The Influence of Short Circuit Level in the Energization Process of Electric Power System's Transmission Lines

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Abstract - **This MSc Thesis discusses short circuit level influence over the recovering of long electric power transmission lines for voltage levels above 230kV. Brief comments are made on all factors that influence the energizing process of extra-high voltage transmission lines, modeling used, and their impact on transient electromagnetic studies.**
ATP, "Alternative Transients Program" software is presented and we discuss the modeling techniques used as well as the field research done to compose the parameters for this program.
More than one hundred electromagnetic transient studies were made do investigate short circuit level impact on long transmission lines using the 500kV transmission system belonging to Eletronorte Company in State o Pará. Results proved that the efficiency of this process was so important that they lead to changes in operational procedures so far adopted in Eletronorte Operation Center and also increased operation security concerning electromagnetic effects on lightning rods during the energizing process of long electric power system transmission lines.

Keywords: Very Fast Transients, Short Circuit Level, Energization Process of Electric Power System's Transmission Lines, Real-Time Monitoring, and Power Quality

I. INTRODUCTION

The Operation Center's team is structured to guarantee the operation and control of the State of Para transmission system. The economic viabilization of the power flow exchanges with northeast and south regions of Brazil are also guaranteed through the use of the Automatic Generation Control – AGC.

The interconnected transmission system in Eletronorte's area has radial characteristics with long transmission lines in 500 and 230 K Volts. This system is supervised and remote controlled by a local area network computational system centralized in Belém Operation Center – COL-BE. The figure 1 presents the electric power system operated by this center.
Since the 90´s Brazilian power transmission system is suffering many changes. Among these changes a very important one is the "deverticalization" of the electric power system model, i.e. the separation of transmission and generation companies. At this new scenario, the revenue of the transmission companies depends on the availability of it's directly connected equipment, and it does not depend on the amount of transported energy.

Two aspects affect transmission companies significantly. The first one is the number of breakdowns of the equipment contracted by the National Operator - ONS. The second one is the availability of the equipment.

Penalties are imposed by ONS if the contracted equipment breaks down, so great losses of revenue of transmission companies are due to inopportune break downs directly related at the unavailability moment.

For the Eletronorte's high voltage transmission system of radial characteristics, most of the time, the transmission lines recovering time is related to the time the operation takes to reduce the voltage value of the source. This time is dictated by electromagnetic transient studies.

The accentuated time to reduce voltage in the source is dictated by recommendations of over-voltages and abnormal energy circulation in time intervals inferior to 100 milliseconds observed in the simulations of electromagnetic transients.

The recommendation of maximum voltage profile were exact for areas that develop special studies that focuses the coordination of isolation of the electric system and preservation of equipments submitted to voltages surges.

Within this context, the operative recommendations imposed by studies of electromagnetic transient during pre-operation phase does not motivate the personal to minimize the transmission companies problem related to the recovering time for long high voltage transmission lines due to the natural load growth and long short circuit time.

The transmission company needs a more operational view of the difficulties presented by the recovering process that brings revenue losses.

Eletronorte looked for a methodological routine to minimize recovering transmission system time. This routine was obtained from a meeting of transmission companies. The primary aspects discussed in this meeting were:

- The influence of short circuit power of the energizing source is related to the number of machines in Tucuruí Power Plant.
- The influence of real representation of the saturation characteristics and of the impedance due to magnetization of autotransformers to reduce electromagnetic effects.

To establish this methodology electromagnetic transient simulations were made in the northeast Para area of Eletronorte's transmission system that is considered the most critical one.

This transmission system, besides been critic is extremely strategic since it assists 97 municipal districts of the 143 existents in the state. It transports 80% of the energy distributed by the local distribution company Rede Celpa. It also transports 100% of the energy used by Aluminum of Brazil – ALBRAS, an electric intensive aluminum company with an average 720 MW consumption.

II. PROBLEM CHARACTERIZATION.

With globalization the Brazilian electric sector went through significative structural procedural changes. Flexibility and the capacity to give fast answers to new situations are a characteristic of this new period.

Eletronorte, a transmission energy company had to adequate itself to the rules of ANEEL, the electric energy regulator agency where main revenues come from the utilization of the Brazilian interlinked basic electric network.

A. Time to Recover a System.

The steady state operating voltage at Tucurui substation is 550 KV so as to achieve maximum energy flows on the Eletronorte interconnections. Considering this voltage level as a primary condition we will discuss two main problems related to the time to recover the system as a function of the imposed voltage energization.

