalent, to model some of the sub-systems, was not a good general practice, as observed in two specific conditions. Finally, as not observed in the standard short circuit studies, using standard and conventional simulation tools, the highest value of current to ground was not related to single line to ground faults.

II. TUCURUI TRANSMISSION SYSTEM

Figure 1 shows a one-line diagram of the *Tucuruí Transmission System*. The diagram shows the possible connections operating in the year *2010*. Three basic configurations were studied. The first is related to the initial step of construction of the *Second Powerhouse* of the *Tucuruí Power Plant – 2004*. The second is an intermediate step – *2007* and the final a heavy load condition related to the year *2010*.

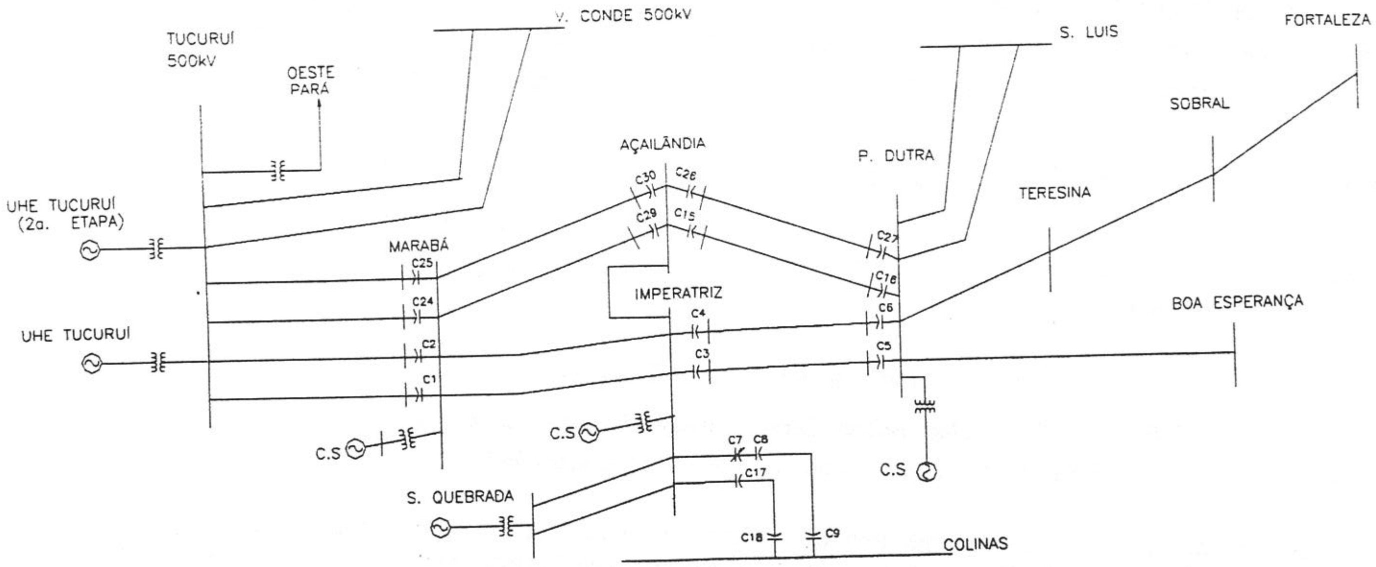

Fig. 1- Year 2010 – Tucuruí Transmission System

The load flow 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 lines. However, the standard short circuit studies considered systems equivalents connected at *Imperatriz – 550kV, Vila do Conde – 550kV, Marabá – 242kV* and *Altamira – 242kV*. *Table 1* shows the results obtained during standard short circuit studies considering the non-limiting condition.

