TUCURUI'S GENERATOR STEP-UP TRANSFORMER FAILURES DUE TO VERY-FAST TRANSIENTS IN GIS

J. F. de Lima Fº C. Machado Jr. W.S. Pinto
Centrais Elétricas do Norte do Brasil - ELETRONORTE
BR 70718-900 SCN Quadra 6 Conj. C Brasília DF-Brazil

J.C.Mendes R.A.Marcondes
ABB Asea Brown Boveri T&D
BR 07190-904 São Paulo , SP-Brazil

ABSTRACT - Many problems in insulation, devices and equipment have been resulted from switching operations in the 500kV (GIS) of Tucuruí power plant.

Disconnect closing or opening action can subject the GIS components to great stresses from excessive voltages at high frequencies caused by successive reflections of traveling waves at discontinuities [1,2,3].

This paper presents the results of analysis of failures in three 13,8/500kV-378MVA step-up transformers, among 12 existing units in the Tucurui power plant, due to very fast transients associated with disconnect switch operation in the 500kV GIS of the Brazilian Northern-Northeast interconnected electric power system, (N/NE) which consists of 3200km, 500kV radial transmission lines that interconnect the Tucuruí power plant (4000MW) and the Paulo Afonso complex (8400MW).

The analysis to confirm the causes of the failures in the three transformers was performed by a team composed of both ELETRONORTE and manufacturer's engineers, with the help of digital simulation by using the ATP (Alternative Transients Program), field measurements (supported by CEPEL- Brazilian Electrical Research Institute) and analysis of the transformer internal insulation withstanding.

This analysis showed that the very fast transients, which were generated by disconnect switching operation, were the fundamental causes of the failures which occurred in 1988 and 1994.

Due to this fact, disconnect switching operation has not been permitted whenever there is voltage on any side of the switches. This imposes severe restrictions on the operation of the system.

KEYWORDS : GIS, Fast Transients, Disconnect Switch Surges, Transformer Failure, Measurement and Simulation.

I. INTRODUCTION

The Tucurui's GIS is made up of 6 identical modules according to the single-line diagram shown in Fig. 1.

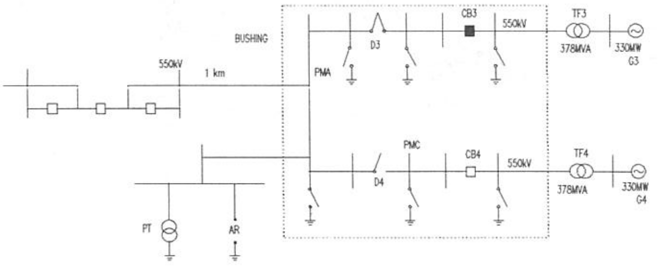

Figura 1 – Single-phase diagram of GIS.

Two generator-transformer groups are connected together to the GIS busbar and interconnected to the 500kV system through an air-insulated 1 km short transmission line and a switchgear substation.

The first Tucurui's generator-transformer group came to operation in 1985.

Nowadays, the Tucuruí power plant has 12 generator-transformer groups in operation. In its final configuration there will be 23 units, and a total installed capacity of 8000 MW.

The Tucuruí power plant is interconnected to the N/NE electric system and covers all the peak load needs of the system.

The 2nd, 4th and 6th units can be operated as synchronous compensators, in order to accommodate load dispatch requirements and avoid generation ranges that may result in turbine cavitation.

When required, the remaining units are disconnected during the light load periods and reconnected during heavy load periods or due to maintenance requirements.

These switching operations always involve a GIS.

Three failures have already occurred in the Tucuruí power plant involving step-up transformers. In two of them, the transformers were completely destroyed due to great fire while in the other one the manufacturer carried out on site repair.

The first failure occurred in May 1988. The transformer, which was connected to the 2nd generator, had been operating for 4 years. The failure started just after the changing of its operation state, from synchronous to generator. The generator group (transformer and generator) was disconnected by both the differential and gas relays of the transformer. Signals of strong electrical discharges were located in the flange of the side wall turret related to phase. A high voltage transformer bushing.

The second failure, involving also the transformer that was connected to the 2nd generator, occurred in June 1988, as showed in photos 1 an 2.

After failure of the second unit, the transformer manufacturer changed the insulation system of the inner HV bushing end shield on side wall turret. This change was extended to all units.