B. Recovering an area inside Para State when other áreas are in normal operating conditions.

Tucurui substation has three radial high voltage lines (figure 1). The first one feeds the northeast region of Para State. The second one feeds the interconnected brazilian system and the last one feeds the west side of the State. In the case of loss of one of those radial lines the company follows the "Operative Instruction" to recover the line. This operative instruction stablishes a maximum voltage level of the order of 525 KV due to transient electromagnetic restrictions.

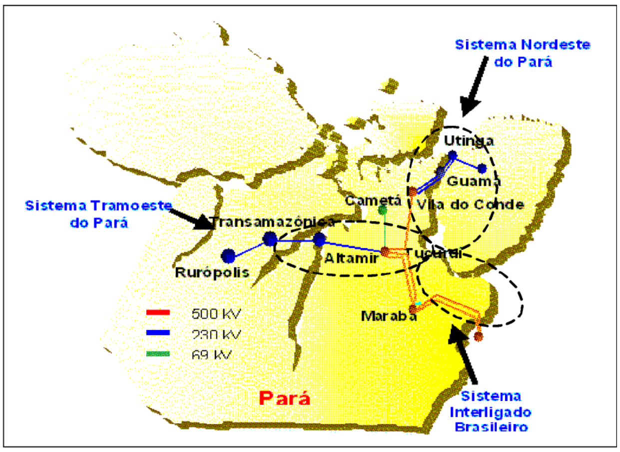

Figure 1 – Eletronorte Transmission System – 500 kV and above

It is necessary to reduce voltage level from 550 KV down to 525 KV. To accomplish this we must reduce energy flow on the interconnection lines between the transmission systems involved: north, northeast and central west systems so as to maintain the dynamic stability.

From this moment on we are commited to regulate voltage as the energy flow becomes smaller. To do this the voltage regulation on the remaining system demmands a mean time of 25 minutes.

This long period of time brings with it high penalties imposed by ANEEL. These penalties reduce the company revenue in U$ 1,414.66 per minute when, for example, the sole transmission line from Tucurui substation to Vila do Conde substation is lost. As shown in figure 1 this line belongs to the northeast area of Para State and its lost for a 25 minutes duration implies a lost in receipt of the order of U$ 35,426.50.

In the worst case, if during this time we also loose the supervisory and control SCADA system located at Belem the time to recover goes to a value between 60 minutes rising the penalties in 2/3. This is due to the dificulties found by the operators. This dificulties are mainly due to:

Lost of all energy flow on-line information so they must coordinate the flow reductions using telephones to communicate with operators presente in susbstations.

Lost of the remaining electric system voltage profile so that the voltage reduction coordinations can only be achieved using telephones to communicate to other substation operators.

Lost of the automatic generation control – AGC of the Tucurui Hidro Electric Power Plant so the controls come to manual and the communications with that HPP must be done by telephone.

Lost of breaker remote control to the 500 KV substations that now must be done locally by the operators of each involved substation.

Lost of the Automatic Voltage Control of the substations involved so that the TAP changes must alse be done locally.

Although not frequent, the lost of the SCADA system occurred 10 times during 21 years of operation so it must be considered. In this worts case the lost in revenues come to U$ 84,999.60 per disturbance.

C. Recovering Para electric system after a blackout.

To recover the Para electric system in the case of blackout we use an "Operating Instruction" which determines the the maximum voltage level to energize is of the order of 498 KV due to electromagnetic transient restrictions.

To process this voltage regulation we must actuate on the Tucurui HPP terminal machine voltages bringing them to their minumum operating condition of 13.11 KV. This demands a long period of time rising the mean recovering time to 74 minutes mainly because each machine voltage regulator must be blocked.

In thist case the penalties per disturbance reaches U$ 106,249.50 and definitly negatively compromises the image of the company.

We must finally emphasize that in the case of loosing the SCADA system this time may come to a 95 minutes recovering time so the penalties may achieve U$ 134,582.70.

III. SIMULATIONS

A. Energization of the Tucuruí / Vila do Conde 500 KV transmission line after a blackout in all Para.

Figure 2 shows the energy absorbed by the lightning rods of the line in 500 KV Vila do Conde substation terminal. The curves represent the phases where the largest over-voltage transients occurred during energization. Data in red considers 3 machines and data in green considers 8 machines turning in the Tucurui Power Plant energizing source.

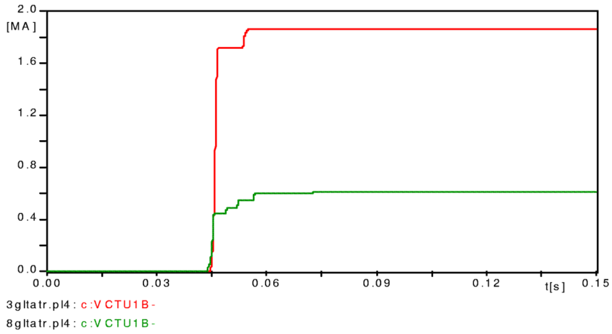

Figure 2 - Energy absorbed by the lightning rods 500 kV in the Substation VC, with generating units to emptiness.