Maximum Short Circuit Level Without Short Circuit Limiting Devices: $X_R=0$; $X_{DLCC}=0$ [kA]				
Year	$I_{3\phi}$	$I_{1\phi}$	$I_{2\phi}$	$I_{2\phi T}$
1999	*23.96*	*28.68*	*20.75*	*27.38*
2003	*31.06*	*36.86*	*26.90*	*35.17*
2004	*34.90*	*41.50*	*30.22*	*39.58*
2007	*42.05*	*49.64*	*36.42*	*47.34*
2010	*43.26*	*50.76*	*37.46*	*48.39*

Table 1 – Results of the Standard Short Circuit Studies

The efficiency of the short circuit current limiting device – from all the possibility it was decided to install a series reactor connecting both powerhouse switchyards, as shown in *Fig.2* – 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. Beyond a reactance of *30 Ω* the reduction of the short circuit current level is not significant.

For sure, there is a construction range for limiting reactors. This range can be addressed, basically, to construction and installation facilities. The limits are also attached to rated and overload system conditions and to the overall system performance. Regarding both *Tucuruí Switchyards* there is no apparent physical limit to the size of the short circuit current limiting reactor, except the ratio reactor cost and efficiency. However, operational conditions under standard and emergency load flow, for the system and for the equipment, must be analyzed. From these conditions are defined the lowest and highest reactance limits. The lowest one is attached to the rated short circuit current of *Tucuruí – I* circuit breakers and the highest to a switchyard or a transmission line overload.

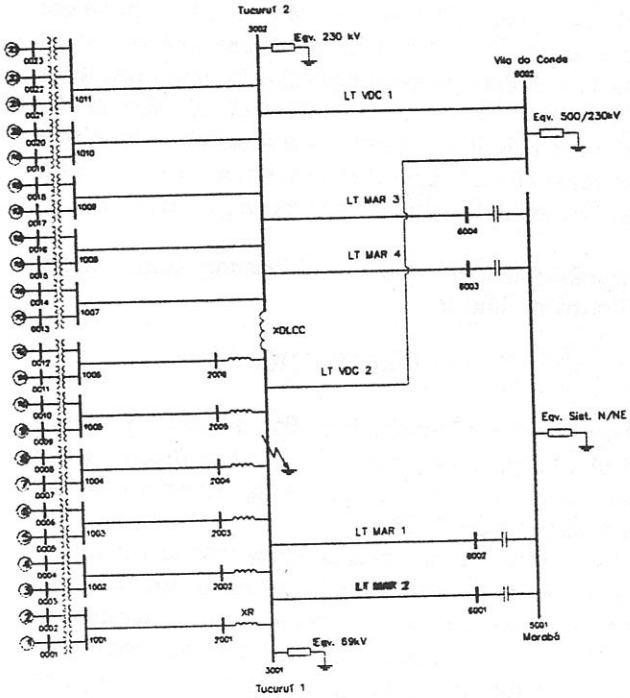

Fig. 2 – System for Short Circuit Studies and the connection of the Current Limiting Device

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

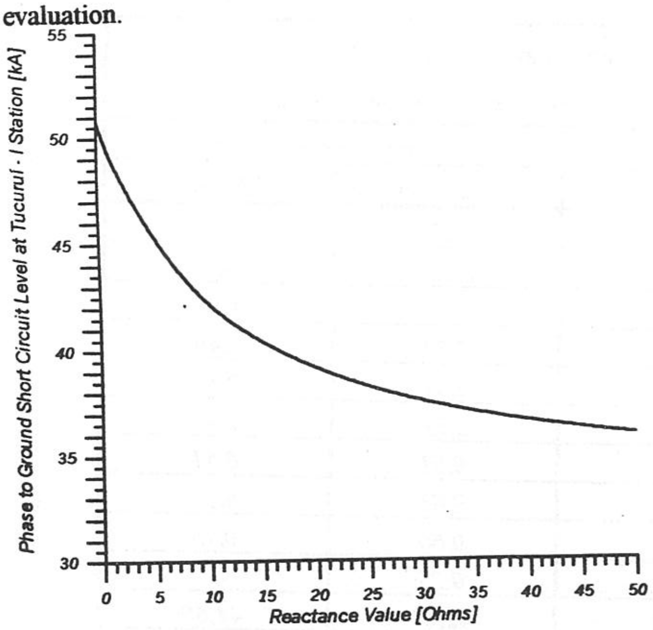

Fig. 3 – Efficiency of the Short Circuit Current Limiting Reactor

Table 2 shows the short circuit current 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 2 – Short Circuit Current Limiting Reactor Basic Dimensions