The third failure occurred in October 1994 with the transformer connected to the 11th generator.
The failure involved mainly:

- turn to turn and coil to coil insulation of disk pairs closest to the HV winding, phase B;
- main duct insulation between HV and LV windings, phase B and
- 13.8 kV surge panel including failure of ZnO surge arrester, surge capacitor and discharge to ground.

In this last case, due to the increase in the load, the 11th generator had to begin operation.

The corresponding breaker closed successfully, synchronizing the generator to the 500 kV system. 820 ms after breaker closing, the transformer differential relay operated. In addition, the line overcurrent relays (1 km, 500 kV-fig. 1), phase B, and the generator differential protection also operated.

The breaker opened 900 ms after the synchronization. At this time an explosion followed by burning of the transformer started.

The oscillograph of Tucuruí substation registered the following voltages (Table 1) and currents (Table 2) under pre-fault and fault conditions, in the interconnecting line:

Table 1 - Pre-fault and fault voltages

VOLTAGE	PRE-FAULT	FAULT
VA(kV)	558	417
VB(kV)	549	132
VC(kV)	549	542
3*Vo(kV)	----	256

Table 2 - Pre-fault and fault currents

CURRENT	PRE-FAULT	FAULT
IA(A)	-----	-----
IB(A)	----	12897
IC(A)	----	-----
3*Io	----	12727

In a preliminary ELETRONORTE/ABB on site inspection, it was detected signals of electrical discharges on the HV winding of phase B, closest to the corresponding winding entry. However, due to limited access and damages, it was carried out a complete disassembly in order to investigate the failure extension. Windings were removed disk after disk, starting from HV and finishing at LV windings. This operation was documented with several photo (3 through 8). The main observations were:

- transformer tank rupture and deformation due to internal explosion associated to gas evolution;
- local rupture of bushing insulator which may give an indication of high mechanical stresses;
- mechanical rupture of one, out of two parallel winding conductors, in the connection between coil disk and HV winding terminal;
- several signals of electrical discharges on the winding conductors of the disk pairs located closest to the HV winding terminal. It was also observed rupture of conductors on crossovers and transpositions of the related coils;
- mechanical deformation of conductors in coils closest to the HV winding terminal;
- directed electrical discharge from HV to inner adjacent LV winding through the main duct insulation;

- rupture and signals of electrical discharges on LV winding conductors located approximately 120 mm bellow the HV winding radial central entry and
- in the 13.8 kV generator unit surge panel it was also found indication of a probable short-circuit to ground, namely: signals of electrical discharges from the surge arresters end terminals and surge capacitors (phase B) to the panel metallic side wall (grounded); signals of external electrical discharges on the ZnO blocks and internal short-circuit in the surge arresters and short-circuited capacitors.

The results of the transformer windings disassembly and detailed on site inspection suggested hypothesis in insulation failure associated to transient voltage stresses or to very fast transients.

A lightning impulse was improbable to reach the transformer terminal due to the power plant configuration.

2. ELETRONORTE ACTIONS

In the first two occurrences, actions were taken only by the manufacturer.

The insulation system of the inner HV bushing end shield on side wall turret was changed in all units .

After failure of the third unit, ELETRONORTE and ABB implemented the following actions:

- preliminary on site inspection of the failed unit, which was considered by both as inadequate to determine the cause of the failure;
- detailed on site inspection, including a complete disassembly of the transformer and corresponding windings, in order to identify related failure consequences, arc discharge tracks and failure modes and
- definition of a work group which the following objectives: investigate the failures cause and establish additional actions in order to keep the remain units under reliable operation and establish the electrical requirements on technical specification of future equipment which will be installed on the future stage of Tucurui power plant.

3. DISCUSSED ALTERNATIVES WITH THE TRANSFORMER MANUFACTURER

A group of engineers, from ELETRONORTE and ABB, evaluated alternatives looking upon availability and reliability of the existing units and specification of future transformers to Tucurui power plant.

The main alternatives were:

- minimize the number of under voltage disconnect switch operation;
- on-line disconnect gap analysis monitoring at least for H2 and CO combustible gases;
- on-line register of transient voltage impressed to the transformer HV bushing; and
- proceed a deep measurement of the transient voltage in the GIS, input frequency dependent admittance of the transformer and high frequency simulations.

