Fast Line Three Phase Reclosing Practice on Brazilian Grid and its Impact on Thermal Generation Plant Shaft

Álvaro J. P. Ramos, *Escola Politécnica da UPE*, Dalton Lima, Termobahia, Egberto Tavares, Main Engenharia; Rita K. Medeiros, ANDESA

***Abstract*--Three Phase reclosing of transmission lines is being an operation practice of Brazilian electric utilities. As the Brazilian power system was almost entirely composed by hydro plants, the impacts of three-phase reclosing on the machine-turbine shaft were not of main concern. With the first large thermal unities, this practice has to be revised. Abrupt variations of generator electrical torque, due system switching may lead to excitation of torsional oscillations of machine shaft. These are low damped oscillation of subsynchronous frequencies typically within the range 10-50 Hz. Three phase faults close to machine terminal constitute two severe abrupt changes on electrical torque, caused by fault application and fault removal. This paper presents an analysis of shaft torque duty of Termobahia Plant caused by tripolar reclosing in its vicinity. The paper discusses the difficulty of obtaining shaft data from manufacturer, modeling aspects and presents results and alternatives to attenuate the problem.**

***Index Terms*--Fast Three Phase reclosing – TPR, shaft duty, Thermal Power plant - TPP.**

I. Introduction

LINE or equipment switching or system faults may cause abrupt variation in machine active power that result in sudden torque imbalance on generator. For hydro units, where the unit's inertia is concentrated on the generator that takes the impact of this imbalance, only little impact is transmitted to others shaft elements, as gas or steam turbines. This is not occur for thermal units where the distribution of inertias along the unit shaft is such that the torque variation is transmitted along the shaft.

This fact gives rise to relative large torsional oscillations along the turbine generation shaft within a typical range of 10 to 50 Hz. These oscillations are relatively low damped and take several seconds to damp out. The occurrence of a three-phase fault close to the thermal unit gives rise to two such events, one upon the fault application, the other upon fault clearance. Due the low damped nature of torsional oscillation, a unsuccessful tripolar reclosing of transmission lines in the vicinity of the plant will constitute in a third (new fault application) and fourth (last fault clearance) impact. Depending upon the instant of reclosing, this third impact may bring energy into the shaft dynamics what mean an amplification of torsional oscillation leading to stress levels significantly in excess of design values.

In Brazil, fast three-phase reclosing is a practice acceptable since the system has been almost entirely hydro. However, as significant number of large thermal plants is scheduled to start operation in next few years in Brazilian system, this practice became questionable and need be revised.

This paper presents the evaluation of stress on shaft of Termobahia Plant due to three-phase reclosing. This was the first situation that had been considered by National System Operator – ONS. Several operational aspects focusing system reliability and machine safety were taken into consideration in the evaluation of problem diagnostic and cost effectiveness alternative of solutions.

Alvaro J. P. Ramos is part time professor with university of Pernambuco and a consultant of ANDESA (alvaro@andesa.com.br).

Rita K. Medeiros is now with CHESF.

II. Studied System

A. Electric System

Termobahia Power Plant is connected to the substation Jacaracanga through two 230 kV transmission lines. Jacaracanga substation is part of a regional system supplied from hydro plants through long 500kV and 230 kV transmission lines. Figure 1 shows a simplified one-line diagram covering the vicinity of Termobahia. The fast tripolar reclosing of lines shown in Figure 1 and its impact on Termobahia machine shaft is the main concern of this paper.

B. Power Plant

Termobahia power plant is comprised of one 300MVA generator, a single axis with one gas and one steam turbine. An additional machine is planned to be installed in future. The manufacturer provided the data required for synchronous machine model 59 of ATP program as well the shaft torsional model as is shown in Figure 2. This is a simplified four masses model expected to be capable of representing the most significant machine torsional modes.