In this simulation a 530 KV voltage was considered in Tucuruí 500 KV substation, the energizing source. The simulation results are shown by the red curve. Clearly, the amount of energy absorbed by the lightning rod of phase B for the 3 machines configuration reaches the order of 1.8 MJ which exceeds the value of 1.6 MJ maximum absorbing capacity. This result definitely forbids Tucuruí – Vila do Conde transmission line energization using 530 KV voltages.

The result presented for an 8 machine configuration in Tucuruí Power Plant indicates a value of 0.6 MJ energy absorption. This value is inferior to the lighting rod's capacity so it does not pose any operative restriction. As far as the lightning rod's capacity is concerned we could use a voltage superior to 530 KV.

Figure 3 presents the transient over-voltages that occurred in Tucuruí / Vila do Conde transmission line. The curve represents the phase where the largest over-voltage occurred during energization. The green curve considers 3 turning machines in the energizing source and the curve in red represents 8 turning machines in Tucuruí Power Plant.

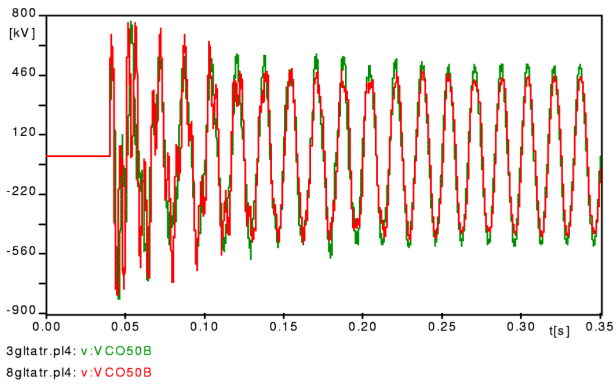

Figure 3 – Transient over-voltages in 500 KV Vila do Conde substation.

The over-voltage results presented above stands for the bearing criteria of the equipments related to the presented over-voltage levels. However, the energization would fail in the 3 machines configuration as the voltages would stabilize in 1.23 pu value actuating the sustained over-voltage relay which has an adjustment of 1.2 pu. For the 8 machines configuration however the voltages would maintain an order of 1.09 pu that allows an energization process with voltages of 530 KV.

III. DISCUSSION.

Usualy studies to check de behavior of overvoltage levels due to electromagnetic phenomena during energization process consider only the influence of the following factors:

The value of the energization voltage.

The capacitive effect of long high voltage lines.

Contact break scattering.

Saturation curve.

Operating directives are elaborated following those rules so that studies are processed limiting overvoltages and overcurrents with a strong investiment on the equipment isolation characteristics fixing minimal short circuit configurations on the energizing sources.

Besides that, conservative rules are aplied on sustained voltages since we consider base operating voltages and we do not exploit nominal isolation equipment voltages involved as the maximum steady state allowed voltage reference.

Main restrictions of Para State energy transmission system related to electromagnetic transients deppend on the lighting-rod absorption capacity and on the sustained steady state voltage.

When an electric power system has these types of electromagnetic restrictions, rising the short circuit level of the energizing source can eliminate lightning-rod capacity restrictions facing the amount of energy involved during energization maneuvres and reduces the sustained steady state voltage.

The following discussing uses facts and datum to point to the importance of considering short circuit level.

A. Comparative analysis of a 3 to 8 machines Tucuruí HPP configuration to energize the Tucuruí to Vila do Conde line in a blackout situation.

Figures 4, 5 and 6 present the results of recovering the Tucurui / Vila do Conde 500 KV line. The overfoltages on the first 6 cycles do not present considerable differences if we compare a 3 to an 8 synchronized machines configuration (figure 4). However to an 8 machines configuration we had a sustained steady state voltage level of 1.15 pu and for a 3 machines configuration that leve went to 1.2 pu (figure 5). this difference indicates that for an 8 machines configuration the recovering achieved and for a 3 machines configuration the sustained voltage level took the temporized overvoltage relay to actuate disconnecting the energized line. From the point of view of the lightning rods integrity, this difference shows that with 8 machines the lightning rods integrity are held as for a 8 machines configuration we had 1.14 MJ of energy and for a 3 machines configuration we had 1.84 MJ (figure 6) wich exceeds theis capacity.