III. RESULTS OF THE TRANSIENTS STUDIES

During the studies to define the equipment specifications of *Tucuruí – II* it was carried out a set of transients studies using the *Program ATP*. The system was modeled considering the real transmission lines, shunt reactors, transformers and other equipment data. The modeled system is shown in *Fig.2*.

The most important observation obtained from the first step of these studies is related to the use of subsystem equivalents. As new computers facilities are fast and efficient it is possible to simulate the operational performance of the *"Complete Tucuruí System"*, i.e., the transmission system starting at *Tucuruí Power Station* ending at *Vila do Conde 242 kV Transmission System*, at *Altamira 242 kV Substation* and at *Imperatriz 550 kV Substation*.

In the traditional way, short circuit studies, for instance to determine *TRT* profiles, started with a pre-applied short circuit followed by an opening of the involved circuit breakers. Therefore, the complete simulation time is normally inferior to *150 ms*. New computers permit to simulate a complete protection cycle, considering relay and transfer-trip time, circuit breaker and breaker failure time and so one. This is a key difference, i.e.; in this case, the simulation time can reach easily more than *500 ms*.

Figure 4 shows the voltage profile at *Vila do Conde 550 kV* after a phase – to – ground fault. As can be seen, after a simulation time of *100 – 150 ms*. the voltage in the sound phases start increasing, and there is neither a reasonable explanation to this fact or even a register of a similar event in the present operating system. After some initial considerations the problem was addressed to the *System Equivalent* at the level of *242 kV* that, according to *Table3*, presents a high impedance value: *Altamira, Vila do Conde* e *Marabá*. During the first simulations steps the equivalents for all sub-systems were modeled by coupled sequence elements. Similar conditions were reported for all faults involving the ground.

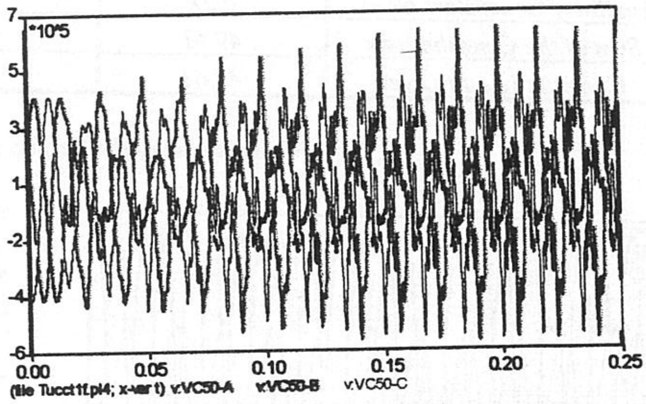

Fig. 4 – Vila do Conde 550 kV Phase Voltages for a Phase – to – Ground Fault – Standard Result

System Equivalents [kV]	R_1	X_1	R_0	X_0
TUC – I – 72.5	-. -	-. -	-. -	-. -
OESTE do PARÁ	*18.904*	*189.035*	*20.189*	*177.189*
VDC – 550/242	*0.336*	*8.762*	*0.189*	*9.452*
MAR – 550/242	*0.52*	*3.730*	*0.056*	*3.198*
IMP – 550	*0.038*	*0.649*	*0.110*	*0.650*

Table 3 – System Short Circuit Equivalents – 100MVA 550kV Base [%]

In order to extend the simulation time it is necessary to solve this abnormal voltage increase. This means to use of a modified *242 kV* sub-system equivalent. The adopted solution asks for using of sub-system phase equivalents, as shown in *Fig. 6*. This was carried out considering the load flow data, the physical configuration of the system and the load profile. The result of applying these equivalents is shown in *Fig. 5*.