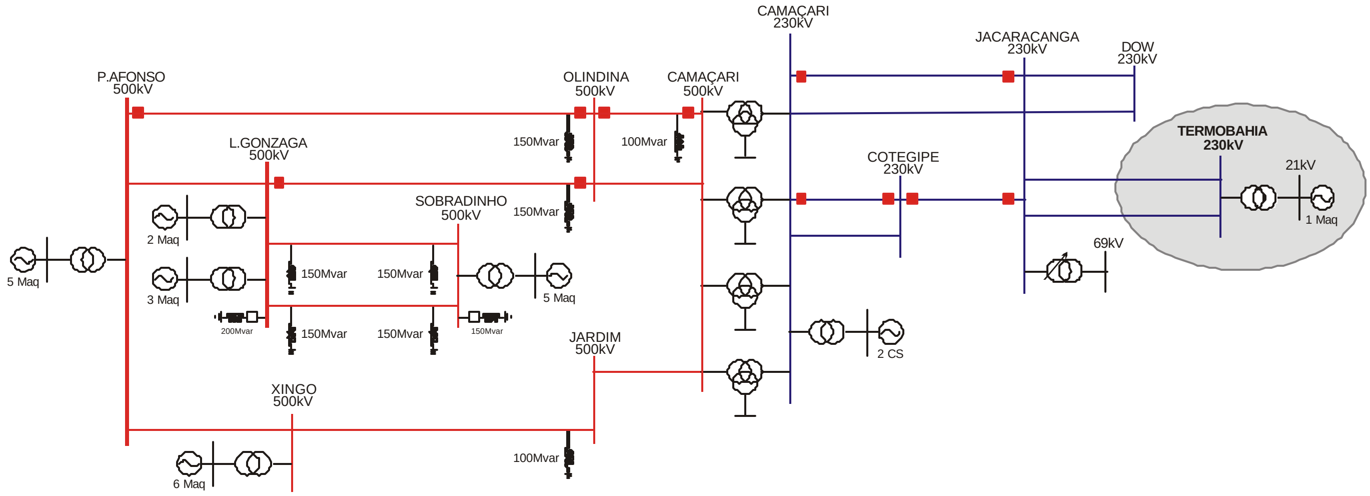

Fig. 1. Simplified one line diagram of the electric system in the vicinity of Termobahia.

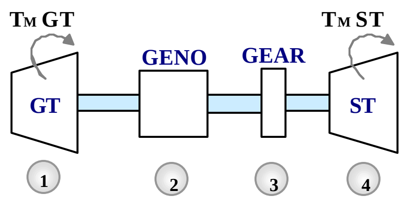

Fig. 2. Configuration of Turbines-Generator Shaft

Table I presents the date of shaft model used in the simulation. Damping effects were not considered.

TABLE I
GENERATOR-TURBINES SHAFT DATA

Nr	Inertia (kg.m2)	Spring Constant (kNm.rad)	Text
1	17880.00	53105.20	GT
2	8537.98	29051.70	GENO
3	314.48	49925.10	GEAR
4	291.94	-	ST

C. Line Reclosing Scheme

All 230 kV and 500 kV transmission lines of the electric system where Termobahia is located make use of tripolar reclosing. Lines protection relays only permit tripolar reclosing with exception of most recently built line Jardim – Camaçari 500 kV for which monopolar reclosing is also possible. The “dead-time”, that is, time interval between the first fault clearance and reclosing, is about 500ms for 500kV lines and varies within the range 1 to 1.5s for the 230 kV lines. Figure 3 presents the sequence of switching for unsuccessful tripolar reclosing cases here analyzed.

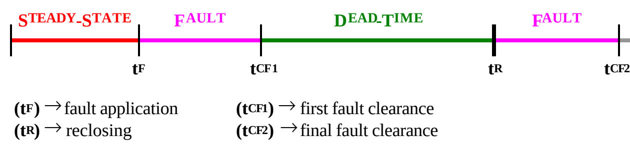

Fig. 3. Definition of switching times of unsuccessful reclosing.

For all cases the fault was applied (t_F=0.1s) in the line terminal closer to Termobahia. It is assumed that first zone protection of both line terminals operates almost simultaneously in 100ms (t_{CF1}=0.2s) tripping the faulted line. As mentioned before, the dead time varies for each particular line, so that there is different reclosing time t_R. The second fault elimination is $t_{CF2}=t_R + 0.1$s.

It should be observed that the 2^o terminal actually never close in case of unsuccessful reclosing (the fault remain on line) because the 1^o terminal trip again before 2^o terminal attempt to close. In case of successful reclosing, the second terminal close only if some procedures realized by the second terminal protection is checked. These procedures are usually referred to as “check of synchronism” and are usually based on voltage and phase angle verifications.

III. IMPACTS ON TURBINES-GENERATOR SHAFT

A. Machine Initial Condition

The analysis considered the machine operating with rated power. The initial operating point is presented in Table II that also defines the meaning of torques TOR1, TOR2 and TOR3. For example, TOR1 is the torque in shaft section between the GT (Gas Turbine) and GEN (Generator). Abbreviation “ST” means “Steam Turbine”.