Considering the specification of the future transformers, the discussed alternatives were:

- include in the technical specification relevant information on expected very fast transients in the GIS, according to measurement and digital simulation results;
- winding dimensioning taking into account very fast transients voltages and internal resonances compared with the expected frequency spectrum of the HV terminal voltages; and
- measure HV winding and transformer frequency response during manufacturing stage. These measurement results may be applied by utility on future reliable protection and operation of the related transformer.

It was found important also to have a close cooperation between utility and manufacturer at specification and design stage of future transformers that are used in GIS.

4. FIELD TESTS AND SIMULATION RESULTS

Opening and closing operations in the Fig. 1 disconnect switch 4 were made and voltage measurement were registered at PMA (phase B SF6/air bushing) and PMC (phase B unit disconnect switch). Fig. 2 shows test field results, Fig. 3 presents the configuration for simulations and Fig. 4 shows simulation results for Fig. 2.

In Fig. 3 the capacitor between nodes PMC and DISJ2A represents the grading capacitor between open contacts of the breaker and the simulations with opposite polarity were performed through generator voltage GER2.

In Fig. 4 the simulation test was performed with 0,04 pu residual voltage and the closing time was changed so that the same 1.23 pu measured overvoltage could be achieved.

A detailed comparison was performed between figure 2 and 4. The latter showed that the greatest overvoltage of 1.23pu happened 141ns after disconnect switch closing, with 4kV/ns rate of rise. The corresponding measured amplitudes were 150ns and 3kV/ns. After 300ns the overvoltages came at 1.18pu (simulation) and 1.19pu(field). The highest observed frequencies, corresponding to the smallest oscillatory amplitudes of Figures 2 and 4 remained around 160MHz (simulation) and 150MHz (field), highlighting the little precision on achieving it through field record.

Extensive analysis of the transformer internal insulation withstanding system was also carried out by the transformer manufacturer. It was considered stresses associated to conventional standard transients voltages and, in approximately way, stresses associated to very fast transients voltages [5].

For conventional standard transients voltages, stresses in the transformer internal main insulation including transient response of the HV winding insulation (turn to turn, coil to coil and coil to ground) were calculated. Comparison between calculated stresses with corresponding statistical withstand voltages, showed safety margins higher than 40%. The critical stresses were in the turn to turn and coil to coil insulation of the interleaved disk pair closest to the HV winding entry.

In addition, stresses in the transformer HV winding internal insulation associated to very fast transients (1.5pu impulse 10/2000ns) were approximately evaluated. First, based on local voltages amplifications described by windings characteristics quality factors (q - factor) [6]. Secondly, by using a more detailed method where the HV disk pairs, closest to the winding entry, are turn by turn represented [7]. Critical stresses, higher than the corresponding approximately withstand voltages, were found in the turn to turn and coil to coil insulation of the interleaved disk pair closest to the HV entry [5,8]. The HV winding presented internal important resonances at 1.5, 1.9 and 2.5MHz frequencies.

The above results were well correlated with the failure modes observed during HV winding disassembly. Failures were found in the disk pairs closest to the HV entry.

5. CONCLUSIONS

Disconnector switch operation establishes very fast transients in GIS which overstrike the connected electrical equipment as power transformers.

Based on measurement, electromagnetic simulation and analysis of the transformer insulation withstanding, it has been accessed critical internal voltages and found correlation between VFT stresses and transformers failures.

A close cooperation between utility and transformer manufacturer must be considered for future specification and design of HV transformers used in GIS.

Operational restrictions on disconnect switches imposed by VFT cause serious difficulties on system operation.