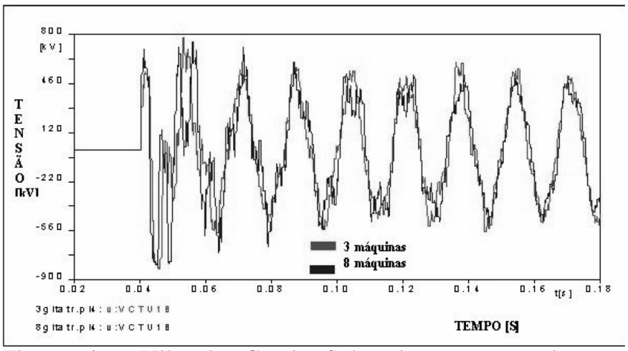

Figure 4 - Vila do Conde Substation – comparing beginning and end voltages – 3 & 8 machines. No load.

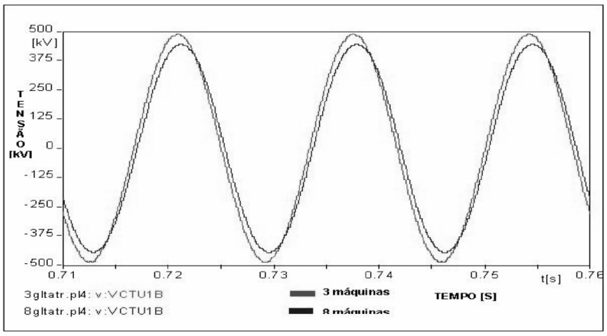

Figure 5 - Vila do Conde Substation - comparing steady state voltage – 3 & 8 machines. No load.

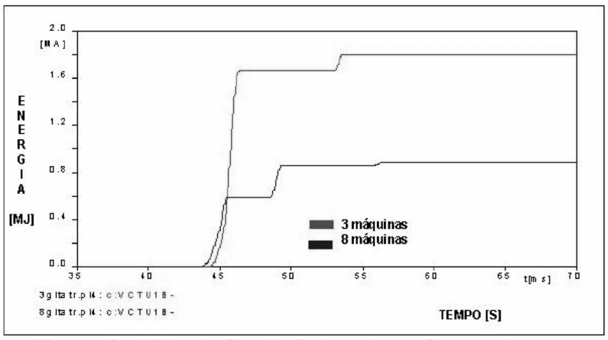

Figure 6 – Vila do Conde Substation – Comparing lightning rods energy – 3 & 8 machines. No load.

The positive effects brought by the rising short circuit level allows a decision to be taking depending on the number of synchronized machines on the Tucuruí HPP (see table 1). In other words, with 8 synchronized machines the energization voltage corresponds to a terminal voltage of 1.00 pu in each of Tucuruí machines (number 3 simulation). This terminal voltage levels can easily be achieve by the operators in a period of time inferior to 5 minutes corresponding to a loss of revenue of U$ 7,083.30 per disturbance (table 2). To a 6 machines configuration, the terminal voltage level comes to 0.98 pu (simulation number 5) also easily achieved in a period of time inferior to 8 minutes corresponding to a loss of revenue of U$ 11,333.28 per disturbance (table 2).

Table 1 – Simulation with energizing source without load.

Energizing source– Tucuruí HPP			
Simulation	Energizing voltage (pu)	Number of machines	Energization
1	1,07	03	Prohibitive
2	1,07	06	Prohibitive
3	1,07	08	Allowed
4	1,05	03	Prohibitive
5	1,05	06	Allowed
6	0,98	03	Allowed

Using the nowadays criterium the “Operating Instruction” stablishes that the recovering of the northeast Para State region with a no-load Tucurui HPP, the energizing voltage must be of 0.97 pu of a 500 KV voltage whenever we have 3 or more machines which leads us to a terminal voltage of 0.93 pu (simulation number 6). This is the situation where the operators find great difficulties to adjust the voltage as the voltage regulators become practicaly blocked with no response. It is in this situation that we go to a 75 minutes to recover time and a U$ 106,249.50 loose in revenue.

Table 5. 1 – Time to recover and financial looses.

Energizing source– Tucuruí HPP				
simulation	Energizing voltage (pu)	Number of machines	Mean time to regulate the voltage (minutes)	Financial loss (U$)
3	1,07	08	5	7.083,30
5	1,05	06	8	11.333,28
6	0,98	03	75	106.249,50

Cases 1, 2 and 4 were not included inside table 5.4 as they are prohibitives.

B. Comparative analysis of a 3 and 8 Tucuruí HPP machines configuration to energize Tucuruí to Vila do Conde transmission line when part of the electrical system is loaded.