Therefore, as carried out, the complete proposed method verifies the *ATP Data* by means of the *Load Flow* and of the *Short Circuit* results. To model *Tucuruí* generators it was used the simplest generator representation, i.e.,

Short Circuit Current [kA]	*Tucuruí Short Circuit Level – Year 2010* *Without Limiting Device – Pre – Fault Voltage 1.10 p.u.*			
	Single – Line – to – Ground Faults		*Three – Phase Faults*	
Contributions	*Standard Results*	*ATP Results*	*Standard Results*	*ATP Results*
Tucuruí – Power Station – I	*23,86*	*22,37*	*18,56*	*19,05*
Tucuruí – PowerStation – II	*15,84*	*17,42*	*13,24*	*14,47*
Marabá – I	*1,67*	*1,75*	*1,88*	*1,98*
Marabá – II	*1,97*	*2,12*	*2,31*	*2,40*
Marabá – III	*1,97*	*2,12*	*2,31*	*2,40*
Marabá – IV	*1,97*	*2,12*	*2,31*	*2,40*
Vila do Conde – I	*0,50*	*0,55*	*0,51*	*0,51*
Vila do Conde – II	*0,61*	*0,68*	*0,63*	*0,63*
Oeste do Pará	*0,86*	*0,92*	*0,66*	*0,75*
Auxiliary Generators 69 kV	*0,37*	*-.-*	*0,25*	*-.-*
Sum of the Contributions	*49,61*	*50,05*	*42,02*	*44,60*
Computed Fault Level	*49,61*	*46,32*	*42,02*	*39,32*

Table 4 – Comparison of the Results of Short Circuit Current Levels

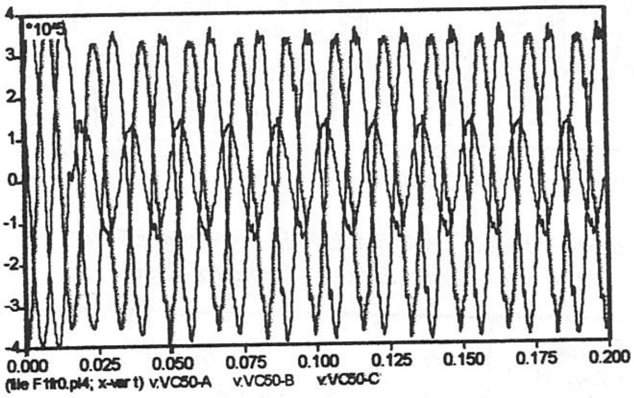

Fig. 5 – Vila do Conde 550 kV Phase Voltages for a Phase – to – Ground Fault – Phase Equivalent

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 of the generators in the order of *100 ms*, a period of time that probably claims for the back protection tripping, this can only result in an extra computational effort. Besides this, it is necessary to consider that the sub – transient impedance is the lowest one. This procedure results, indirectly, in a higher safety margin for the circuit breakers, a fact of extreme importance for the equipment installed at the *Tucuruí – I* switchyard.

Table 4 shows a comparison between the results of short circuit level obtained using the traditional simulation tools – standard short circuit studies – and using the *ATP*. The sum of the short circuit contributions, i.e., without considering the phase of the short circuit current presents as a result a value practically coincident with the standard one. This is a result quite expected, once this corresponds to consider all the voltage phases, before the fault application, as equal, for instance to zero.

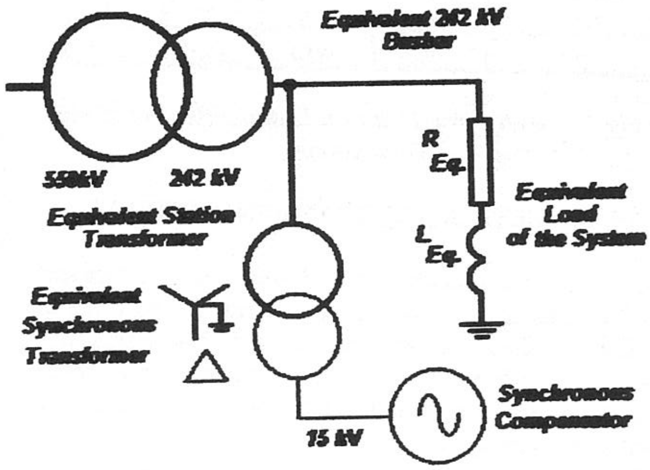

Fig 6. - Sub-System Phase Equivalents Applied to the Substation of Vila do Conde, Marabá and Altamira 242kV