TABLE II
TURBINE-GENERATOR (UNIT 1) INITIAL CONDITION (FULL LOAD)

Quantity	Value	Unit
Active Power (P)	193	MW
Reactive Power (Q)	-46.	Mvar
Voltage (V)	1.0	pu (21kV)
Generator Electrical Torque (TQ GEN)	0.51272	Million N.m
Torque T (GT+GENO) → TOR1	0.43581	Million N.m
Torque T (GENO+GEAR) → TOR2	0.0769	Million N.m
Torque T (GEAR+ST) → TOR3	0.0769	Million N.m

B. Torsional Natural Frequencies and Modes Shapes

The natural frequencies were determined by using modal analysis technique with the calculation of the state variable matrix A that express the set of linear differential equation (1) associated with the shaft dynamics:

$$\dot{X} = A.X + B.U \qquad (1)$$

where X is the state variable vector composed of masses angles and speeds and U is the control vector comprising mechanical torques.

Here the mechanical torque applied on gas turbine and steam turbine is assumed to be constant. The eigenvalues of A give the natural frequencies of the shaft system and the corresponding eigenvectors give the mode shape that reflect how each eigenvalue affect the different state variable.

Figure 4 shows the modes shape for the torsional frequencies f1=14.8Hz, f2=33.7Hz and f3=98Hz.

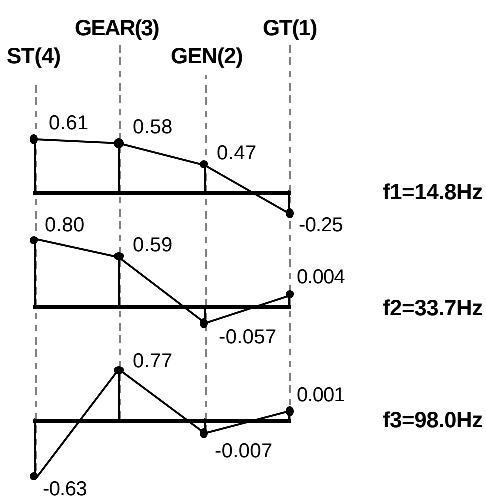

Fig. 4. Mode shape of torsional frequencies.

With eigenvalue analysis all torsional oscillation modes are identified what may be difficult with time simulations. For example, the participation of f3 on state variables is very low so that this frequency does not appear clearly in time simulation results. Figure 5 shows speed of mass 3 after a fault, where f1 and f2 are mixed together and f3 cannot be observed.

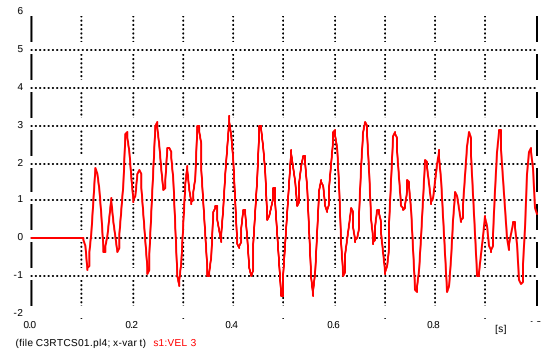

Fig. 5. Speed of mass 3 after a fault in the system.

Fourier analysis realized on this time result and performed within the frame 0.1 to 0.2 second is shown in Figure 6.

Just for convenience of calculation with ATP, the fundamental frequency is considered equal to 2 Hz in Figure 6, so that harmonic 17 means 34Hz as indicated by vertical gray bar. Frequency f3=98 Hz also appears, but very small as harmonic 49. Oscillation mode f1=14.8Hz is revealed by harmonic 7 and 8 (14 to 16 Hz).

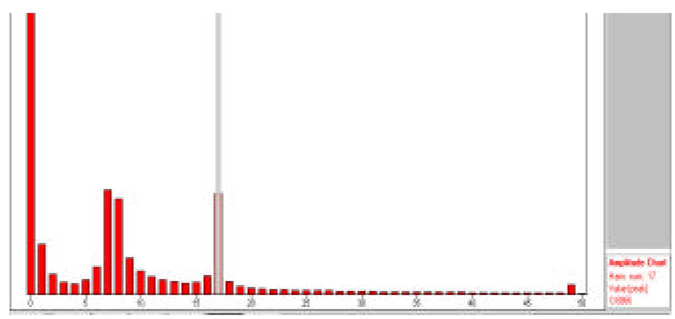

Fig. 6. Fourier analysis. Speed of mass 3 (Figure 5).