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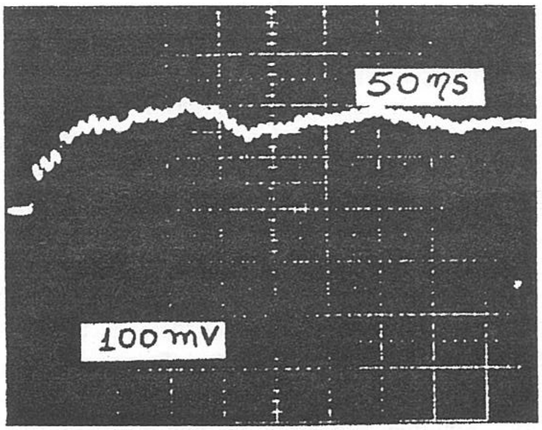

Figure 2 - Closing field record

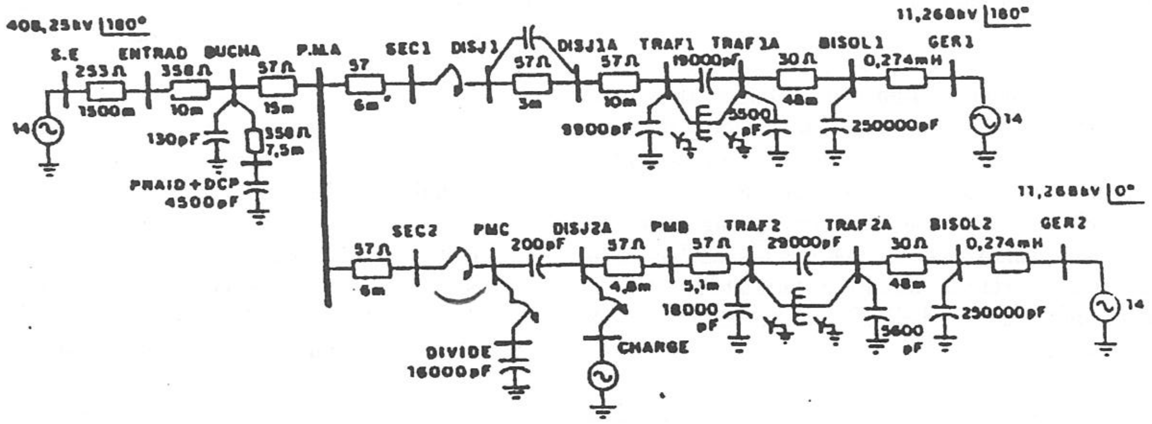

Figure 3 - Basic configuration modeling

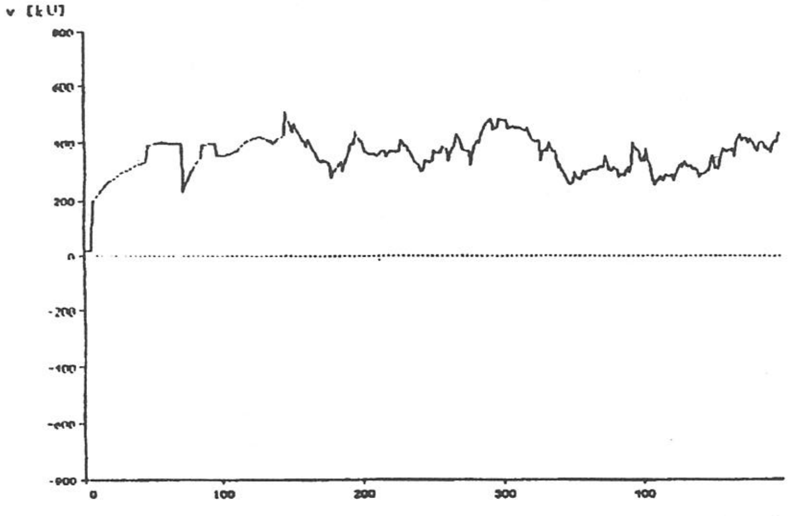

Figure 4 - Closing simulation

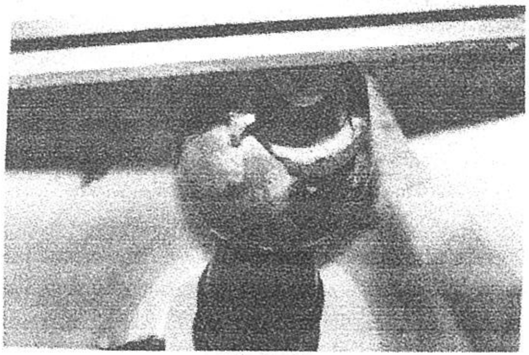