As shown in *Table 4*, the use of the *ATP Program* to compute the short circuit current resulted in a short circuit level that is, at least, *7.5%* lower than the standard. This is a normal, and well known, result. However, considering the size, as can be seen in *Table 2*, therefore, the cost of the limiting reactors and also the necessity of retrofitting of all the SF_6 circuit breakers of *Tucuruí – I Switchyard* and *Powerhouse*, designed for *40 kA*, this conclusion is a very important one.

Reactance of the Current limiting Device [Ω]	Short Circuit Level – Year 2010 – Pre – Fault Voltage 1.10 p.u.	
	Single line – to –Ground Faults [kA]	Three – Phase Faults [kA]
17	36,42	31,47
20	35.75	31,11
27	34,51	29,77

Table 5 – Comparison of the Results of Short Circuit Current Levels and The Reactance of the Current limiting Device

The difference between the short circuit levels, considering the results obtained with the *ATP Program*, indicates the possibility and the necessity of reevaluating the reactance of the short circuit current limiting device. This is shown in *Table 5*. 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 a value close to *17 Ohms*. Therefore, probably will have dimensions quite similar to of that one. This means a strong economy in equipment and installation facilities.

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 6 – Results of the Short Circuit Studies Using the ATP Program

As shown in *Table 6* the highest short circuit current through the circuit breakers installed at *Tucuruí – I Switchyard* is associated to a single phase – to – ground fault. However, the short circuit current injected into the ground, as shown in *Fig. 7* is highest – *42.42 kA*, almost *20%* higher than the standard single phase – to – ground short circuit current. This is level – *42.42 kA* – that must be considered in to the design of the system grounding.

IV. COMMENTS ON THE OBTAINED RESULTS

Sometimes, as can be seen in this paper, it is very interesting to use transient programs to compute the short circuit level. The application of this procedure can be carried out during the planning phase of the system or to verify equipment overstresses because by the use of this procedure can result in a strong economy in equipment and in installation.

However, the possibility of using transient programs to compute short circuit levels, mainly by maintenance and operation teams, is strongly addressed to new computer facilities and therefore few reports exits in this field.

In these cases, the simulation time can reach *500 ms* or even more. As it is well known the short circuit currents computed by means of transient programs are lower than the correspondent ones computed by standard procedures. This difference can be addressed to the phase angles of the pre-fault voltages that in most of the standard cases are assumed as equal to zero.

As observed, it is also interesting and probably necessary to verify the accuracy of the sub-system equivalents that can introduce simulation errors, mainly in radial system configurations, as the observed in *Tucuruí Transmission System*.

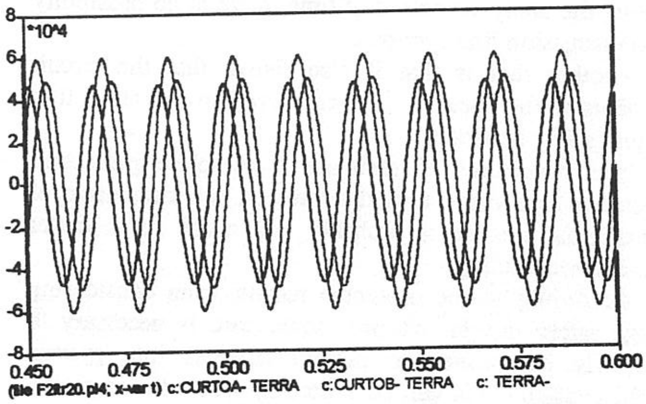

Fig. 7 – Tucuruí – I 550 kV Switchyard – Short Circuit Currents Due to a Double Phase Fault – to – Ground

The computation of the short circuit current injected into the ground can be also verified with a higher accuracy. In real bases, this is not a strong problem to the grounding design because it is normal to adopt very large safety margins. However, the observed difference between the values of the phase – to – ground and the double – phase – to – ground short circuit current can explain some grounding relay false operation. Therefore, an important field of application of this technique is in the definition of the system protection requirements.