C. Three Phase Short-Circuit on Machine Terminal

According to ANSI C50.13-1989 [01] the generator must withstand a three-phase fault at its terminal. Figure 7 shows the electrical torque transient containing a decaying 60 Hz oscillatory component whose magnitude changes abruptly for the instants of fault application and clearance.

The 14Hz oscillation appears clearly in TOR1 (Figure 8) while TOR2 (Figure 9) and TOR3 (Figure 10) contain 14Hz and 34 Hz.

Note that TOR2 reaches peak value close to 4.0pu, considering the value 1.0pu as being the torque initial value.

It is expected that machine shaft withstand these stress value.

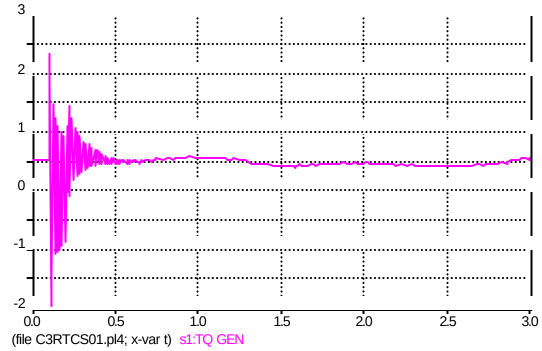

Fig. 7. Electrical torque for a three-phase fault.

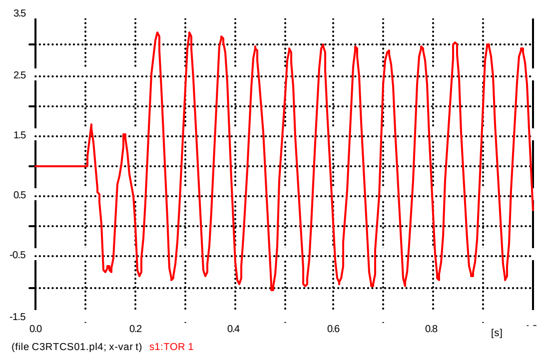

Fig. 8. Mechanical torque between gas turbine and generator (TOR1).

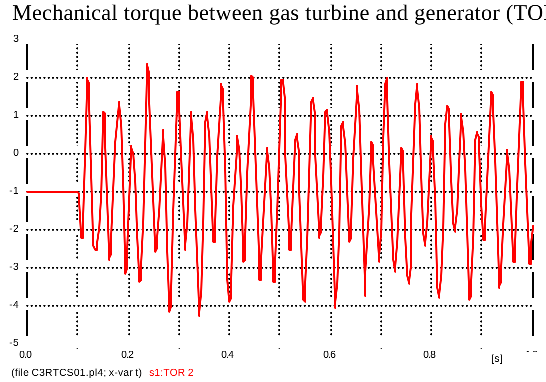

Fig. 9. Mechanical torque between generator and gear (TOR2).

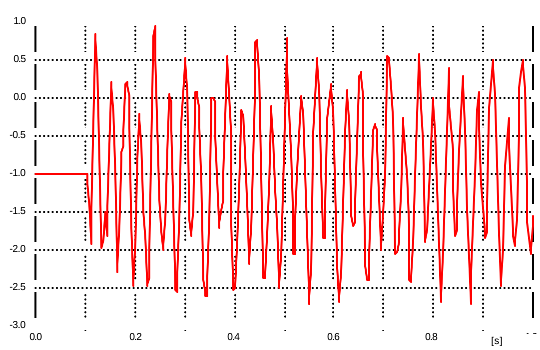

Fig. 10. Mechanical torque between gear and steam turbine (TOR3).

D. High Speed Reclosing of Transmission Lines

The reclosing scheme of lines as implemented on site was simulated where some variability was considered in looking for most severe situations. In fact, the instant of reclosing is critical to determine the level of shaft duty. Figure 11 and 12 show the transient torque in a shaft section of Termobahia unity resulting from a line unsuccessful reclosing at 1600ms and 1583ms, that is, a time difference of only 17ms. In case of amplification (Figure 12) torque TOR1 reaches values above 4,0pu.

This demonstrates that three-phase reclosing is a practice that leads to a risk for machine shaft since it is not possible to control the break instant of reclosing with precision of 17ms. The study has shown that torque greater than 6,0pu was obtained in some situations as shown in Figure 13. This fact needs an evaluation of manufacturer concerning with shaft withstand.