Photo 1

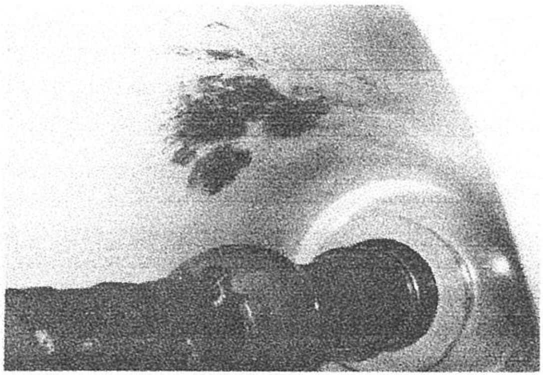

Photo 2

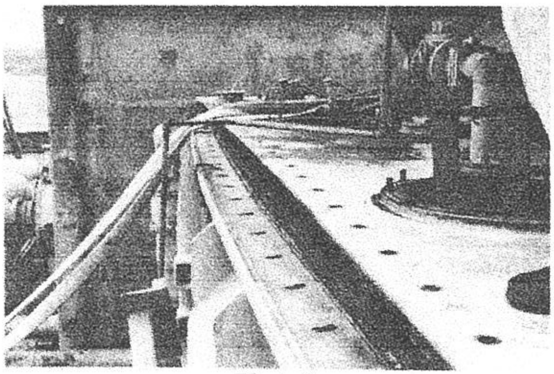

Photo 3

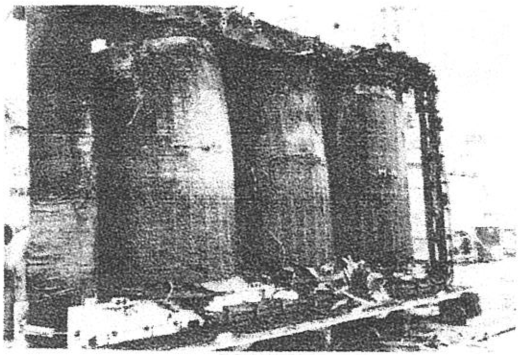

Photo 4

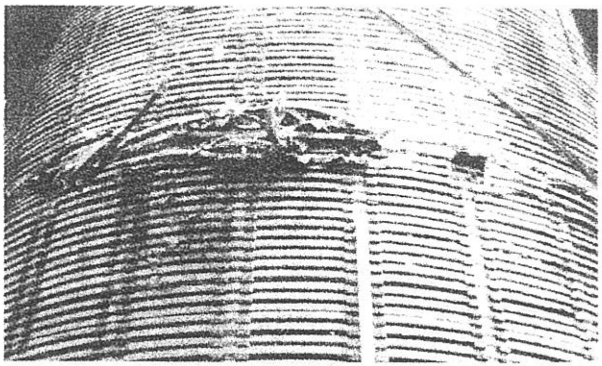

Photo 5

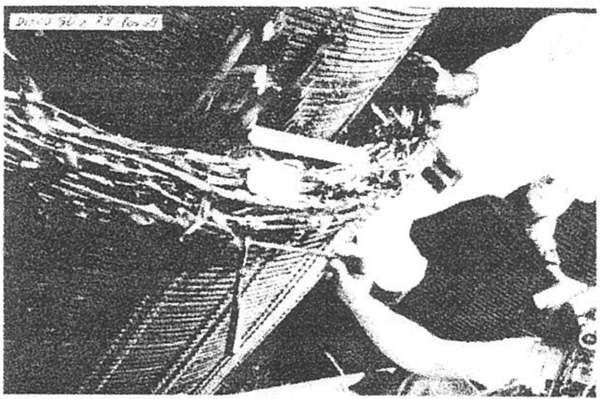

Photo 6

Photo 7

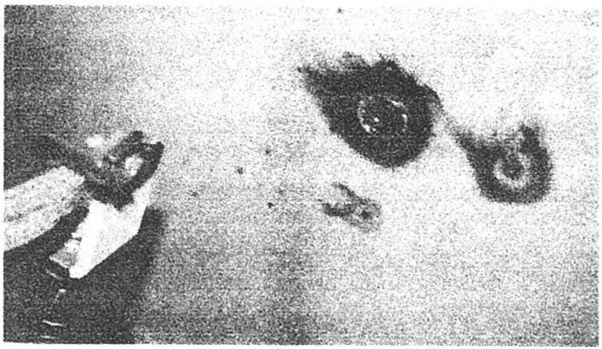

Photo 8