As observed in this paper, the proposed method of determining the short circuit level using transient programs can be a powerful instrument mainly during the determination of equipment overstress, a task normally carried out by maintenance and operation departments with the help of standard techniques. In the present case, the application of the above procedure was responsible, at least, for avoiding the necessity of retrofit of *12 GIS – 550 kV* and *17 Air Insulated SF_6 – 550 kV* circuit breakers. To avoid circuit breakers and other equipment retrofit or even complete replacement, for sure, means a lot of money; i.e., an impressive economy, even considering the size of the *Tucuruí* global investment.

However, more data based in systems with physical configuration different from that presented by *Tucuruí Transmission System* must be obtained before to state this as a standard procedure.

V. CONCLUSIONS

In fact, the request to carry out transient studies to verify the performance of the proposed short circuit current limiting device of *Tucuruí Power Station* is part of a series of system requests. However, to extend these studies to determine the short circuit level was a necessity associated to the proposal of accurately dimensioning of the reactance of the short circuit current limiting device.

The most important fact is that this study shown the possibility of reducing the reactance value, which presents a strong economical impact. This new condition resulted in an increase in the system operational margin, because, during the analyzed period of time, there is no possibility of transmission line overload.

Another fact is that it also shown that the circuit breakers of the *Tucuruí – I Switchyard* can operate with a higher safety margin.

The possibility of simulate a complete protection operation was also verified. However, the simulation of breaker failure events probably will claim for a better generator modeling.

According to the presented results, even considering large safety design margins, some care is necessary to correctly determine the current injected into ground during faults. This can be especially true when defining the short circuit current of the standard *OPGW* cables.

Even without considering the correct cost figures the level of economy that these studies resulted was very high. Therefore, in case of doubts they are always recommended.

Another important point that must be stressed is the one related to the protection tripping requirements. As shown by *Table 3* there is some differences between the short circuit levels computed by the standard techniques and by the *ATP Program*. By the moment, there is no sufficient experience, at least in our country, to define a reasonable standard difference margin between the results. However, it appears that to this difference can be addressed a series of protection malfunctioning, an event quite common in some complex systems. In fact, in some special cases, involving large double bus bar substations, it is very interesting to verify this possibility, mainly when it is necessary to define the requirements of the back protection system.

Considering the above statements it is strongly recommended to introduce the transient simulation tooling to the maintenance and also to the protection teams, a practice that in a close future, probably, will be a standard one.

As observed, the techniques applied in this study are well known. However, the results in terms of economy in investment or even retrofit are very impressive. The differences of short circuit currents verified with the application of standard short circuit tools and the *ATP Program* are summarized in *Table 4*. It was also observed that it is necessary to take care with sub-systems equivalents in order to avoid unexpected and incorrect voltage profiles. To extend this procedure to verify system or equipment overstresses, a task usually carried out by the operation people, appears to be a very strong recommendation.

Finally, according to a standard technique used by the Brazilian planning teams – *Custos Modulares [3]*, *"General Substation and Equipment Costs – Brazil Data"*, the application of this procedure results in an economy – at *Tucuruí Power Station* – of at least *US$ 4,500,000.00* with *29 - 550 kV* circuit breakers retrofit (*25%* of a new circuit breaker cost).

VI. REFERENCES

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

[2] *ATP Reference Rule Book* – 1990.

[3] ELETROBRÁS, *Custos Modulares da ELETROBRÁS, Edição 1997*, 1997 Rio de Janeiro.