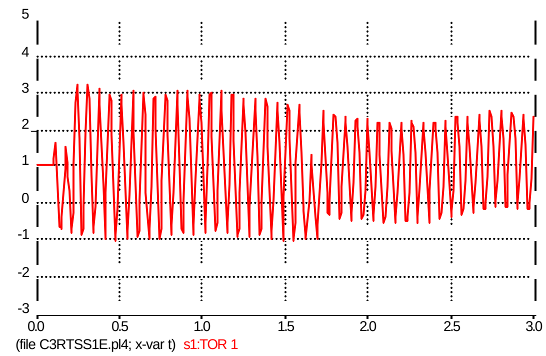

Fig. 11. Torque on generator-gas turbine section for a three-phase fault and unsuccessful reclosing of Jacaracanga – Camaçari line at 1600ms. Here, reclosing leads to attenuation.

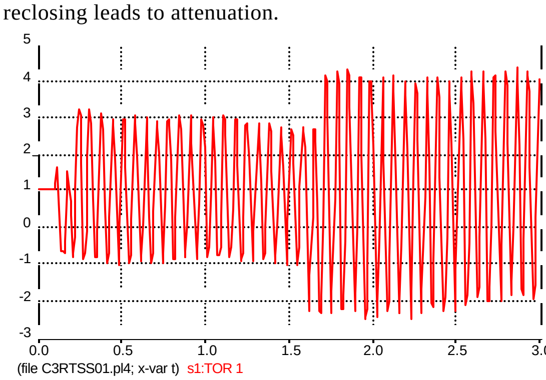

Fig. 12. Torque on generator-gas turbine section for a three-phase fault and unsuccessful reclosing of Jacaracanga – Camaçari line at 1583ms. Here, reclosing leads to amplification.

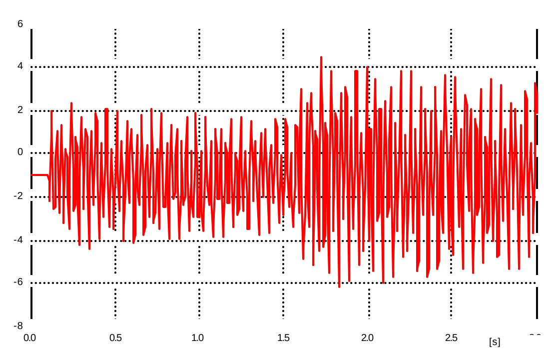

Fig. 13. Torque TOR2 for a three-phase fault and unsuccessful reclosing of Camaçari – Jacaracanga 230 kV line.

IV. Alternatives of Shaft Duty Mitigation

A. General Comments

The simulations of unsuccessful tripolar reclosing were based on machine and shaft model provided by the manufacturer, detailed network representation and realistic reclosing scheme. The stress on shaft sections were evaluated for expected most severe situations.

However, some questions of main concern still need a clear answer:

a) Can machine withstand such duty without risk of damage?
b) How these shaft duties contribute for material fatigue and premature machine loss of life?
c) How much detailed must be the shaft model to give reliable results or, in others words, how many masses are necessary to appropriate representation of shaft torsional dynamics?

Machine shaft is a complex mechanical system composed of several parts tied together. The evaluation of how the transient torques will impact the different parts of the shaft, demand a strongly detailed representation of machine shaft. This is certainly a task to be carried out by the manufacturer. Besides such technical complexity, the commercial aspects associated with machine guarantees also give rise to difficulties to the management of this problem.

The ANSI C50.13-1989 [1] establishes that the generator must withstand three-phase fault at its terminal. This is a standard for generators and it is not clear if it also covers the complete machine including shaft parts and turbines. If it is applicable to complete machine, the shaft duty verified due machine terminal three-phase fault could be used as a reference limit. For a three-phase fault at Termobahia machine terminals, a maximum torque of 4.0pu was obtained for TOR2 (generator/gear). This would be considered the limit of torque that machine withstand without risk of failure.

Our experience to date indicates that the machine manufacture hesitate to have a clear position about above issues leading the machine owner to an uncomfortable position of assuming the risks of eventual unsuccessful tripolar reclosing. On the other hand, the System Operator refuses to eliminate tripolar reclosing without a consistent evaluation of machine risk.