Table 3 presents a comparison between energizing voltages in Tucurui / Vila do conde 500 KV transmission line with a line reactor in Vila do Conde substation when the remaining of the linked electric brazilian system in normal operation. It becames evident that positive effects of the rising of the short circuit level of the energizing source during recovering of the norteast region of Para State.

Table 3 – Simulations with loaded energizing source.

Energizing source – Tucuruí HPP			
Simulation	Energizing voltage (pu)	Number of the energizing source machines	Energization
1	1,1	09	Allowed
2	1,1	06	Prohibitive
3	1,08	07	Allowed
4	1,08	06	Prohibitive
5	1,05	06	Allowed
6	1,05	03	Prohibitive

Once more the positive effect caused by the rising of short circuit level allows a decision making as a function of Tucurui HPP machine configuration (table 3). That is, with 9 synchronized machines the energizing voltage corresponds to a terminal voltage of 1.03 pu at Tucurui HPP (simulation number 1). This former level is already attained as the steady state operating level is a 500 KV 1.10 pu. So, in this case we do not have a loss of revenue. For a 7 synchronized machines terminal voltage is 1.01 pu (simulation number 3). This level can be obtained in a period of time inferior to 10 minutes causing a U$ 14,166.60 per disturbance loss.

IV. CONCLUSION

The results of this study showed the importance of considering the short circuit level factor in electric power system when we want to eliminate electromagnetic restrictions due to high voltage sustained level or due to the surpassing lightning-rods capacity. The results allow the use of this methodology in restrictive situations in other areas of Eletronorte Transmission System.

During the first ten cycles, voltage levels are not affected by short circuit level when the line from Tucurui to Vila do Conde is energized. High capacitive effect of the energized line (485 Mvar) prevails within the first moments.

If the Tucurui Hidro-electric power plant uses a configuration with more then 8 machines and with part ot the electric power brazilian system in steady state normal operation, the energizing voltage level on the Tucurui to Vila do Conde line may achieve 1.10 pu so that line can be immediately connected. This means that the northeast power system of the State of Para needs no time to be energized.

If the Tucurui Hidro-electric power plant uses a configuration with 7 machines and if part ot the electric power brazilian system is in steady state normal operation, the energizing voltage level on the Tucurui to Vila do Conde line may achieve 1.80 pu. This brings the actual 25 minutes energizing time to 10 minutes. This reduction in time brings us to a R$21,249.00 savings in penalties per disturbance. Also, although not yet adopted by the Brazilian Electric Power Sector, the social interrupt cost is of the order of U$26,000.00 / minute which means a U$156,000.00 social penalties reduction.

It takes a 5 minutes time interval to synchronize each of a 6 machines configuration at Tucurui HPP. This fact definitly consolidates the rising of short circuit level on the energizing source as a aid to be explored.

Below 1.03 pu (515 KV), when load is present in part of the electric system, the operators find difficulties to reduce terminal machine voltage levels at Tucurui as these levels become near the blocking regulators voltage levels. In this situation we have a long recovering time.

During an Eletronorte transmission system blackout the energization voltage level at Tucurui / Vila do Conde line may achieve 1.05 pu (525 KV). This must reduce recovering time from the actual 75 minutes down to 8 minutes. It must be noted that this time recuction eliminates U$ 94,916.12 penalties per disturbance. Although not yet adopted by the Brazilian Electric Power Sector, the social interrupt cost is of the order of U$ 26,000.00 / minute which means a U$ 1,742,000.00 social penalties reduction.

In march 2002 we had an automatic disconnection of Tucurui / Vila do Conde transmission line leading to a blackout of all northeast of Para State. Tucurui HPP was left with 7 machines feeding the interconnected brazilian system. The methodology described in this paper was adopted in that circunstance recovering that line with a voltage level of 1.08 pu. The result was an 8 minutes recovering time record. In april 2002, in a similar disturbance, 1.08 pu voltage level was again used achieving 8 minutes recovering time. The overall reduction in receipt losses were of the order of U$ 21,249.90 per disturbance.

The results found in simulations were legalized by the National Operator ONS after analizing the procedures adopted when both disturbances occured and that institution created a new Operating Instruction to recover the area of Para.
The modeling using the base voltage shock correction of the auto-transformers through fictitious TAPs used by ONS inside the program to simulate steady state is not, by all means, adequate as it presents value deviations found in equipments for voltage regulation such as the synchronous compensators at Vila do Conde of the order of 50 %. Nevertheless the base shock correction by impedances showed consistent. They presented deviations below 5 % when compared to field values.

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