B. Increasing Reclosing Dead-Time

It is interest of machine owner to reduce as much as possible the shaft stress due transmission lines reclosing. When the dead time is enough larger to assure that torsional transient is finished, the tripolar unsuccessful reclosing represent only a new simple three-phase fault. Given that damping parameters are seldom available in torsional models, it is not possible to determine adequate and safety dead time for line reclosing by means of simulations.

C. Sequential Reclosing

This is means that the 1^0 terminal to reclosing is remote from the power plant. Only after the "check of synchronism" be performed, to assure that the fault was eliminated, the plant end breaker (2^0 terminal) is allowed to close.

Unfortunately, for our present system, the effectiveness of sequential reclosing is low for 230 kV lines due the existence of several others short lines in the region making the remote terminal electrically close to the plant. Sequential reclosing is used for the 500 kV lines (Figure 1).

D. Selective Reclosing

The selective reclosing needs a mean of distinguishing the type of fault and permit line reclosing only for single phase and phase-to-phase faults. This needs line protection schemes capable of identifying fault type.

There is the risk that the fault initiates as phase to phase and become three-phase during dead time period. This may be likely to occur in cases of fire under or close to transmission lines. Farmers sometimes make use of this practice to clean up plantation areas.

V. Final Remarks

Three-phase reclosing of lines in the vicinity of thermal units should not be a practice without a careful analysis of machine torsional stress levels. The possibility of unsuccessful reclosure may lead to torsional stresses that exceed machine limits. In Brazil tripolar reclosing is a normal practice but this has not been a problem so far because almost generation were hydro.

The installation of thermal unit in Brazilian system demands detailed analysis of machine shaft transient torques. These studies have to be carried out with appropriate modeling of electric system and machine with realist parameters.

As long as the authors are acquainted, there are no standards or technical guidelines establishing shaft torsional stress levels that machine should withstand. Machine manufacturer should be requested to provide this information so that plant owner can preserve machine guarantees and avoid risk of damages or premature loss of life.

VI. References

[1] ANSI C50.13-1989, American National Standard for Rotating Electrical
Machinery – Cylindrical-Rotor Synchronous Generators

[2] C. E. J. Bowler, F. G. Brown, D. N. Walker, "Evaluation of the Effect of Power Circuit Breaker Reclosing Practices on Turbine-Generator Shafts", IEEE, TRANS on PAS, Vol. PAS-99, No 5, Sept/Oct. 1980.

[3] J. M. Undrill, L. H. Hannett, “Turbine-Generator Impact Torque in Routine and Fault Operations”, Paper and discussions .IEEE, TRANS on PAS, Vol. PAS-98, N0 2, March/April 1979

VII. Biographies

Alvaro J. P. Ramos was born in Recife, Brazil, on 1951. He graduated from the Federal University of Pernambuco in 1973 and received the MSc degree from Federal Engineering School of Itajubá in 1975. In 1974 he joined CHESF where he was engaged on electric studies up to 1998. In 1998 he founded ANDESA a consulting company that provides electric studies for many utilities in Brazil. Since 1977 he is part time professor at Escola Politécnica of Pernambuco University. He is a Senior Member of IEEE.

Dalton Lima was born in Picos, Piauí - Brazil, on October , 1950. He graduated from the Federal University of Pernambuco - UFPE, 1974... His employment experience included the Oil Refinery- Refinaria Landulpho Alves - Petrobras, and Cicle Combined Power Plant, Termobahia S/A. Nowadays, he is Termobahia’s Administrative Director.

Egberto P. Tavares is graduated in Electrical Engineer UNIFEI in 1971, Master in Sciences in Electrical Engineering UNIFEI in 1975. He joined ELETROBRÁS in 1975 where he worked up to1996. Since 1996 is Technical Director of CTM Engineers. Professor at UNIFEI (19723/75), PUC-Rio de Janeiro (1975/878), Universidade do Estado do Rio de Janeiro (1993/89) and since 1983 , at Universidade Federal Fluminense. He is author of the book "Electrical Distribution Planning and has several technical articles published. He is Owner's Engineer of Termobahia project and is taking care of the issues related to the Brazilian Electrical Sector Organization, including Contracts, Agreements and approval of Switchyard, Transmission Line and connection to the Grid substation documents

Rita K. Medeiros was born in Recife, Brazil, on January 27, 1974. She graduated from the Escola Politécnica de Pernambuco – UPE in 1997. In 1998 she joined ANDESA where she was involved with dynamic and electromagnetic studies. She was with ANDESA up to October 2002 when she joined CHESF.